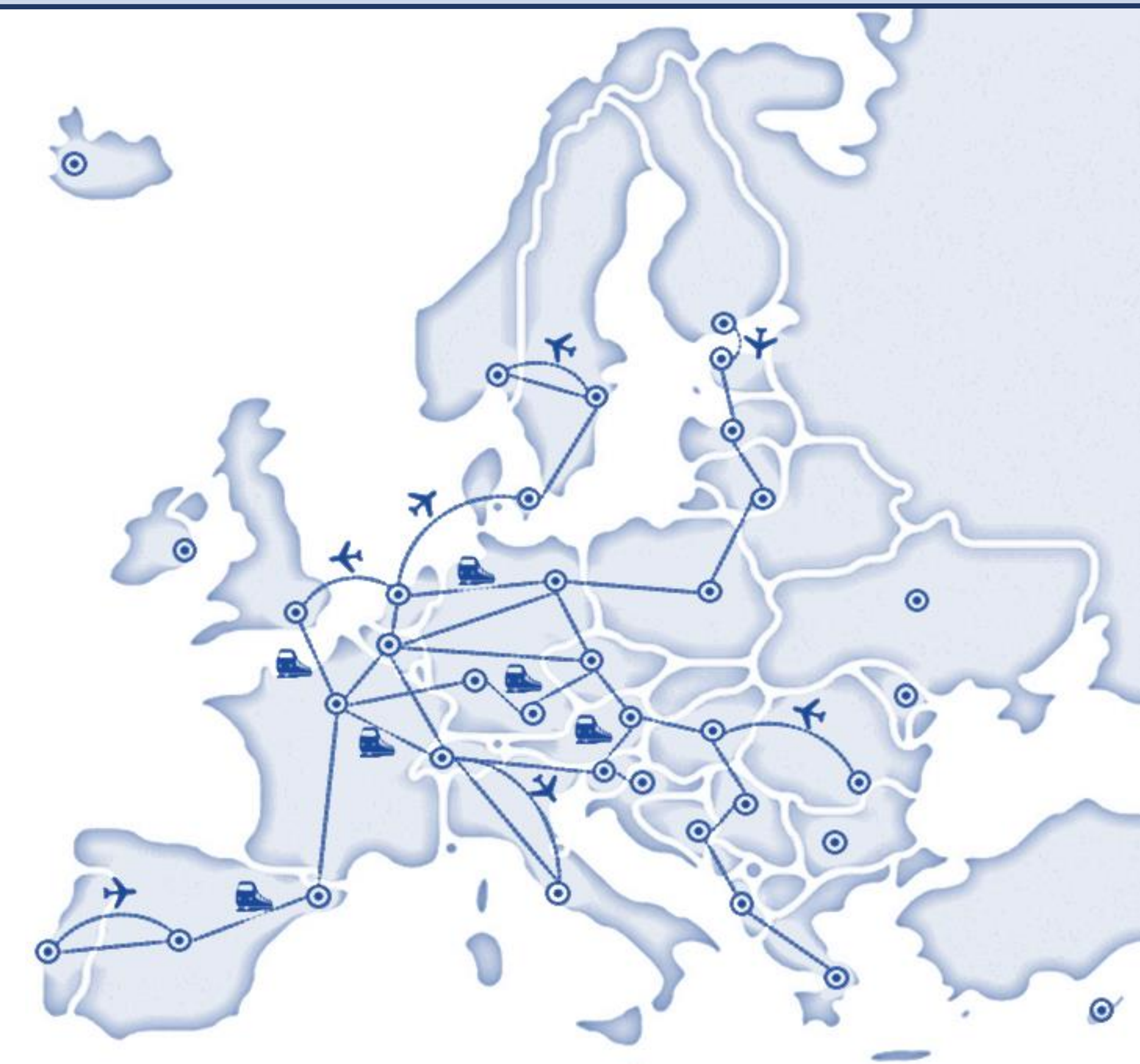
Infrastructure implications of intra-European short-haul flight substitution with high-speed rail

A supply-based network design problem

Panagiotis D. Christopoulos | MSc Thesis



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Infrastructure implications of intra-European short-haul flight substitution with high-speed rail

A supply-based network design problem

By

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in Transport, Infrastructure and Logistics
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Preface

This thesis project with the title "Infrastructure implications of intra-European short-haul flight substitution with high-speed rail: A supply-based network design problem", marks the final step towards completing my Master of Science degree in Transport, Infrastructure and Logistics, at Delft University of Technology. Throughout my academic journey, I faced numerous challenges, but through determination and focused effort, I was able to overcome them and achieve my goals.

I would like to thank everyone who have supported me during this journey. My heartfelt thanks go to my academic supervisors, Alessandro Bombelli and Maarten Kroesen, and my committee chair, Oded Cats. Their expertise, patience, and guidance were invaluable, while their unwavering support and encouragement were instrumental in the completion of this thesis, offering me both academic and personal advice.

As this project was conducted in collaboration with Royal HaskoningDHV, special thanks go to my company supervisor Barth Donners, who constantly aided me in overcoming challenges. His precise feedback and personal guidance were crucial in improving my work and staying on track. Working with him offered me significant practical insights and industry knowledge, making this a unique and enriching experience. I would also like to thank the company members I met during my thesis, for creating a professional and supportive work environment during my time there.

Finally, I would like to thank my friends and family who continuously supported me during my studies, and especially my girlfriend who was always by my side, encouraging me and making everything seem easier during this journey. This would not have been as rewarding and successful without the support and encouragement from everyone.

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Panagiotis Dimitrios Christopoulos

Abstract

Short-haul flights are often perceived as more carbon-intensive compared to medium and long-haul flights, primarily due to their higher fuel consumption relative to the distance covered. High-speed rail presents a viable alternative to these flights, offering significant environmental benefits while maintaining a competitive service level. However, due to lack of knowledge regarding the design of large-scale high-speed rail networks, there is a notable gap in understanding how existing infrastructure can strategically influence network modifications, for the development of a more integrated rail network across Europe. This relates to how the network is utilized in terms of meeting the substituted demand, as well as the costs involved in operating services within this reconfigured setup.

This research attempted to develop a model that adapts the “Transit Network Design and Frequency Setting Problem”, commonly used in transit planning, to a high-speed rail setting. This model identifies the optimal routes and their corresponding lines, and computes their respective frequencies, based on an existing network. This was achieved through a manual optimization approach, which in contrast to traditional optimization problems, constraints are incorporated into a specially developed Line Generation Algorithm, where parameters are input to generate a set of paths. Subsequently, frequencies treated as decision variables in the model, and objectives are calculated using a Frequency Setting Algorithm. The methodology was applied to the European high-speed rail network as a case study. By using different demand distributions for two scenarios (each varying in the geographical extent of the analyzed area within Europe), the study was able to assess the impacts of modified network designs.

The scenarios revealed that the impact of modifications varies based on the implementation area and the state of existing infrastructure. In a smaller, more developed, and centralized network, the need for creating new operational lines is less pronounced. Instead, primary modifications involve frequency adjustments of existing services, which incurs high operating costs due to the tactical nature of such planning. Conversely, in a larger area with a varying infrastructure level of development, there is a greater need for configuration changes and the creation of new lines. This scenario involves fewer operational vehicles and, consequently, lower costs, with vehicles spread over a wider area. Moreover, the model presented various alternatives where a balance between maximizing capacity utilization and minimizing costs can be achieved. This provides stakeholders with multiple implementation options, allowing them to choose based on their unique perspectives and goals. Informed decisions can be made based on the networks’ performance assessment in terms of coverage, since it was observed that in larger areas, it might not be feasible to serve all destinations, as well as in terms of expansion potential, considering the network's capacity to handle increased demand that could be effectively met by the proposed modifications.

Overall, this study showcased the possibility of utilizing current infrastructure and network layouts to propose efficient modifications for expansion and accommodating passengers transitioning from air to rail. This approach fosters a deeper understanding of high-speed rail network design, focusing on enhancing and integrating existing networks rather than designing new ones, highlighting the potential for improved mobility and sustainability on a large scale from a supply-based perspective. Future research could contribute by exploring various case studies differing in size and location, and by including both user and social perspectives on costs. This would allow for the development of design alternatives that consider a wider range of viewpoints, instead of only the operator's focus on minimizing operating costs. Incorporating elements like timetabling and operational factors could further broaden the scope, enabling a comprehensive evaluation of results across the entire spectrum of planning, from high-level strategy to daily operations and implementation.

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Introduction

In recent years, the aviation industry has made significant progress towards sustainability, however, its large environmental footprint highlights the need for more stringent measures. Despite technological advancements that enhance efficiency and reduce emissions such as new aircraft, the rapid growth in air travel indicates that aviation continues to be a significant contributor to climate change. Air transport accounts for approximately 2% of man-made carbon dioxide (CO_2) emissions worldwide, and roughly 5% of the total greenhouse gas (GHG) emissions when considering all emission types (IATA, 2020). Even though longer flights result in more emissions overall, short-haul flights are particularly carbon-intensive due to their high fuel consumption per passenger-km. To combat these negative externalities, national and EU authorities are exploring strategies to encourage greener transportation options. One strategy involves banning short-haul flights and enabling modal shift towards environmentally friendly alternatives where technically possible. Among these alternatives, rail emerges as one of the most sustainable and secure mode of transportation, with the potential to significantly reduce GHG emissions and align with the EU's environmental goals of cutting transportation-related emissions up to 90% by 2050 (European Commission, 2021-a). Due to major investments, European railroads have already decreased their carbon footprint almost by half, compared to 1990, while simultaneously increased passenger and freight volumes (Lochman & Fikar, 2020). Due to comparable travel times and distances, high-speed rail (HSR) systems have emerged as the most prominent candidate to substitute air transportation in the short-medium haul markets. Nevertheless, such an air-to-rail transition inevitably will result in modifications to both the air and rail networks, as well as significant impacts on the industries' environmental and financial aspects.

This chapter introduces the broader context of this study. A research background exploration is performed is *section 1.1* regarding the short-haul flight's negative externalities and potential substitution by HSR. Following, the problem statement, the identified research gaps and the overall scope and objective of this study are presented in *sections 1.2*, *1.3* and *1.4* respectively, while the formulated research questions that are aimed to be addressed in this research are given in *section 1.5*. The relevance of this research by scientific, practical and company perspectives is presented in Section *1.6*. Finally, *sections 1.7* and *1.8* provide an overview of the study's methodological approach and the structure of the report respectively.

1.1 Research Setting

Aviation industry and short-haul travel

Since the introduction of commercial air travel, the aviation industry has experienced rapid growth worldwide, making it one of the fastest-growing sectors in terms of the global economy (Bernardo & Fageda, 2019). In addition, the industry has demonstrated how rising economies and populations in emerging nations are linked to an increase in air travel over time. When it comes to traveling long distances, airplane is the most dominant mode of transport. However, due to urbanization and the emergence of large cities that require efficient connections, flights covering shorter distances have also significantly increased (Filimonau et al., 2014). To adapt to the ongoing globalization, air travel will continue to increase in international trade and tourism between countries around the world, as well as within the countries themselves (Bernardo & Fageda, 2019).

Although civil aviation is an efficient way for transportation, it also brings significant environmental externalities, since various aviation-related emissions including carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur dioxide (SO_2), and carbon monoxide (CO), have a substantial impact on people's living conditions and health (Liao et al. 2021). According to Filippone & Parkes (2021), there is a lot of variation in emissions even throughout a single route, depending on the weather, flight paths, and altitudes, and as a result they are strongly related to the flight trajectory.

During the last decade where air transport has experienced its largest growth, as well as massive efficiency improvements (Ritchie, 2020), several studies have investigated aviation-related environmental effects on national and international scale, with the findings suggesting that short and medium-haul flights account for a large percentage of the overall emissions regardless of their smaller travel distance (Giaconia et al., 2013; Lund et al., 2017). Specifically, a recent environmental analysis by Graver et al. (2019), indicates that short-haul flights below 1,500 km account for one-third of passenger emissions and that almost 6% of all passenger CO_2 emissions are from regional flights of less than 500 km, roughly the distance at which aircraft compete directly with other types of passenger transport. Crucially, the carbon intensity of these flights, which is measured as the quantity of CO_2 per revenue-passenger-km, is the highest. These findings are also visualized in *Figure 1.1*, where the percentages of passenger CO_2 emissions per flight distance are displayed. Besides its environmental effects, short-haul travel provides several economic benefits to the industry. These flights facilitate quick and cost-effective city-to-city commuting for individuals, boosting local economies and enabling trade by promoting tourism (IATA, 2021). Additionally, short-haul flights play a critical role in connecting smaller regional airports with major hub airports, providing passengers with access to long-haul international flights.

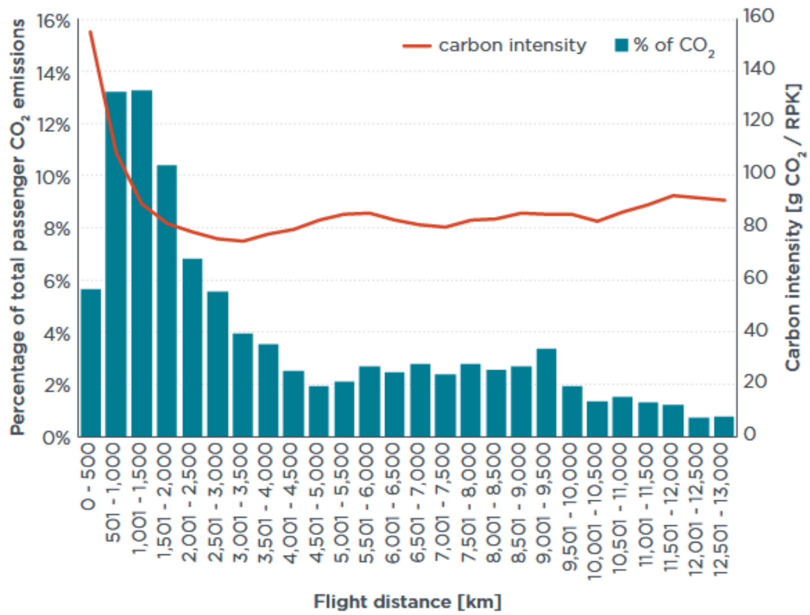

Figure 1.1: Share of passenger CO2 emissions and carbon intensity in 2018, by stage length (Graver et al., 2019)

According to Chen et al. (2023), air pollution can have a bidirectional relation between the environmental and financial aspects of short-haul travel. Significant amounts of an airport's local air pollution are caused by runway congestion due to weather conditions, network delays, or air traffic regulations. Airborne particles that reduce atmospheric visibility, which in turn reduce airport capacity and hinder ground handling operations, might result in flight delays or cancellations, leading to additional airline costs. Multiple factors were identified by Hilditch et al. (2023), including high workload, insufficient rest opportunities, schedule changes, and long sit times, all of which, in addition to increasing operational risk, also have financial repercussions for the aviation industry.

Current practises for emission reduction

Currently, the climate impact of air travel is receiving increased attention. Airlines and governments are actively considering actions to address the growing issue, since existing regulations such as the International Civil Aviation Organization's (ICAO) "CO_2 standard" for new aircraft and its "Carbon Offsetting and Reduction Scheme for International Aviation" are not expected to have a significant impact on aviation emissions (Graver et al., 2019). In addition, unlike the International Maritime Organization (IMO) in charge of international shipping, the ICAO has not yet established a 2050 climate goal. Consequently, there is a need for further action and the implementation of efficient mitigation policies, supported by the best available evidence on the effects of aircraft pollutants and information on the origin and area of effect of those emissions. In order to minimize aircraft emissions, several countries have implemented various policies, while airports and airlines have tested practical solutions. Aviation fuel taxes (Fukui & Miyoshi, 2017), ticket taxes (Oesingmann, 2022), biofuels and other alternative aviation fuels (Kousoulidou & Lonza, 2016; Dahal et al., 2021) are some of the implemented policies that have attracted most of the attention. On the other hand, strategies regarding network optimization through arrival time predictions and route selection (Achenbach & Spinler, 2018; Koo et al., 2023), or the utilization of electric passenger aircraft (Barke et al., 2022) and sustainable airport infrastructure (Hubbard & Hubbard, 2019) have also emerged as promising solutions for the reduction of GHG emissions.

High-speed rail potential

Several studies have identified the ability to reduce the highly-polluting short-haul flights with the use of greener modes. Land-based transportation that can keep up in travel time, and hence, compete with these flights, are an appropriate replacement (Baumeister & Leung, 2021). Specifically, when comparing similar travel itineraries, high-speed trains have a lower energy consumption per seat-km than aircraft for short and medium-distance trips, directly translating to lower emissions. Moreover, it is found that a considerable percentage of flights from international hub airports in Europe do not travel more than 750 km, a distance range for which HSR can compete with air travel. According to Adler et al. (2010), the evaluation of rail modal shares in a competitive long-distance transportation market revealed that the rail system could attract almost 25% of passengers for trips under 750 km, but that percentage drops to 9% for longer distances.

Furthermore, it is noted that integrated air-rail services can improve the accessibility and connectivity of passengers (Avogadro et al., 2021), while well-connected infrastructure and transport facilities could develop transportation clusters where both air and rail travel options are provided (Wang et al., 2020). Although information on the indirect effects of short-haul flight cancellation to the long-haul travellers who will not be able to switch to HSR is lacking, it could be argued that airports that are well integrated with surface transport modes, would not require short-haul flights for hub transfers since incoming rail services could feed passengers to the long-haul flights. Even so, as quoted by Reiter et al. (2022), “most European airports are still far from delivering that level of seamless connectivity across modes”, and thus, in order to facilitate hub transfers, several short-haul flights will inevitably remain essential.

Consequently, despite the discussions on HSR growth, it is crucial to recognize that air-to-rail substitution could lead to substantial consequences, most significantly the decline in both airline and airport revenues (ERAA, 2022), as well as emissions produced by large-scale construction projects for new infrastructure to address capacity issues (Jiang et al., 2021). Therefore, there is a clear need for a wider scope of analysis that takes into account all effects of such a transition.

1.2 Problem Statement

One of the primary concerns of the aviation industry and other associated international organizations is mitigating the adverse environmental effects of aviation. A substantial portion of aviation-related emissions is attributable to short-haul travel, which produces a greater carbon footprint compared to long-haul trips. Although these flights benefit the industry economically, their major environmental externalities, driven by multiple factors, are of vital importance. Over the past decade, several policies and initiatives have been implemented, with the adoption of high-speed rail (HSR) systems as a viable alternative to short-haul flights in terms of travel time and distance emerging as the most favourable strategy.

Naturally, the shift of passengers from air to rail, as a result of this mode substitution, will necessitate alterations to both air and rail networks. This is because these two modes of transportation are influenced by different factors, and therefore, a more in-depth investigation is needed to comprehensively understand the benefits and drawbacks of such a substitution. In principle, this shift will lead to an increase in rail passengers, resulting in a greater demand for train services and connections to replace the origin-destination (OD) locations previously served by flights that are being replaced. However, as this transition is being discussed on a continental scale, it is expected that the overall rail network, composed of several sub-networks of different development levels, will require substantial changes to its fundamental infrastructure. These changes can be influenced by a range of performance indicators used in both the aviation and railway industries, but most importantly, by the type of substitution based on the extent of modal shifts, namely the flights being replaced and, consequently, the number of passengers affected.

Nevertheless, knowledge is lacking regarding different categories of short-haul flight that can be substituted, as well as the factors that can impact the substitution process. Therefore, it is essential to gain a better understanding of these elements to transpire appropriate network modifications, particularly the changes needed in the core HSR infrastructure that would successfully promote the flight substitution, while minimizing disruptions to existing operations as much as possible. In summary, the problem that needs to be addressed can be described as follows:

“Classification of short-haul flights that can be replaced by high-speed rail and identification of fundamental modifications in rail infrastructure to accommodate the shift of passengers.”

Therefore, the primary focus of this research centres on evaluating of the design and performance of the high-speed rail infrastructure supply for a continental scale network, considering various categories of short-haul flight substitution.

1.3 Research Gap

The problem statement indicates that there is still insufficient knowledge regarding the design of fundamental high-speed rail infrastructure and that an overall strategy regarding the possible substitution is lacking. The identified research gaps can be defined as scientific and practical as described below.

Scientific gap

In the field of network planning problems extensive literature is available, as well as broader material on HSR systems. While most of this literature delves into demand-based network design for railway systems, where projected demands are utilized to design the network layout from the beginning, only a few studies take into account the capabilities and limitations of existing infrastructure. Moreover, given the complexity and scale of HSR networks, no research has yet tackled the challenges of infrastructure and capacity planning within an integrated continental high-speed rail system. Consequently, the specific requirements that derive from the unique characteristics of such an integrated continental HSR environment remain uncertain. The absence of a well-defined approach for addressing large-scale network planning problems, highlights the gap in knowledge associated with supply-side infrastructure design for HSR systems.

Practical gap

By making more unified decisions regarding the design of HSR infrastructure, it is possible to improve the efficiency of the European high-speed rail network. Currently, the comprehensive understanding of the diverse parameters that can impact network infrastructure at a continental level, while effectively aligning with policy objectives, is lacking. This knowledge gap arises due to the multidimensional nature of the challenge and the multitude of associated aspects involved. This includes not only practical design considerations, such as identifying which networks possess the required infrastructure capacity to accommodate the influx of passengers resulting from an air-to-rail shift and evaluating the extent of modal substitution, but also encompasses an assessment of the financial and environmental consequences linked to the various design modifications.

1.4 Research Scope and Objective

Scope

Given the growing need for new measures to reduce the harmful emissions generated by short-haul flights, HSR substitution has emerged as the most prominent solution to address the ongoing issue, especially considering the recent rapid global expansion of HSR networks. To facilitate a seamless shift from air to rail travel, it is essential to ensure that the rail infrastructure is sufficiently adaptable to accommodate the anticipated demand shift, and hence, appropriate modifications to its design are required, depending on the level of substitution. Therefore, the main goal of this project is to identify the necessary modifications to the fundamental HSR infrastructure for the successful transition from short-haul flights to high-speed rail.

Objective

This thesis aims to determine the potential effects resulting from the enhancement of high-speed rail infrastructure and to identify how these network configurations should look like, considering both physical attributes, as well as sustainability aspects. This is accomplished by first studying the substitutability of short-haul flights based on modal shift factors and flight classification, and subsequently, by investigating the current state of the examined networks and analyzing different HSR network designs in terms of capacity, costs and environmental effects, based on different substitution scenarios of short-haul flight passengers.

1.5 Research Questions

Considering the identified research gaps and the project's objective, the following main research question has been established:

"What are the implications on network service capacity and economic sustainability at a strategic level, resulting from the redesign of Europe's rail network to substitute short-haul flights with high-speed rail?"

To thoroughly assess alternative designs of modified network that can accommodate the passenger shift without disrupting current operations, it is essential to examine multiple facets of the current state of the industry regarding its infrastructure. Consequently, the formulated sub-questions below aim to answer the main research question by outlining the sequential steps required to initially analyze the possible levels at which a transition from short-haul flights to high-speed rail can be deemed effective, as well as the current state of the HSR network infrastrucre elements related to strategic design, and subsequently, provide potential redesigned networks for implementation and evaluate their performance from both transportation and non-transportation perspectives.

SQ1. What factors can influence the development of substitution scenarios that can effectively facilitate the air-to-rail transition?
SQ2. What rail infrastructure elements of the strategic planning phase are critical for the redesign of a continental HSR network?
SQ3. What are the key modifications to the design of HSR network infrastructure that overcome capacity limitations?
SQ4. What is the performance of the redesigned networks in terms of transport efficiency and economic sustainability?

1.6 Research Relevance

Scientific relevance

The existing knowledge on network design problems for HSR and long-distance transport systems has limited applicability. However, this research extends its scientific relevance beyond the immediate scope of the thesis. By demonstrating the ability to efficiently utilize pre-existing networks as a basis for improvement, rather than constructing new ones, it can contribute to the evolution of conventional demand-based network design problems by seamlessly integrating the existing supply of infrastructure and capacity constraints. This approach provides a more holistic perspective on efficient railway system planning, especially in the complex HSR environment, which has the potential to establish the groundwork for a new field characterized by its unique properties and characteristics. Furthermore, by utilizing network design problems commonly employed in urban transit systems to the context of continental HSR, innovative solutions can emerge, broadening the applicability of established research methodologies and tools. This expansion offers a deeper understanding of HSR's performance potential and could enable innovative approaches for large-scale railway network optimization.

Practical relevance

Short-haul travel has environmental drawbacks, but also offers mobility and social benefits. As such, it is impractical to expect that air travel demand can be reduced through a simplistic suggestion of reduced flying. Instead, it is essential to introduce a viable alternative that can naturally decrease the demand for air travel. Enhancing HSR infrastructure, can further promote it as a competitive and appealing option for international travel, while contributing to the sustainability of both industries. However, the options for capacity improvement are limited and related projects are complex and expensive. Therefore, the insights gained from this study can contribute in efficient network improvements that ultimately can benefit the transportation industry as a whole.

Company relevance

Given the expressed interest in improving HSR corridors and the existing knowledge gap in their efficient development, this thesis on sustainable mobility aligns closely with the work of Royal HaskoningDHV. As an independent engineering consultancy company, Royal HaskoningDHV recognizes the opportunity to offer valuable guidance to stakeholders in this field. It also aligns with the company's overarching goal of reducing transportation emissions in Europe, while addressing other mobility challenges such as increased international travel demand. By gaining more expertise through this research, more effective solutions for sustainable development in the transportation sector can be provided.

1.7 Methodological Approach

The methodological approach employed in this thesis centres on conducting a comprehensive analysis of the potential effects associated with the enhancement of HSR infrastructure in Europe, with a primary focus on understanding how these network designs should be modified to accommodate different passenger shifts from short-haul flights.

To address the challenges posed by the large scale and complexity of European HSR network designs, a quantitative experiment is conducted, with the goal to simulate the high-level railway planning process for HSR infrastructure in a context of various substitution scenarios. The experiment is based on the principles of Transit Network Design and Frequency Setting Problems (TNDFSP), which concern the strategic design of transit networks and are typically utilized for designing urban transit systems. However, in this research, the focus is on assessing if the existing HSR infrastructure can seamlessly accommodate the air-to-rail transition. When considering the fundamental rail infrastructure in the TNDFSP, the primary parameters subject to design are stations, lines, capacity, and frequency. These factors are crucial in the design process, as they determine the effectiveness and efficiency of the HSR network. Since this study is the first to attempt a supply-based network design problem on a continental scale and specifically for HSR and its distinctive characteristics, several modelling and case study assumptions are made in order to provide a robust context of application while maintaining a reasonable computation time and result accuracy.

Overall, to achieve the objective of this thesis, the research is divided into three phases. The first phase delves into exploring the factors influencing the substitutability of short-haul travel, specifically examining the modal shift dynamics. The second phase concerns the current state of both the European short-haul flight and high-speed rail networks. This entails a detailed examination of their geographical distribution, capacities, and operational aspects. Finally, in the third and largest phase, optimization modelling techniques are employed to compute various network designs for each of the demand substitution scenarios, followed by an evaluation of their performance based on selected performance metrics.

1.8 Report Structure

The report is structured in six main chapters as described below and illustrated in *Figure 1.2*. Following the introductory chapter, *Chapter 2* delves into relevant literature in the areas of flight classification and modal shift for long-distance travel, presents study findings regarding railway network design optimization principles, particularly for supply-based issues, and gives information on performance indicators used to assess transport networks. *Chapter 3* explains the precise methodology employed in this research, including the development of the TNDFSP model for the HSR supply-based problem. Following, *Chapter 4* focuses on operationalizing the defined problem within the European region case study by detailing the selected database, but also encompasses the gathering of essential information serving as inputs for the modelling process and introduces the scenarios used as demand inputs. In *Chapter 5*, the model's results are analysed and discussed, while the evaluation of the alternative designs also takes place by examining the performance metrics derived from the modelling process outputs. Finally, *Chapter 6* concludes the study, offering insights drawn from all the previous analyses, critically assessing the conducted research, acknowledging its limitations and providing suggestions for future directions and advancements in the field.

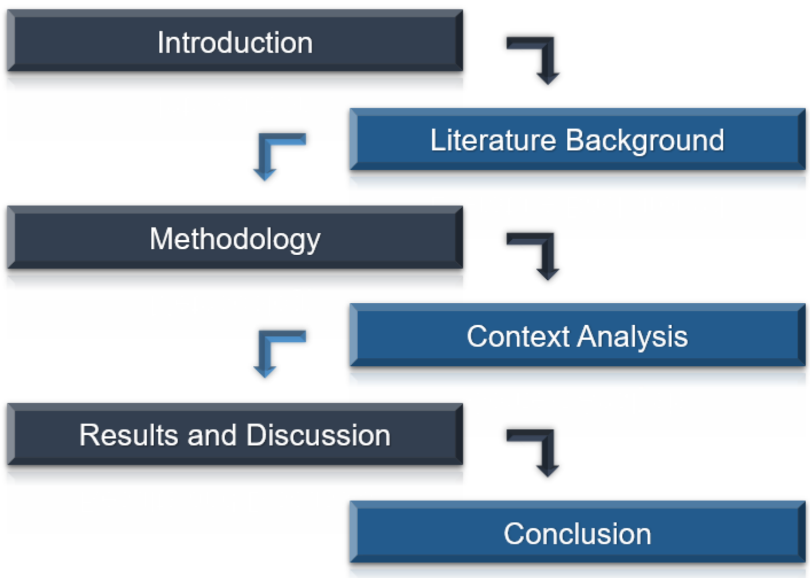

Figure 1.2: Report structure

2

Literature Background

This chapter presents findings regarding the substitution of air passengers and the transition to a unified high-speed rail network. The aim is to offer insights into the identification of flights suitable for substitution to devise substitution scenarios with varying demands, as well as to explore prior research on network design problems related to supply issues in order to formulate the characteristics of an optimization model that could be applied to address the challenge of designing an HSR network within this study, along with methods for assessing its performance. Specifically, in *section 2.1,* insights are given on proposed methods to classify flights that can be banned or substituted, as well as information on modal shift for long-distance travel. Subsequently, studies in the field of railway network design optimization are analysed in *section 2.2*, for an implementation in a high-speed rail environment on a strategic level planning concept. In *section 2.3*, indicators that can be utilized to assess the performance of a network system's design are identified. Finally, an overview of the relevance and contribution of the above findings to this research is given in *section 2.4*.

2.1 Short-Haul Flight Substitution

Sustainable transportation is currently prioritized globally due to growing environmental concerns and the pressing need to combat climate change. Governments and transportation agencies recognize that cutting carbon emissions in the aviation sector is crucial. Consequently, they are actively investigating various new strategies to promote environmentally friendly travel options. One of the most frequently discussed solutions regarding the reduction of GHG emissions from the aviation industry is banning short-haul flights, initially at the national level, and if practical, expanding it to larger regions like the European Union.

2.1.1. Flight classification

Flights can be categorized in several ways depending on the purpose of classification. Typically, flights are sorted by operators, considering factors such as route (domestic or international) and intended operational purpose (passenger or cargo), but also based on the type of aircraft used or their capacity (e.g. number of seats). Instead, from a user's perspective, flights are often distinguished based on the type of fare offered, essentially categorizing the service level such as low-cost or premium.

For the purpose of travel mode comparison, flights can be classified based on their travel distance and/or travel time. These travel characteristics are not only relevant for the classification of flights, but can also serve as crucial factors influencing passengers' mode choice when deciding between air and rail transportation. As defined by ICAO (2015), flight time is "The total time from the moment an airplane first moves for the purpose of taking off until the moment it finally comes to rest at the end of the flight", while flight distance refers to the distance of a flight between its origin and destination airports. Usually it is measured along the great-circle distance which is the shortest distance between two geographical points, but it may vary due to factors like weather conditions and air traffic.

The length of a flight is commonly characterized in aviation by the term "Flight Haul Type". These types can be defined using either flight distance or flight time and are typically categorized into four main groups: short-haul, medium-haul, long-haul, and ultra-long-haul. According to IATA (2015), they can be distinguished based on flight time as follows:

- Short-haul: < 3 hours
- Medium-haul: between 3 - 6 hours
- Long-haul: between 6 - 16 hours
- Ultra-long-haul > 16 hours

On the contrary, several authors disagree on the specific distance thresholds that define each flight haul type, while different distance-based definitions are commonly utilized across continents and by various airlines. Especially regarding short-haul flights, there is a strong lack of agreement, with authors offering different definitions of the distance that qualifies a flight as short-haul (*Table 2.1*). The definition of flights that are extremely short is even more challenging. While certain authors have focused on ultra-long-haul air services, little attention to defining terms such as "ultra-short-haul" flights, resulting in the absence of a widely accepted definition (Dobruszkes et al, 2022).

Table 2.1: Flight distance for short-haul flights

Source	Distance
Baumeister & Leung (2021)	500 – 1000 km
Eurocontrol (2021)	500 – 1500 km
Graver et al. (2019)	< 1500 km
ICAO (2015)	< 2200 km
Rodrigue (2020)	< 1000 km

In the context of this paper, it makes sense to consider the criteria established by public authorities for restricting the shortest flights. Numerous research studies have provided evidence supporting the potential substitution of air travel with HSR under a given travel time. As such, this research focuses on the criteria related to rail travel times.

In Europe, the inclination toward substituting shorter flights with rail travel has been evident since 2011, where the European Commission stated that "by 2050 the majority of medium-distance passenger transport should go by rail" (European Commission, 2011). In addition, some EU Member States have already discussed or implemented schemes to ban or discourage short-haul flights based on an action plan for the enhancement of long-distance and cross-border passenger rail services proposed by the European Commission. This plan builds upon the initiatives taken by Member States to improve connections between cities by efficiently managing capacity, coordinating timetables, establishing facilities for sharing rolling stock, and enhancing infrastructure to encourage the introduction of new train services (European Commission, 2020). Examples of such schemes, either in operation or under consideration by certain Member States, are given in *Table 2.2.*

Table 2.2: Member States' initiatives against short-haul flights

Country	Scheme
Austria	Domestic flight ban for flights served by rail alternative within 3 hours train travel on specific corridors
Belgium	Extra tax per departing passenger on flights shorter than 500km, excluding connections
France	Domestic flight ban where a direct rail service alternative is available, operated several times a day and within 2.5 hours, excluding connections
Netherlands	Commercial flight ban between Amsterdam Airport Schiphol and Brussels Airport (distance 150km) and use of high-speed rail service through

Furthermore, as explained by Szymczak (2021), different levels of a ban measure are possible based on the availability of rail alternative, as well as the different policies instituted in each country, such as restriction of point-to-point passengers and the use of short-haul feeder flights for transfer passengers, complete ban of domestic flights within countries or on a continental scale, and ban of flight routes that can be served by daytime or overnight trains. High-speed trains constitute 31% of the overall passenger kilometres travelled by rail in the EU, with countries like Spain and France utilizing trains of travelling speed above 200km/h for almost 60%. Nevertheless, more than half of the Member States lack any high-speed railway infrastructure (Brons et al., 2023).

2.1.2. Modal shift

European transport policy is focused on achieving a more sustainable distribution of transportation modes, which involves various modes competing in integrated networks. Modal competition occurs when there is an overlap in transport markets, geographical characteristics, and levels of service, which in turn can lead into modal substitution, meaning that one mode becomes more advantageous over another for the same route or market (Rodrigue, 2020). While a modal shift can lead to growth in both concerned modes, it primarily involves increased demand for one mode at the expense of another.

Despite the modern complexity of transportation networks, the mechanism behind modal shift remains consistent. Understanding the factors influencing modal choice, including socio-demographic factors, journey characteristics, and spatial patterns (Pastori et al., 2018), is essential for comprehending modal shift and developing strategies that could result in a change in transportation mode. These determinants play a crucial role in understanding travel behaviour and assessing potential shifts in mode choice under varying circumstances. Frequently, the shift between transportation modes can be explained by the relative benefits they offer in terms of travel cost and time, convenience, comfort, reliability, accessibility, environmental concerns, personal preferences, or social norms. However, due to the fact that modal substitution effects are highly context-dependent, there is no general rule for its application (Fearnley et al., 2018). Depending on specific conditions and personal preferences, every factor might have varying degrees of relevance. For example, it is frequently thought that basic preferences such as shorter travel distances and lower costs, are advantageous variables that may motivate people to switch between modes. Conversely, individuals who are concerned about sustainability and the environment may favour modes that are seen as being more environmentally friendly.

Researchers in transportation planning and policy use surveys, travel diaries, and statistical analysis to analyze the relationships between modal substitution factors and travel behaviour. This knowledge informs the development of transportation models and policy interventions that encourage sustainable mode shifts, reduce congestion, improve air quality, and enhance transportation efficiency. As such, modal substitution factors play a pivotal role in transportation planning and policy-making, facilitating the development of sustainable and user-centric transportation systems.

Going from these insights to the prospect of shifting from air to rail is not straightforward. Such a shift demands new infrastructure, and its feasibility depends greatly on geographical variations (Dobruszkes, 2011). The availability of transport infrastructure varies widely, with corridors experiencing the highest modal competition, since corridors offer diverse modes that collectively ensure an efficient commercial environment. However, certain areas lack services, forcing passengers to use available modes that might not be the most efficient for their needs. While technological advancements aim to adapt infrastructure to evolving needs, it's essential to ensure that the environmental benefits of new rail investments offset the environmental pressures associated with construction and maintenance (European Environmental Agency, 2020). New rail infrastructure can quickly result in net GHG emission reductions, especially when it involves minimal GHG-intensive elements like tunnels and bridges, as it encourages passengers to shift from high GHG-intensive transportation modes to rail due to consistently high occupancy rates.

However, the attractiveness of rail options can lead to increased demand, potentially undermining the environmental benefits of an air-to-rail shift. Therefore, assessing the railway system's capacity to accommodate additional demand is crucial (Dobruszkes, 2011). In the short-term, passenger growth relies on optimizing occupancy and services on existing infrastructure based on the availability of maximum capacity and rolling stock. Medium-term expansion involves procuring rolling stock and upgrading rail lines in order to increase capacity, while long-term growth entails construction of new rail lines.

2.2 Railway Transport Planning

2.2.1. Transport planning concept

Transportation serves a vital role in facilitating people's movement between activities, however, the growing population and travel demands have led to increased mobility-related issues such as congestion and pollution. Although public transportation systems are recommended to mitigate these drawbacks, a balanced design that considers service quality for users, cost-effectiveness for operators, and overall system impact is necessary (Guihaire & Hao, 2008). Transport planning is an intricate process, extensively studied in scientific research and practical analyses, due to the multidimensional nature of the environment and stakeholder interests, which involves strategic, tactical, and operational decision-making levels. Illustrated as the "Hierarchical Public Transport Planning Concept" in *Figure 2.1*, this approach involves a sequence of tasks from high-level planning down to implementation, incorporating feedback loops to address vertical dependencies (Ibarra-Rojas et al, 2015).

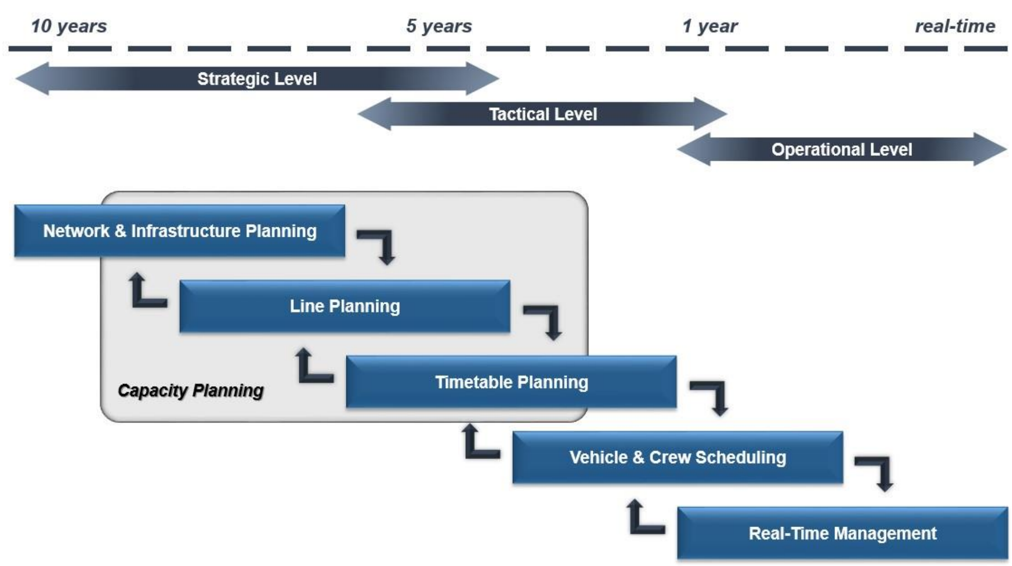

Figure 2.1: Hierarchical transport planning concept and the role of capacity planning

The initial phase of “Network & Infrastructure Planning”, primarily revolves around the development of new or the adjustment of existing infrastructure, based on the evaluation of transportation demand to understand the anticipated origin-destination traffic. Based on this demand, the “Line Planning” phase determines the routes, stopping policies, and frequencies for lines or services in the network. Given the major infrastructure investments and the long duration of the implementation process, these problems are typically associated with the strategic long-term planning of systems. During “Timetable Planning”, a tactical approach is employed, where specific arrival and departure times are established. Following, vehicles are assigned to the designed lines and operational staff are allocated their duties in the “Vehicle & Crew Scheduling phase. The focal point of the tactical phase is enhancing system performance, whether that means generating profit or aligning with policy objectives. Lastly, the operational level refers to day-to-day activities or “Real-Time Management” and represents the lowest tier of the transport planning structure.

While the division between these three levels might appear rigid, it's important to acknowledge that the precise placement of phases within these levels can be adapted according to specific problems, as well as depending on the varying fields of transport. Specifically in railway, capacity planning is incorporated during strategic and tactical planning. Its primary focus is the estimation of the expected service quality for a specific set of trains operating on a given section of infrastructure and over a specified time period, under certain operational conditions. Depending on the specific objectives, it encompasses various aspects, such as assessing the optimal number of trains that can be effectively supported by a given infrastructure or enhancing the resilience and efficiency of an already fully constructed timetable (Abril et al., 2008).

2.2.2. Transit network planning problems

Due to the significant interests and costs associated with the design of transport systems, numerous efforts have been made to optimize this process. Utilizing the hierarchical concept of public transport planning, Ibarra-Rojas et al. (2015) developed a framework known as “Transit Network Planning Problem” (TNPP), which offers a structure for addressing the inherent challenges of this process. This framework is broken down into smaller sub-problems that align with various phases of public transport planning as explained above.

Given the interconnected nature of the sub-problems, it is often preferable to merge multiple sub-problems into one. Three multi-level problems related to strategic and high-level tactical phases are provided by Guihaire & Hao (2008), which encompass all three sub-problems regarding design, frequency setting, and timetabling. This study aims to provide different design alternatives on a strategic level from a supply perspective, namely the configurations of lines along with their corresponding frequencies and capacities, hence, the problem falls under the category labelled as "Transit Network Design and Frequency Setting Problem" (TNDFSP). A visual representation of the sub-problems, including their inputs and outputs, regarding the strategic and tactical levels, is presented in *Figure 2.2*.

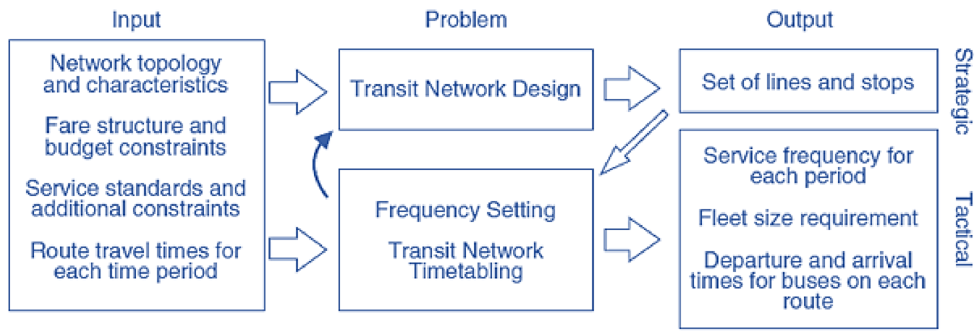

Figure 2.2: Interaction between strategic and tactical levels of the planning process

As illustrated above, the TNDFSP encompasses both a design problem, which involves establishing a series of routes including terminals and intermediate stops, based on the geographical layout of an area, as well as a frequency setting problem, aiming to determine suitable service frequencies within a specific timeframe. These problems are initiated with a given demand and are subject to a combination of objectives and constraints. One of the primary limitations inherent in both of these problems revolves around the capacity of the relevant infrastructure elements. Optimizing the use of infrastructure, is a complex and difficult task, since the additional traffic that can be accommodated by the existing infrastructure and the level of investment for new infrastructure must be determined (Abril et al., 2008). Addressing such a limitation is essential in order to provide regional and national authorities, as well as infrastructure owners, with evidence that support the necessity and financial viability of investing in the expansion and enhancement of the network.

2.2.3. Railway capacity planning in TNDFSP

Various concepts of railway capacity have been discussed and applied in the field of railway transport planning. The term "theoretical capacity" refers to a capacity concept based on the number of trains that can theoretically be scheduled on a given infrastructure, regardless of the quality of operations. However, since the system becomes unstable even with minor disruptions when designed with this capacity, operators use the "practical capacity" of the system. This capacity is defined as the number of trains that can be effectively operated within a specified timeframe on a given infrastructure while meeting predetermined quality requirements, often referred to as the "level of service" (UIC, 2004).

Theoretical capacity can be achieved under ideal circumstances, however, in practise, practical capacity tends to be considerably lower due to various limitations and imperfections, such as train delays, which are not taken into account during the calculation of theoretical capacity (Lindfeldt, 2015). While theoretical capacity serves as a valuable metric for long-term strategic capacity planning, practical capacity becomes the focal point when it comes to tactical and operational considerations.

There are several methods that tackle capacity planning problems, ranging from stochastic and simulation models to optimization techniques. However, TNDFSPs are typically solved with mathematical optimization methods due to their complex nature, as well as due to the recent surge in computational power availability, which can tackle the large number of components that can be included in the modelling process. Although such problems have been extensively researched, while analyzing existing review papers and their approaches to transit network problems, it is evident that there are notable variations in how these issues are defined.

Invariably, capacity planning is either incorporated as a system constraint, or lines and frequencies are designed without considering capacity restrictions. More specifically, network design problems are typically addressed from a user-centric perspective primarily driven by demand considerations. The lack of supply-oriented research is aimed to be tackled by this study. However, the limited body of existing work necessitates an exploration of the structures and components of demand-oriented TNDFSPs to identify relevant elements applicable to supply-oriented problems. Furthermore, an adaption of these concepts to a large scale network problem is also necessary, since the majority of network planning researches are focused on urban bus and rail systems. The papers outlined in *Table 2.3* are used as a basis to identify relevant modelling characteristics and extract information on how to formulate a supply-based network design problem on a continental level for HSR.

Table 2.3: Review papers for high-level TNPP

Source	Title
Guihaire & Hao (2008)	Transit network design and scheduling: A global review
Ibarra-Rojas et al. (2015)	Planning, operation, and control of bus transport systems: A literature review
Jorik (2020)	A Unified Design of the European High-Speed Rail Network
Kepaptsoglou & Karlaftis (2009)	Transit Route Network Design Problem: Review
López-Ramos (2014)	Integrating network design and frequency setting in public transportation networks: a survey
Schöbel (2012)	Line planning in public transport: models and methods

2.2.4. Structure and components of the TNDFSP

The TNDFSP's structure consists of several essential elements that collaborate to tackle the strategic planning of transit networks. At its essence, the TNDFSP involves determining the best arrangement for transit infrastructure, including stations, lines, capacity, and frequency, with the aim of achieving transit operations that are both efficient and effective (Guihaire & Hao, 2008). These elements are interconnected and have an impact on the overall performance and quality of the transit network. Stations play a critical role as pivotal points where passengers enter the system, while the lines connect these stations, forming the network's core structure. The capacity of both stations and lines affects the system's ability to manage passenger demand, whereas frequency dictates how often transit services are available. The TNDFSP framework offers the flexibility to explore various design alternatives and assess their effects on network performance, allowing for the identification of optimal solutions that strike a balance between efficient operations, service excellence, and resource utilization (Kepaptsoglou & Karlaftis, 2009).

In addition to the structural components, the TNDFSP also incorporates various mathematical and optimization techniques to solve the design problem. Mathematical models are developed to represent the relationships between network components, passenger demand, and performance measurements. Optimization algorithms are employed to search for the most favourable design solutions within the given constraints and objectives as mentioned by López-Ramos (2014). These techniques ensure that the TNDFSP addresses the complexity of transit network design and frequency setting, enabling planners and decision-makers to make informed choices based on data-driven analysis and evaluation. Overall, the structure and components of the TNDFSP provide a systematic and analytical approach to transit network design, facilitating the development of efficient, reliable, and sustainable transit systems.

Due to its complex nature with multiple components, the characteristics of a TNDFSP optimization model are divided into (i) objective(s), (ii) decision variables, (iii) parameters, and (iv) constraints. Each of these aspects is explored in the subsequent subsections, with an overview of the most frequently utilized components that could be employed and/or adapted to a supply-based problem are presented at the end in *Table 2.4*.

<u>Problem objectives</u>

In optimisation problems in general, the objective function represents a mathematical formulation involving the decision variables. In the context of the TNDFSP, the objective function serves to convert potential decisions, represented by feasible line configurations, into a quantifiable score for comparison.

Traditionally, transit planning involves two primary stakeholders: the operator aiming to reduce costs and the user striving to maximize benefits. These objectives can be formulated differently, but typically, the operator's costs are associated with overall route length, while the user's costs are often defined by the deviation from the shortest paths. Kepaptsoglou & Karlaftis (2009) confirm this observation while noting that certain studies incorporate additional factors such as external costs, societal welfare, transfer reduction, capacity enhancement, minimizing travel time, or reducing fuel consumption.

Problem decision variables

Decision variables serve as representations of quantifiable choices that need to be determined by solving the problem at hand. These decision variables are situated within the parameters layer. The framework's creators, Kepaptsoglou & Karlaftis (2009), observe that, the Two-Node Disjoint Fixed-Path Transit Network Design Problem (TNDFSP) primarily involves two key decision variables: the line plan and frequencies.

However, it is important to note that numerous additional decision variables are implicitly considered. This stems from the fact that opting for a specific line brings with it inherent characteristics such as route lengths, locations of stops, degree of directness, and the absence thereof. Moreover, the combination of lines and frequencies indirectly influences the actual number of transported passengers. Beyond these main decision variables, it's evident that literature occasionally incorporates some less frequently mentioned options. Examples of these lesser-discussed variables include fares, stop locations, capacities, and vehicle types (Kepaptsoglou & Karlaftis, 2009).

When examining the perspective of HSR, it becomes apparent that many parallels can be drawn with other modes of transit. This is due to the fact that the aforementioned decision variables all revolve around the overarching network structure and passenger movement, rather than delving into operational factors. Consequently, this leads to a lack of further expansion of decision variables for HSR in this context.

Problem parameters

The parameters can be divided into demand and network characteristics, as has been done below. The filling that is given to these components is most typical for the exact situation that the model tries to describe.

- *Network characteristics*

The structure of a TNDFSP encompasses various essential components: “vertices” representing stops or stations, “edges” indicating direct connections between these vertices, “lines” denoting passenger services following a sequence of connected edges, and “paths” representing passenger routes between two vertices by following one or more lines (Schöbel, 2012). Kepaptsoglou & Karlaftis (2009) outline three general network configurations: simplified radial and rectangular grid structures, prevalent since the 1980s, and more recent realistic irregular grid structures.

Applying this to the context of HSR, characteristic is the presence of infrastructural limitations and substantial investment costs. These factors often justify the analysis of a single corridor or line, where emphasis is placed on frequency, stopping locations, and the creation of a viable timetable. This results in a bi-level problem, combining strategic line planning (frequency planning) with tactical timetable generation.

- *Demand characteristics*

The demand characteristics represent the people’s desire to move between locations such that they can perform activities. Accurately modelling this demand and the behavioural interaction with the transport supply can increase the level of realism. Since this is a supply-oriented TNDFSP, the demand characteristics are not looked into depth but instead are used with different scenarios to come up with different alternatives.

Problem constraints

Introducing limitations to optimization problems serves the purpose of ensuring that attainable and realistic solutions are discovered. Moreover, this strategy contributes to alleviating the computational load by narrowing down the scope of potential solutions. The nature of these limitations tends to be specific to each case, depending on the particular problem at hand. Nevertheless, recurring types of constraint patterns emerge when scrutinizing studies in the domain of transit planning.

In addition, Schöbel (2012) outlined several fundamental constraints. These predominantly revolve around overarching financial considerations, capacity limitations, and connectivity prerequisites. Another perspective, grounded more in practicality, was provided by López-Ramos (2014). Within this overview, constraints of a more specific nature were delineated. Instances include operational routes (to respect existing lines), express services (enabling non-stop travel on certain segments), and time horizon specifications (maximum time allocated for each vehicle to complete all services).

Many of the outlined constraint categories might find relevance in the context of a high-speed rail scenario. However, it's conceivable that this mode of transportation introduces a plethora of novel and scenario-specific limitations. A defining feature of rail infrastructure is the strong interconnection between strategic planning and operational restrictions, given the substantial reliance of a rail system on its infrastructure. An overview of the components relevant for this study is given in the table below.

Table 2.4: Overview of frequently used TNDFSP components

Component	Description
Objectives	Vehicle capacity
	Infrastructure capacity
	Operator costs
	Total system and user cost
Decision Variables	Routes, frequencies
	Route spacing, headways
	Routes, stops
Constraints	Budget, Capacity, Lower/Higher node/edge frequency, Connected paths
	Infrastructure restrictions, Working Lines, Stretch capacity, Vehicle fleet size, Time horizon
	Route shape, Directness, Feasible frequencies, Load factor boundaries, Min/Max line length, Operational budgets
	Demand satisfaction, Vehicle capacity, Stop capacity, Link capacity

2.3 Transport Network Performance Measurement

Performance measures are quantitative or qualitative metrics used to evaluate the performance or effectiveness of systems or projects. Selecting appropriate indicators is crucial in performance measurement, since these metrics fundamentally reflect the various stakeholder perspectives. Moreover, they provide objective information to assess progress, identify areas for improvement, and make informed decisions. Due to inherent differences within same modes of transport, such as varying business models, network sizes, ownership structures, and geographical settings, evaluating the efficiency and effectiveness of transport networks is challenging.

High-speed rail occupies a unique position between the conventional land-based transit systems and airlines, as it covers substantial distances while also relying on route infrastructure. In order to evaluate a substitution between these two modes and assess network design performance effectively, it is necessary to conduct a review that includes perspectives from both industries to determine a set of well-defined and integrated key performance indicators (KPIs) for a HSR system.

2.3.1. Strategic level indicators

In the aviation industry, the most common KPIs used to assess the performance of an airline regarding aspects that cover the strategic, planning levels, are traffic-based and financial-based indicators (Belobaba et al., 2011). Traffic can be quantified based on the Available Seat Kilometres (ASK) or Revenue Seat Kilometres (RPK), which refer to the number of seats or revenue passengers respectively per flown kilometre. In turn these indicators can be used to measure the costs and revenues per seat or passenger with the corresponding indicators of

Cost per ASK (CASK), Revenue per ASK (RASK), and Revenue per RPK known as Yield. Combining the financial and traffic based indicators, the "operating profit" can be determined by subtracting the expenses from the earnings. Similarly, these indicators can be utilized to assess long-distance transport such as HSR.

Researchers state that network performance indicators should be based on strategic objectives in order to provide strategic alignment and achieve efficiency throughout the whole cycle of planning phases, while they should also be able to assess operating conditions and/or service levels from both a transport and non-transport standpoint (NASEM, 2010). Strategic level transport indicators should provide insights into the overall performance and effectiveness of various transport network designs at a higher level, guiding long-term planning and decision-making processes. On the other hand, non-transport indicators concern broader objectives relating to sustainability goals. An overview these indicators is given in *Table 2.5*.

Table 2.5: Network performance strategic indicators

Transport indicators	Non-transport indicators
Network coverage	Social
Market share	Economic
Intermodal integration	Environmental
Network expansion opportunities	
Network resilience	

Several studies have explored common performance indicators utilized by various transportation agencies, as well as various frameworks that illustrate the inherent relationships between transportation system performance and the expectations of multiple stakeholders. As presented by Zhao et al. (2011), these indicators can be categorized into inputs, outputs and outcomes for a transportation system, where inputs represent investments, outputs denote direct achievements and outcomes indicate the consequential effects that outputs have on both users and the community (*Figure 2.3*).

It is essential to highlight that outcomes related to sustainability can be subdivided into three aspects regarding environmental, social and economic sustainability, with different indicators such as emissions, accidents, and travel costs correspondingly, all of which can aid in the development of an efficient network structure. Similarly, a research specifically regarding performance measures for sustainable transportation, categorizes sustainability into three "sustainability goals" namely, environmental quality, economic development, and social equity, similarly highlighting the three aspects mentioned above (EPA, 2011).

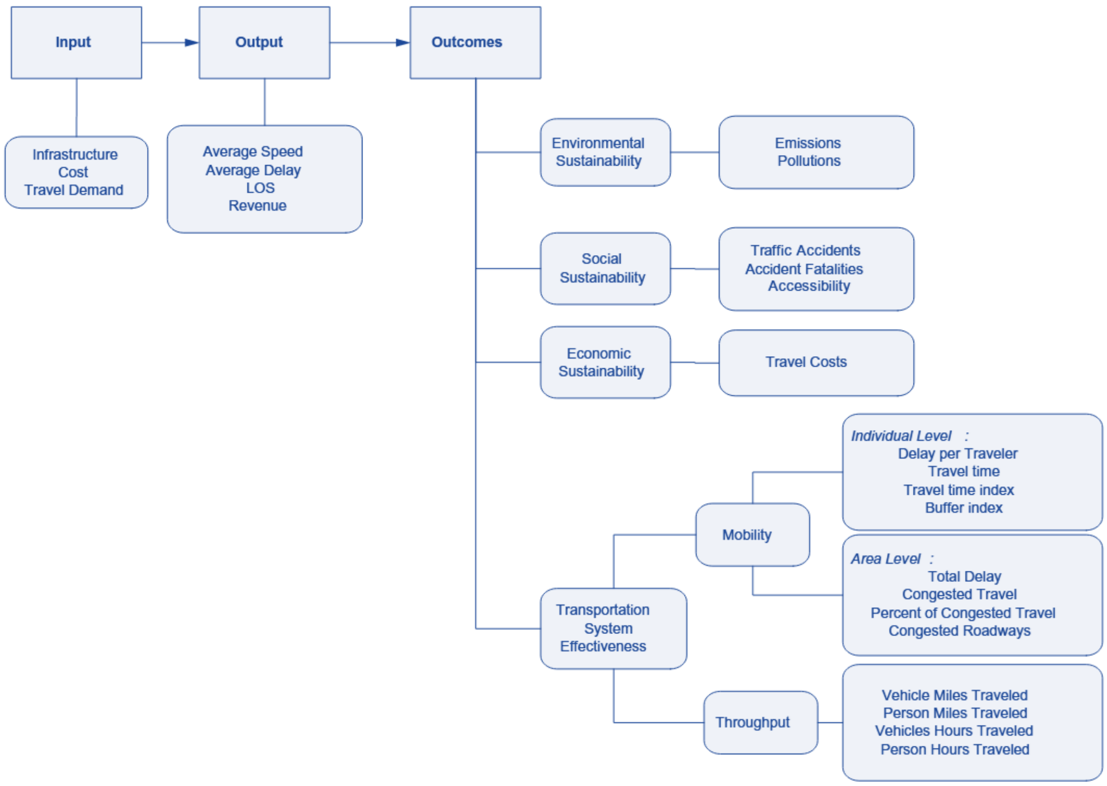

Figure 2.3: Transportation input-output-outcome system (Zhao et al., 2011)

2.3.2. High-speed rail infrastructure performance

Specifically for HSR, infrastructure performance indicators should focus on evaluating the supply of transport networks or services. To achieve this, it is essential to measure specific metrics, such as maximum line frequency and line length. These metrics align with the strategic-level planning phase, as detailed in *section 2.2*, and can effectively assess the capacity of rail network designs.

Furthermore, incorporating strategic-level KPIs regarding the sustainability of network infrastructure is crucial, in order to enable comparison between different design alternatives that best align with the high-level design objectives (Jeon & Amekudzi, 2005). Since changes to the infrastructure mainly concern the operator stakeholders who are primarily concerned with economic and environmental sustainability aspects, it is logical to evaluate different designs from their perspective, while social aspects mostly user-centric.

In terms of environmental sustainability, the most commonly employed methods to assess the environmental footprint of a transportation mode include emissions and other pollutants. Metrics such as energy consumption, carbon emissions, noise levels, air pollution, or land use requirements, can quantify the environmental impact of a mode. Notably, carbon emissions have the most significant impact, particularly in the case of carbon-intensive travel options such as flying.

Typically, carbon footprint tools focus on the operational phase and energy provision, often neglecting the environmental effects of infrastructure and rolling stock construction (Baron et al., 2011). To comprehensively capture these effects and evaluate the supply of a network, emissions related to the construction of new or the expansion of existing infrastructure are crucial, which can be measured by CO_2 emissions per passenger-km.

Conversely, to quantify economic aspects related to cost-effectiveness and efficiency in transportation, metrics such as capital costs, operational costs, maintenance expenses, energy consumption, or cost per passenger-km are utilized. Similar to emissions, costs are typically computed for the operation phase, with infrastructure costs calculated at a more macroscopic level, taking into account budget constraints. Transport infrastructure costs encompass various elements, including investments in new infrastructure, renewal costs for existing infrastructure, maintenance expenses, and operational expenditures necessary to enable the use of transport infrastructure (Schroten et al., 2019). Costs related to the construction and expansion of infrastructure that incorporate both fixed and maintenance expenses, which can be measured by euros (€) per passenger-kilometre, are the most relevant that can be employed together with operational costs to assess the economic performance of a network at a high level.

2.4 Research Contribution

From the literature review in this chapter, it was found that while flights can be categorized in several ways, there is no universal distinction for classifying them in terms of modal substitution due to the context-dependent nature of the problem. Nonetheless, there is a substantial body of research as well as practical initiatives regarding their substitution by equivalent rail services, which could serve as insights to define substitution scenarios. Even though a detailed classification of flights into scenarios for the modelling process of this research would yield greater benefits in terms of precision and depth, it was decided that time-wise and due to content availability, it is most practical to define substitution scenarios (presented in *section 4.4*) based on the existing literature.

In addition, it was observed that the idea of banning flights is met with controversy, and thus, detailed environmental and financial analyses are proposed in order to further explore its benefits more precisely. While existing literature indicates various indicators employed for network performance assessment, primarily at a strategic level, metrics linked to economic and environmental sustainability typically focus solely on assessing the operational aspects of infrastructure. Consequently, the costs and emissions associated with the construction of new infrastructure or the enhancement of existing facilities tend to be disregarded. In this study, a range of transport and non-transport indicators were chosen to evaluate network performance. This assessment not only focuses on the network configuration and its capacity (gained from the model outputs (discussed in *section 3.4*), but also examines the extent of coverage for served destinations and the network's potential to expand and meet additional demands. Additionally, it considers economic and environmental sustainability indicators, including operational and maintenance costs, and emissions produced during operation. The selection of these indicators aligns with the insights regarding commonly used aviation industry indicators and high-speed rail infrastrucre, identified in the literature.

Finally, findings highlight a scientific gap in supply-based research within the field of transit network design In contrast, extensive research has delved into the specific design of transit line configurations concerning TNDFSP problems, primarily from a demand-based perspective. Although certain studies have incorporated aspects of supply considerations, none have made it their central focus. In the context of network design in a HSR environment, there is minimal contribution. Consequently, the specific requirements associated with the unique elements of long-distance transportation, such as infrastructural possibilities and scalability, remain largely unexplored. Additionally, the question of what kind of model should be devised to address this challenge also remains unanswered. Aiming to provide insights into the above, this research aims to bridge the aforementioned gaps by developing a model for this purpose.

3

Methodology

The main goal of this research as explained in the introductory chapter, is to identify the modifications to the strategic-level rail infrastructure that are needed for the successful transition of passengers from short-haul flights to high-speed rail. Due to the size, complexity and lack of qualitative knowledge in the topic of HSR network design, a quantitative experiment was conducted. This experiment simulated the long-distance transport environment's transit planning process for HSR network designs, by performing different demand scenarios and interpreting the design alternatives outputs from a transport and a sustainability perspective. The assumptions made for the simplification of the modelling process, along with an overview of the employed methodology in this study, are defined in *section 3.1*. Following, the characteristics of the model are presented in detail in *section 3.2,* while information specifically regarding the formulation of the algorithmic model to address the bi-objective problem is given in *section 3.3*. Finally, the model's outputs that are used for the assessment of its results are presented in *section 3.4*.

3.1 General Approach

In order to simplify the problem and emphasize the strategic focus of the research, several key modelling assumptions were established. These assumptions either concern various categories or influence the network design itself, and are all of significant importance. Main things to assume are regarding passenger demand, infrastructure, mode of transport, as well as technical and operational data. From an overall perspective, the study considers a situation which is in a continuous state, such that current short-haul flights are considered as the only demand influx to the rail network with no anticipated future changes. It is presumed that rolling stock is homogenous and static, while no operational strategies that are used on the operational level of design are included. A detailed list of all the modelling assumptions is presented in *Table 3.1*.

Table 3.1: Modelling assumptions

Assumption
1. Total demand is considered fixed, thus eliminating the effects of demand generation and temporal variations
2. Existing HSR lines are assumed to operate at 50% capacity based on current demand levels

3. The model does not consider future induced demand for the network design
4. The network is designed symmetrically for each origin-destination pair
5. Transfers are possible at all vertices within the network
6. The indirect paths are restricted to include no more than one transfer
7. The fleet of high-speed trains is homogenous across the entire network
8. Vehicles operate under the same speed profile and are unaffected by local traffic conditions
9. Operational strategies such as deadheading and short-turning are not considered
10. All available rail infrastructure is considered interoperable for the network

In addition, the research methodology that was followed, from data collection and analysis through model development and algorithm formulation, is illustrated in *Figure 3.1*, providing a high-level roadmap of the research process.

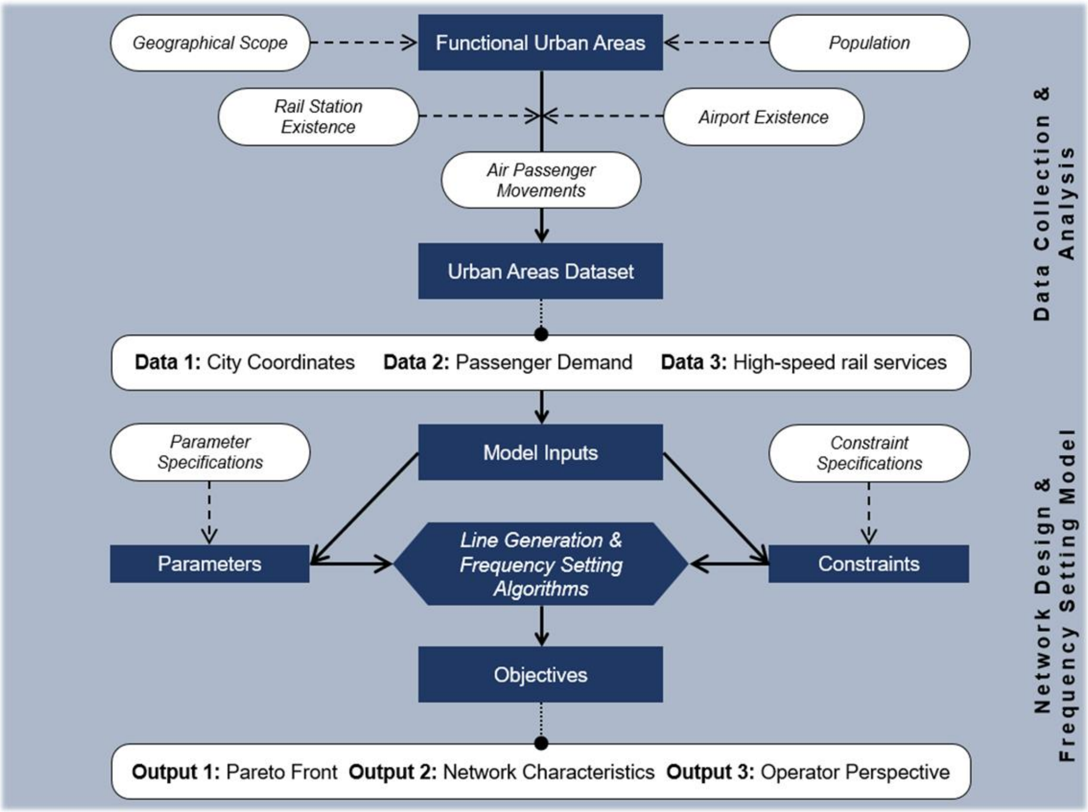

Figure 3.1: Methodology overview

The methodology encompasses gathering and analyzing necessary data, required to establish model parameters for the network design and frequency setting problem. The process begins by defining functional urban areas (as explained in *section 4.1*) within the geographical scope of this research, as well as based on the population of the selected countries. This step includes identifying the main rail stations and airports in these areas, filtering out those lacking either facility. Subsequently, a data cleaning process is conducted based on airport passenger numbers, leading to the final selection of urban areas.

For these chosen areas, three primary data types are collected for use as model inputs: the coordinates (latitude and longitude) of each urban area's main city, the air passenger demand between each urban area pair, and the existing high-speed rail services connecting two or more areas. These data inputs are crucial for defining and calculating the model's parameters and constraints, together with their respective specifications as outlined in *section 4.4*. These elements are then inserted into the algorithms as described in *section 3.3*, where network design modifications based on existing designs are calculated first, and then, the corresponding services to meet demand in the modified network are computed. Consequently, the objective values are derived from the algorithm-calculated elements.

The final step involves extracting the characteristics of the modified network, regarding the strategic infrastructure design and operational elements, along with the different objective-balanced solutions. These characteristics are crucial for evaluating the network modifications from both large-scale transport and economic sustainability perspectives.

3.2 Problem Characteristics

3.2.1. Problem general definition

In *section 2.2*, it was found that the standard problems which quantitatively describe the search towards optimal transit systems are called Transit Network Planning Problems. More specifically, problems controlling for the selection of lines and their according frequencies, but also include capacity planning characteristics are called Transit Network Design and Frequency Setting Problems. Consequently, a modified version of a TNDFSP is defined, such that it can describe the design of any HSR system in a long-distance transport network by also considering the existing situation of the network.

3.2.2. Problem sets and indices

Given the application-driven character of transit network planning problems, it is found that different notations are used over the literature. Below, an explanation of terms and notations as used for this specific problem is provided. The network is expressed as an undirected and incomplete "graph" $G = [V, E]$, which is composed of a finite set of cities that are represented as "vertices" $V = [v_1, v_2, \dots, v_i]$, and a finite set of connections between these cities that are represented as "edges" $E = [e_1, e_2, \dots, e_k]$.

Following this given graph, a "line" can be defined as a service that is a sequence of directly connected vertices. Combining multiple of these separate line together results in a set of lines $L = [l_1, l_2, \dots, l_m]$. Passengers travelling through this network using a single line follow a "direct path" p^d and passengers requiring a transfer to make their trip follow a “transfer path” p^t. Together, these paths form the set of paths $P = [p_1, p_2, \dots, p]$, where each OD pair has either a direct or transfer path, with its corresponding demand being distributed to that single path. An overview of the indices and sets used is presented in *Table 3.2*.

Table 3.2: Overview of the model’s indices and sets

Name	Symbol	Index	Set
Vertex	v	$i, j \in V$	$V = [v_1, v_2, \dots, v_i]$
Edge	e	$k \in E$	$E = [e_1, e_2, \dots, e_k]$
Line	l	$m \in L$	$L = [l_1, l_2, \dots, l_m]$
Direct path	p^d	$d \subset P$	$P = [p_1, p_2, \dots, p]$
Transfer path	p^t	$t \subset P$	$P = [p_1, p_2, \dots, p]$
Graph	G	-	$G = [V, E]$

3.2.3. Problem parameters

As previously explained, the graph G of this network consists of vertices v, edges e and lines l. Within this graph, either direct paths pd or indirect paths pt using lines can be used to travel across vertices. The travel demand is given by the number of passengers originally served by short-haul flights that are now shifted to high-speed rail services. The services are operated by high-speed trains of the same properties in order to simulate a unified high-speed rail network. The characteristics of the five entities (vertices, edges, lines, demand, vehicles) provide the problem with its structural operating environment, for which a more detailed elaboration is provided below.

Vertex parameters

The vertices in the graph correspond to cities that have a function as origins and destinations for the transport demand, where the total number of vertices is defined as V. These cities geographical locations are represented by their latitudes φ_v and longitudes λ_v, which describe their angle relative to the equator and the meridian. The parameter $Dist_{i,j}$ gives the vital measurement of the distance between two vertices, offering the spatial span between them in kilometres, calculated by the Haversine formula. The current maximum capacity of a vertex, is captured by the parameter Cap_v^{exs} that serves as a quantitative measure denoted in vehicles per day, indicating the vertex's load-bearing capability of high-speed trains within a full operational day. An overview of the vertex parameters is given in *Table 3.3*.

Table 3.3: Overview of the model’s vertex parameters

Parameter	Description	Units
$\boldsymbol{V}$	Number of vertices v	[-]
$\boldsymbol{\varphi_v}$	Latitude of vertex v	[deg]
$\boldsymbol{\lambda_v}$	Longitude of vertex v	[deg]
$\boldsymbol{Dist_{i,j}}$	Distance between vertices v_i and v_j	[km]
$\boldsymbol{Cap_v^{exs}}$	Existing maximum capacity of vertex v	[veh/day]

Edge parameters

The individual vertices are linked by the edges. These edges represent the presence of connections, which are denoted by the term $e^{exs}(v_i, v_j)$, which describes the actual existence of an edge between nodes v_i and v_j. This is done in a binary form, where $true = 1$ and $false = 0$. Each of the edges comes with its unique set of properties. The edge-specific characteristics concern the length of an edge represented as Len_e, which is given by the calculated distance between the two vertices the edge is comprised of, as well as the average travel time expressed as $Time_e$ that is required to traverse the edge. An overview of the edge parameters is given in *Table 3.4*.

Table 3.4: Overview of the model's edge parameters

Parameter	Description	Units
$\boldsymbol{E}$	Number of edges e	[-]
$\boldsymbol{Existence_e(v_i, v_j)}$	Existence of edge e between vertices v_i and v_j $(true = 1, false = 0)$	[-]
$\boldsymbol{Len_e}$	Length of edge e	[km]
$\boldsymbol{Time_e}$	Average travel time of edge e	[hr]

Line parameters

Chaining a series of consecutive vertices that are linked by edges, makes a line. Lines can be used by passengers to travel between the vertices that are part of this line. Similarly to the edges, lines also have line-specific characteristics that derive from the existing services of the network, such as the existing maximum capacity $Cap_l^{exs}$and the number of existing stops $Stops_l^{exs}$. The total length of a line is defined as Len_l and can be determined by summing the stretching length of the individual edges Len_e that are included in the line, of which the comprising set is denoted as Ω_l. In addition, the existing frequency of a line is defined to capture operating lines that could serve the inserted passenger demand Frq_l^{exs}. An overview of the line parameters is given in *Table 3.5*.

Table 3.5: Overview of the model's line parameters

Parameter	Description	Units
$\boldsymbol{\Omega_l}$	Set of edges assigned to line l	[-]
$\boldsymbol{Stops_l^{exs}}$	Existing stops of line l	[-]
$\boldsymbol{Len_l^{exs}}$	Existing length of line l	[km]
$\boldsymbol{Frq_l^{exs}}$	Existing frequency on line l	[veh/day]
$\boldsymbol{Cap_l^{exs}}$	Existing maximum capacity of line l	[pax/day]

Demand parameters

The optimization model involves several key parameters that define and manage passenger transportation demands and capacities within a network. The parameter $D_{i,j}$ signifies the total passenger demand between two specific vertices, reflecting the number of individuals requiring travel between these points, while the parameter D_v quantifies the demand for each vertex based on the total number of passengers boarding or alighting at the vertex. For the computed paths, $D_{i,j}^{p^d}$ characterizes the demand for direct travel between the vertices, following the designated direct path, while $D_{i,j}^{p^t}$ captures the demand for movement along a transfer path. From the path-level demands, the demand allocated to the lines specifically is given by D_l. Finally, the parameter Q_l defines the maximum passenger flow that a given HSR line can accommodate, outlining the capacity of that route in terms of the number of passengers it can serve. The calculated parameters collectively guide the optimization model in efficiently allocating passenger demands across various routes while respecting the capacities of the transportation lines. An overview of the demand parameters is given in *Table 3.6*.

Table 3.6: Overview of the model's demand parameters

Parameter	Description	Units
$\boldsymbol{D_{i,j}}$	Demand between vertices v_i and v_j	[pax/day]
$\boldsymbol{D_v}$	Demand on vertex v	[pax/day]
$\boldsymbol{D_{i,j}^{p^d}}$	Demand between vertices v_i and v_j along direct path pd_r	[pax/day]
$\boldsymbol{D_{i,j}^{p^t}}$	Demand between vertices v_i and v_j along transfer path pt_s	[pax/day]
$\boldsymbol{D_l}$	Demand on line l	[pax/day]
$\boldsymbol{Q_l}$	Maximum passenger flow on line l	[pax/day]

Vehicle parameters

Unique vehicle characteristics are required to fully shape the performance of the model. Specifically, the seating capacity of the vehicle SC, measured in passengers per vehicle, provides a fundamental insight into the maximum occupancy the vehicle can accommodate, while its design load factor LF, indicates the ratio of the actual load carried by the vehicle to its maximum load-bearing capacity, thus calculating the appropriate frequency on a line as further explained below. Finally, the parameter SP characterizes the average travel speed of the vehicle, expressed in kilometres per hour, which influences the ability to operate on existing edges and line of specific maximum speed. An overview of the vehicle parameters is presented in *Table 3.7*.

Table 3.7: Overview of the model's vehicle parameters

Parameter	Description	Units
$\boldsymbol{SC}$	Seating capacity	[pax/veh]
$\boldsymbol{LF}$	Design passenger load factor	[-]
$\boldsymbol{SP}$	Average travel speed	[km/h]

3.2.4. Problem decision variables

In the literature background, it was described that the TNDFSP is characterised by two distinct decision variables: the lines to be chosen and the frequencies applied on these lines. Given their inherent connection to the TNDFSP, these two are also employed is this research, however, with the number of lines being optimally defined during the first algorithm (based on the problem constraints explained in a following subsection), and thus, used as an input for the determination of the frequencies. The values of maximum passenger flow per line can be combined with the vehicle seating capacity and design load factor to find the number of vehicles needed to facilitate the line demand, namely the frequency of the designed line, as shown in *Equation 3.1*. The line frequency frq_l is the dependent variable that computes capacities for vertices and lines as explained in the first objective. Therefore, it is considered as the single decision variable for this problem, and it is given in *Table 3.8*.

$$frq_l = \left\lceil \frac{Q_l}{SC * LF} \right\rceil \tag{3.1}$$

Table 3.8: Overview of the model's decision variables

Parameter	Description	Units
$\boldsymbol{frq_l}$	Frequency on line l	[veh/day]

3.2.5. Problem objectives

The problem as formulated for this research is a bi-objective combinatorial optimization problem, with the primary aim of improving and maximizing the utilization of existing rail network infrastructure within feasible budget constraints. This falls under the Transit Route Network Design Problem, where the central objective is to enhance the overall capacity of the transit network through strategic resource allocation and utilization. Key considerations for this objective include the type of rolling stock, passenger demand accommodation, and crucially, the limitations posed by the existing infrastructure.

<u>Objective function statement</u>

The optimization question of this research can be expressed by the following statement: "Maximize the total capacity utilization while minimizing operational costs across all vertices and lines".

This objective is twofold: firstly, it seeks to maximize capacity utilization by focusing on infrastructure capacity components; secondly, it aims to minimize operator costs, thereby ensuring that capacity expansion remains within logical financial limits.

<u>Infrastructure capacity components</u> ($Max\colon Z1 = Vertex + Line$)

The infrastructural capacity in this problem encompasses both station and line capacities, in order to provide a comprehensive view of the network's overall capacity utilization. As identified in *section 2.2*, stations and lines are strategic-level infrastructure elements in transit networks, hence, both capacities directly influence the network's ability to meet passenger demand and adapt to changes in usage patterns. Although the capacity of stations and lines is generally independent, in this problem it is influenced by the frequency of the operating lines, which makes it essential to consider both in conjunction. This approach ensures that both stations and lines are used to their fullest potential, enhancing overall network efficiency.

The optimization aims to maximize the accommodation of air-to-rail substitution passengers within the redesigned infrastructure. The capacity utilization of stations is calculated by balancing the factors that influence passenger flow in stations. This involves considering the station-specific demand, the infrastructure's intrinsic capacity, the excess capacity available to absorb fluctuations, the frequency of services across various lines, and the infrastructure’s adaptability. Similarly, the capacity utilization of the lines focuses on evaluating the collective capacity of the interconnected lines. Elements such as line-specific demand, the available seating capacity of each line based on the type of operating trains, service potential based on excess capacity, and most importantly the frequency of services, shape the equation's outcome. The two capacity components are expressed by *Equation 3.2* and *Equation 3.3* respectively, utilizing the elements mentioned above. Overall, the following statement can be used to express the objective of the network’s capacity: “Maximize the number of substitution passengers that can be served”.

$$Vertex = \sum_{v \in V} \left(\frac{D_v}{Cap_v * \ SC} \right) \tag{3.2}$$

$$Line = \sum_{l \in L} \left(\frac{D_l}{Cap_l} \right) \tag{3.3}$$

<u>Operator cost components</u> ($Min\colon Z2 = Costs + Emissions$)

In this problem, the entity responsible for funding the system assumes the role of the operator. Accordingly, this stakeholder is primarily concerned with minimizing the expenses associated with providing the service. As indicated by (Zschoche et al., 2012), operation-related costs encompass the continuous expenditures linked to delivering the necessary services for the functioning of a (high-speed) railway network. These include expenses related to train personnel, energy consumption, administrative overhead, track usage fees, and station management. The authors note that in the context of the United Kingdom's railway network, personnel expenses and maintenance costs for rolling stock constitute the largest proportion of expenses. Consequently, the focus of this research includes two aspects: (i) the operational expenses and (ii) the maintenance expenses associated with the high-speed rail system.

In addition to these direct costs, this research also considers the environmental impact of the railway operation, specifically CO_2 emissions, as an integral part of the operator-related costs. This inclusion stems from the understanding that emissions, while environmental in nature, have significant long-term economic implications. By converting emissions in monetary units, the model aligns with a broader perspective of operation-related costs that encompasses both financial and environmental perspectives. Therefore, the operator in this research is responsible for both economic efficiency and environmental responsibility. This dual consideration ensures that the operator's decisions on a high-level are not only financially sound but also environmentally sustainable.

These two components of cost are defined in *Equation 3.4* and *Equation 3.5* respectively, utilizing the marginal costs per kilometre framework that correlates with the specific operator cost categories, as well as CO_2 emissions produced during operation paired with a value of carbon convertor. The following statement can be used to express the objective of the operator costs: “Minimize the operator-related costs for operating and maintaining train lines”.

$$Costs = \sum_{l \in L} (2 * len_l * frq_l * SC) * (C^{oper} + C^{main}) \tag{3.4}$$

$$Emissions = \sum_{l \in L} (2 * len_l * frq_l * SC) * (Em^{oper} * VoC) \tag{3.5}$$

3.2.6. Problem constraints

To ensure feasible results that also remain within computational limits, the model’s solution possibilities are bounded by a series of constraints (*Equation 3.7* to *Equation 3.16*). The constraints apply to multiple aspects of the problem and serve different functions. For structure reasons, they are divided into three categories: (i) Capacity, (ii) Line design, and (iii) Frequency. A general non-negativity constraint regarding flow on edges is also included for modelling purposes. All defined constraints are implemented and satisfied during the steps of the algorithms as explained in the following section. A list of the utilized constraints in this work is given below.

Capacity constraints

In the realm of TNDFSP, the consideration of capacity constraints encompasses the management of passenger flows at various levels, including vertices, edges, and lines, with the overarching goal of preventing capacity overruns and maintaining the integrity of the transit network. For this research, in order to ensure the maximum number of passengers travelling at any segment of a certain line can be met for the whole network, line capacities must exceed the maximum number of passengers within an operational day.

- Maximum passenger flow at each line should not exceed its capacity

$$Q_l \leq Cap_l, \quad \forall \quad l \in L \tag{3.6}$$

Line design constraints

The influence of line design constraints on this project is evident in two key aspects. Firstly, by setting specific parameters for line design, such as length and number of stops, the feasibility of the proposed solution is improved by eliminating impractical line options. Additionally, the computational load of the problem is significantly affected by the quantity of lines requiring assessment. Consequently, limiting the number of potential lines through transfer restrictions is crucial in expediting the process of finding a solution.

- Minimum line length

$$len_l \geq len_l^{min}, \quad \forall \quad l \in L \tag{3.7}$$

- Maximum line length

$$len_l \leq len_l^{max}, \quad \forall \quad l \in L \tag{3.8}$$

- Minimum number of stops

$$stops_l \geq stops_l^{min}, \quad \forall \quad l \in L \tag{3.9}$$

- Maximum number of stops

$$stops_l \leq stops_l^{max}, \quad \forall \quad l \in L \tag{3.10}$$

- Line symmetry

$$l_{m(i,j)} = l_{m(j,i)}, \quad \forall \quad i,j \in V \tag{3.11}$$

- Maximum number of transfers

$$n_{p^t}^{trf} \leq n_{p^t}^{trf,max}, \quad \forall \quad p^t \in P \tag{3.12}$$

Frequency constraints

Numerous TNDFSP studies typically focus on establishing a range of viable line frequencies and vehicle headways, which aids in the development of user-friendly schedules during subsequent design stages. However, due to the extended time horizon and the relatively infrequent nature of long-distance travel, this research does not take these factors into account. Nevertheless, three essential requirements, derived from the previously mentioned standard, are still upheld to guarantee a feasible outcome.

- Integer frequencies

$$frq_l = \mathbb{Z}, \qquad \forall \quad l \in L \tag{3.13}$$

- Minimum frequency

$$frq_l \geq frq_l^{min}, \qquad \forall \quad l \in L \tag{3.14}$$

- Frequency symmetry

$$frq_{l(i,j)} = frq_{l(j,i)}, \qquad \forall \quad i, j \in V \tag{3.15}$$

3.3 Model Formulation

As outlined in the methodology overview of *Figure 3.1*, all predefined parameters and constraints are utilized to compute the steps of the developed algorithms, in order to determine the decision variables, and consequently, the objective values of the problem. The model formulated to address this problem emulates a manual optimization process, consisting of a sequential, integrated use of two algorithms. The process begins with the construction of the modified network layout, including the design of new lines and potential transfer options, and is followed by the calculation of suitable frequencies for the network, and ultimately, the determination of the objective values. In conventional optimization problems, these steps are typically automated by an optimization solver. However, due to the interdependent nature of the first objective function components, an automated approach is not feasible since the problem is not linear. Therefore, the steps are executed through algorithms in this manual optimization process.

To achieve this, extensive data processing and adjustment of model parameters are necessary to meet the model's constraints, determine the decision variables, and compute the objectives. Initiating this process requires defining the parameters from the model's dataset, which paves the way for generating new lines as well as all the possible travel paths.

Subsequently, these paths are analyzed to determine the frequency of both existing and new line services. This process is facilitated by two constructed algorithms: the Line Generation Algorithm (LGA) and the Frequency Setting Algorithm (FSA) respectively.

Most of the model parameters as defined in *section 3.2* serve as inputs for the LGA. This algorithm is structured in a systematic approach to design a modified network for high-speed rail services, aiming to enhance the connectivity among cities, which are depicted as nodes in a network graph, based on the existing network infrastructure. This methodology is executed through a series of distinct steps illustrated in *Figure 3.2*, and as defined below:

1. **Graph Creation:** The algorithm begins by constructing a graph where cities are nodes, and their existing line connections are edges. Travel times between cities are calculated based on distance and average vehicle speed, which are then assigned as weights to the edges. Isolated nodes are also included for the case of cities without direct connections.
2. **Existing Network Tolerance:** Following, the algorithm integrates demand data with existing network capacities, converting train frequencies to passenger capacities. It then assesses the capacity surplus or shortage for each vertex, identifying those where demand exceeds capacity, for which primarily a service redesign is required.
3. **Analysis of Overloaded Vertices:** The identified overloaded vertices with insufficient capacity are analyzed to determine all potential direct and indirect paths within the predefined network structure, considering feasible transfer paths. The algorithm distinguishes between OD pairs served by existing direct paths and those that are not, preparing the groundwork for generating new lines, by creating all the connection possibilities between lines and subsequently, identifying which paths can be served by direct services and which by a combination of these lines. The process involves identifying viable paths by filtering them according to specific design constraints for line creation, which aims to establish single lines and their potential combinations within the predefined design boundaries. This step is notably the most computationally intensive in the algorithm, as it begins with generating a substantial number of paths, which are then progressively filtered out through iterative refinement.
4. **New Edges and Lines Generation:** Subsequently, the algorithm identifies paths that can serve unserved transfers, focusing on the shortest paths based on travel time. It prioritizes direct paths when they are more efficient (based on number of stops and line length) or equivalent to indirect paths. New potential lines are then generated, expanding the network to accommodate the identified paths.

5. **Analysis of Missing Edges:** Finally, the algorithm searches for any missing edges in the expanded network, including for the non-overloaded vertices, with the aim to achieve the best possible connectivity. It creates reverse paths for existing ones to match with missing edges, thus finalizing the network model with all possible paths that can serve the edges.

Figure 3.2: Line Generation Algorithm inputs and outputs per step

Throughout the process, the algorithm comprehensively constructs a modified high-speed rail network in detail by utilizing current capacities, demand, and connections. It strategically enhances the network by introducing new lines and paths, ensuring the most efficient travel times and addressing capacity shortages. The result is a robust model that can inform the optimization of services to meet passenger demand effectively.

Subsequently, the identified possible paths are used to compute the frequencies for the lines that will be allocated in the modified network, with the FSA. This algorithm is designed to select optimized frequencies of the high speed rail lines based on demand distribution and the capacity of utilized train fleet. The algorithm is defined as a function in the programming environment, which utilizes various parameters, including demand data, percentage adjustments, and detailed path information from the LGA.

The function's goal is to calculate the objective functions that reflect different demand scenarios and to determine the optimal frequency of service for each selected line. The algorithm adjusts the base demand data by applying different percentage levels. This simulates various demand scenarios, allowing the algorithm to plan for different levels of passenger usage. The consecutive steps of this process (*Figure 3.3*) are defined as follows:

1. **Demand Distribution:** At the start, the algorithm calculates the demand between each pair of vertices along every possible computed path, and then, it distributes the demand based on the shortest path or equally among paths of the same length if there are multiple shortest paths. Afterwards, the path-level demand is converted into line-level demand. For paths that are not formed by a single line, and hence concern transfers, the total demand is assigned to both the connected lines separately.
2. **Maximum Passenger Flow:** Subsequently, the algorithm determines the maximum passenger flow on each line by examining the demand added and removed at each vertex along the line. Through this process, the segments of each line with the highest passenger flow are identified.
3. **Frequency Setting:** Using the calculated maximum passenger flows per line, the algorithm calculates the frequency for each line. It ensures that the frequency is sufficient to handle the maximum passenger flow, considering the load factor and seating capacity parameters. Following, it adjusts the frequency to ensure that all lines have the capacity to meet the demand, rounding up to ensure full coverage, as well as taking into account the preferred line symmetry.
4. **Capacity and Demand Calculation:** Before the calculation of the objectives, all frequency-dependent variables are computed. The algorithm calculates the capacity and demand at each vertex and line, as well as the length and stops of the final designed HSR lines.
5. **Objective Calculation:** With all required variables calculated, the objectives are computed in the final step of the algorithm. The first objective aims to maximize the utilization of capacity by assessing how well the demand is met by the available capacity at each vertex and on each line. Conversely, the second objective aims to minimize the costs to the operator by considering operational and maintenance costs, as well as environmental costs represented by produced emissions during operation, as defined more elaborately in *section 4.5*. Ultimately, the algorithm returns the values of the two objective functions, providing a quantitative measure of the network's efficiency and cost-effectiveness under the given demand scenarios.

Figure 3.3: Frequency Setting Algorithm inputs and outputs per step

Consequently, the FSA can dynamically adapt to different demand levels and take into account various factors to ensure that the designed HSR services are both efficient as well as cost-effective from an infrastructure perspective for the operators.

Finally, in order to compute the optimal solutions for the bi-objective problem the Pareto front analysis is employed. The Pareto front is a powerful and essential tool in multi-objective mathematical optimization problems, especially in situations where conflicting objectives need to be balanced (Xu et al., 2023). In the context of the bi-objective problem in this work, where the rail network's capacity is aimed to be maximized for the influx of passengers from the substituted flights, while also minimizing the costs of the operators, the Pareto front analysis is an ideal approach to tackle such a challenge. It represents a boundary in the objective space beyond which no further improvements can be made to one objective without causing a detriment to the other. Consequently, it is the set of all non-dominated solutions, each reflecting a different trade-off between the objectives.

To construct the Pareto front for this problem, the potential solutions based on the demand percentage distribution are evaluated. Each solution is a point in the objective space that reflects a specific trade-off between network capacity utilization and operator costs. The Pareto front is the collection of these points and is defined by the following conditions:

$Maximize: Network\ capacity\ utilization$
$Minimize: Operator\ costs$

$Subject\ to: No\ other\ solution\ can\ improve\ one\ objective\ without\ worsening\ the\ other$

By varying the demand distribution, a set of trade-off solutions that represent the optimal combinations of capacity and operational costs are generated. These solutions form the Pareto front, where no further improvement in one objective can be achieved without sacrificing the other. The Pareto front is visualized by mapping these Pareto-optimal solutions, with network capacity on one axis and operational costs on the other. This visualization delineates the frontier of optimal trade-offs between the two objectives. Decision-makers can then choose a solution from this Pareto front based on their preferences, considering the trade-offs between maximizing capacity and minimizing operational costs that align with the stakeholder's strategic goals.

3.4 Model Outputs

The model's outputs, derived from the algorithmic processes and the resulting designs, are utilized for interpretation, performance evaluation, and the comparison of various scenarios through key performance indicators. In *section 2.3*, performance indicators commonly employed in both airline and transit systems were analyzed. Given the unique nature of this research which examines both domains and considers the context of long-distance travel in a HSR network, it is decided to employ KPIs from both research fields. Resulting from this, three categories explained in the subsections below are selected.

<u>Objective values</u>

The objective values generated by the Pareto front analysis, give insights into the effectivity of a tested scenario. Considering both capacity and operational costs, values $Z1$ and $Z2$ give an overall leading performance score across varying demand distributions. Specifically, due to the generation of a range of optimal solutions, each set of values balances capacity and operational costs differently. Therefore, these scores are pivotal for decision-makers, offering insights into the trade-offs between the objectives and aiding in the selection of strategies that best align with operational goals and service expectations under fluctuating demand conditions.

HSR network characteristics

The properties of the network describe the structure of the proposed solution, offering an understanding of its performance characteristics. First, the number of active lines are indicated, along with a range of simple KPIs explaining the typical distance, stop, and frequency properties. Subsequently, vertex and line capacities are utilized to assess the modified infrastructure from a supply perspective. The final KPIs in this category give insights on network utilization, specifically which vertices and edges are more or less critical in the network's operation.

HSR operator's perspectives

The drive to minimize costs extends beyond immediate operational expenses for operators, since including long-term maintenance and environmental impacts are critical in sustainability-focused landscapes. The KPIs associated with the generalized operator costs as defined and calculated for each line, provide a holistic view of network efficiency, encapsulating the interaction between costs and emissions. This approach evaluates the provided service efficiency and supports the making of informed decisions regarding the provision of high-quality and sustainable services that align with the diverging interests of the various stakeholders.

4

Case Study

This chapter outlines the contextual analysis of this study. Specifically, information is given on the case study that is selected for this work in *section 4.1,* for which the described methodology is applied, with detailed information regarding the geographical scope of the study, the specification of urban areas and the assumptions made in order to simplify the case study characteristics. Following, the market of short-haul flights is analysed, as well as the existing HSR network infrastructure in Europe (*section 4.2*), in order to acquire general information on which flights and existing rail networks respectively should be considered for the selected case study. Subsequently, the selected dataset is briefly explained in *section 4.3*, while finally, the parameterisation of the main network components, as well as the determination of the demand scenarios is explained in *section 4.4*.

4.1 General Context

4.1.1. Geographical scope

One of the objectives of this study is to analyze the potential of air-to-rail substitution of short-haul flights by HSR, based on existing rail infrastructure on a continental level. Therefore, the study's geographical scope has been limited to the European continent. To elaborate further, a group of countries has been selected, starting with the 27 European Union (EU) Member States. From this initial set, certain countries have been excluded and others included based on specific criteria.

The first criterion concerns countries that are not part of the EU, but can be included in the set due to certain associations with the European continent. Specifically, countries that can be included are those part of the European Free Trade Association (EFTA), namely Iceland, Liechtenstein, Norway and Switzerland. Moreover, candidate countries or potential candidates for the EU, (Albania, Bosnia and Herzegovina, Moldova, Montenegro, North Macedonia, Serbia, Türkiye, and Ukraine) can also be added to the set, as well as nations that are not part of the EU, but are still connected to the European rail networks, such as, Belarus, Russia, and the United Kingdom (UK).

The second criterion involves the prerequisite that all considered countries must be directly linked to the international rail network of Europe, while the third criterion rules out countries with small populations, and thus, few passenger movements, as well as territories that are under the dependency of other countries. Consequently, the following countries, island nations, and territories are excluded from the set:

- ❖ Cyprus (EU member)
- ❖ Faroe Islands (Denmark)
- ❖ Gibraltar (United Kingdom)
- ❖ Iceland (EFTA)
- ❖ Ireland (EU member)
- ❖ Isle of Man (United Kingdom)
- ❖ Liechtenstein (EFTA)
- ❖ Malta (EU member)
- ❖ Monaco (Independent - small)
- ❖ Northern Ireland (United Kingdom)
- ❖ San Marino (Independent - small)
- ❖ Vatican City (Independent - small)

Due to the Russo-Ukrainian war and the suspension of flights between Belarus, Ukraine, Russia, and Europe are suspended, as well due to lack of data reliability, these countries are also excluded from the set.

Furthermore, despite the undeniable allure for tourism of several islands of the selected countries, maintaining comparability between air and rail networks on a more aggregate level was deemed of greater importance. As such, the third criterion narrows the scope to territories inside the mainland of the European continent, excluding several overseas territories, islands and archipelagos of certain countries as listed below:

- ❖ France: French Guiana, Guadeloupe, Martinique, Mayotte, La Réunion, Corsica
- ❖ Greece: Aegean Islands, Crete, Ionian Islands
- ❖ Italy: Sardinia
- ❖ Norway: Svalbard
- ❖ Portugal: Azores, Madeira
- ❖ Spain: Balearic Islands, Canary Islands

4.1.2. Urban areas

Following the initial selection of the group of countries under consideration, a consistent, comprehensive, and standardized dataset at the aggregation level is essential. This necessity arises to acquire reliable results at the continental scale, which aligns with the goals of this study. Dijkstra et al. (2019) highlight the formidable challenges of comparing international cities due to differing definitions, even within the EU. Despite the apparent clarity of an urban center as a node, accurately defining the urban area's scope proves intricate. It is also emphasized that urban area demarcations often rely on administrative or legal boundaries, failing to capture the functional and economic reach of metropolitan regions.

Consequently, this topic lacks a universally accepted definition, sparking widespread debate among researchers. For this study, to enhance precision and detail, the definition used when referred to urban areas adhere to the following description given by Moreno-Monroy et al. (2021): "densely populated urban centres and their surrounding and interconnected regions with lower population density".

The key institutions considered in this context are the statistical office of the European Union, Eurostat, and the Organization for Economic Cooperation and Development (OECD). They have established a consistent framework for representing various spatial levels across diverse nations, aiming to foster a unified comprehension of cities and their interconnected areas of influence.

Eurostat's Urban Audit encompasses data for regions, cities, metropolitan regions, and rural zones, utilizing diverse classifications and typologies. Within this framework, three primary spatial levels for urban areas are pinpointed, all based on the NUTS (Nomenclature of Territorial Units for Statistics) regions. The NUTS classification functions as a geographical system that divides the economic territory of both the EU and the UK into hierarchical tiers, as illustrated in *Figure 4.1*. This classification aids in the development of European regional statistics, socio-economic assessments of regions, and the formulation of EU regional policies. Specifically, the three spatial levels within this context are (i) City, (ii) Greater City, and (iii) Functional Urban Area (FUA).

To start with, as stated by Eurostat (n.d.-b) cities are identified as local administrative units (LAUs) where the majority of the population lives in an urban center with a minimum of 50,000 residents, as stated by the European Commission and Eurostat in 2019. Subsequently, the concept of the greater city emerges when the urban center extends significantly beyond the confines of the administrative city boundaries. Finally, FUAs or Larger Urban Zones (LUZs), encompass not only the densely populated city itself but also the surrounding commuting zone. This zone is defined as the peripheral regions where a minimum of 15% of employed residents work in the central city, according to the European Commission and Eurostat's 2019 definitions.

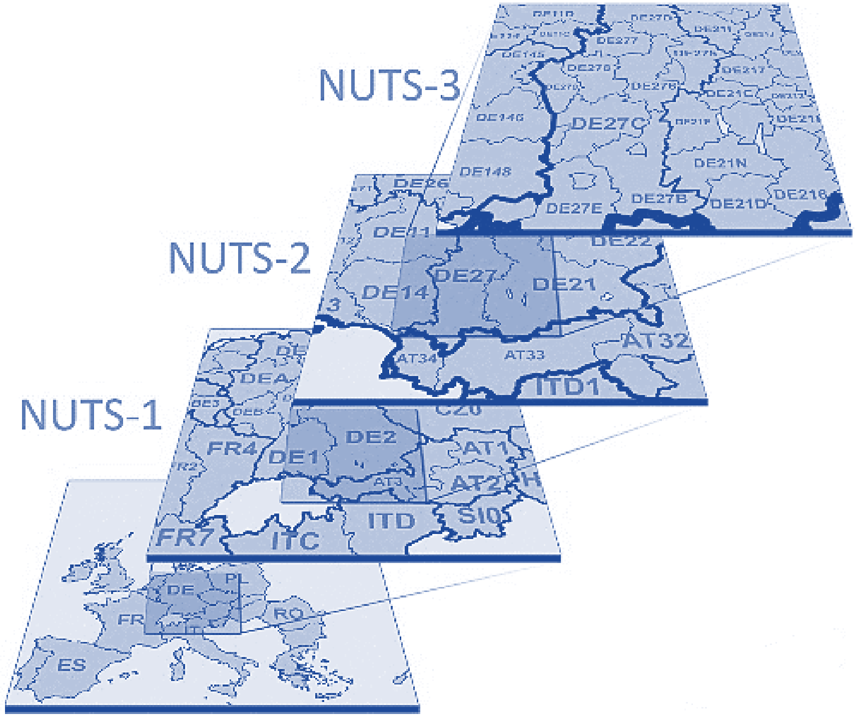

Figure 4.1: NUTS classification example (Eurostat, n.d.-a)

The utilization of city and greater city levels is avoided primarily due to their association with administrative boundaries (LUAs), which leads to a significant risk of introducing biased results when comparing different countries. Moreover, their level of disaggregation is also a factor. These levels often have limited coverage and thus do not adequately represent the true catchment areas of international transportation hubs like stations and airports. These transportation hubs are essential elements in this study and must be accurately represented as the nodes defining the areas under examination. Likewise, the broader definition of metropolitan areas, as outlined by the European Union, is not appropriate for this study. Similar to cities, these areas are closely tied to administrative boundaries, specifically by the NUTS-3 regions. Consequently, they may encompass not only urban regions but also adjacent rural areas. This could result in exceeding the study's intended scope, which focuses on specific areas of interest containing stations and airports.

Therefore, statistical geographic units that most closely matched the descriptions of urban areas provided in the following paragraphs were identified as Functional Urban Areas (FUAs). This level of aggregation was chosen as the most appropriate for addressing the scope of the issue under investigation in this research.

4.1.3. Case study assumptions

In order to simplify the examined area and emphasize the research goal, several case study assumptions were formed. A list of all the case study assumptions is presented in *Table 4.1*.

Table 4.1: Case study assumptions

Assumption
1. The study focuses on large Functional Urban Areas to limit the computational and dataset sizes while maintaining continental coverage
2. Only existing infrastructure and expansion plans in the immediate future are considered, excluding potential future developments
3. Restrictive policies that could influence network modifications are not considered
4. No distinction is made between OD and transfer passengers, treating all passenger movements uniformly
5. Passenger movements are assumed consistent throughout the year, without differentiating between high and low seasons.
6. Airports are chosen based on the highest passenger movements in each urban area, focusing on major travel hubs
7. For simplification only the main rail station in each urban area are considered
8. Night trains that are considered high-speed services are not included
9. No other cities in the UK except from London are considered due to its position in the UK rail network and connection to the rest of Europe

4.2 Long-distance Travel Market in Europe

During the last decade of increased climate change concerns and the environmental impact of travel, Europe has been at the forefront of adapting to changes in long-distance transportation. The dynamics of the long-distance market have changed significantly over the years, transitioning from the rise of short-haul flights and predominance of air travel, to addressing the challenges of airspace congestion with the expansion of rail networks for an alternative and sustainable unified transport network in Europe.

The European flight market stands out for its extensive network of international airport hubs, each playing a pivotal role in facilitating seamless and convenient travel across the continent. These international airports serve as critical entry points and transfer hubs for passengers, enhancing connectivity and contributing to the economic development of Europe. The major international airport hubs of Europe during the last years have been London Heathrow Airport, Frankfurt Airport, Amsterdam Airport Schiphol, and Paris Charles de Gaulle Airport. These airports handle substantial passenger traffic due to their strategic locations, and serve as central points for both short-haul and long-haul flights. Beyond serving intra-European travel, they also function as global aviation hubs, connecting travellers to destinations worldwide. Post-Covid-19 pandemic, passenger traffic has been rebounding, approaching the pre-pandemic levels of 2019, a benchmark year for air travel analysis. *Table 4.2* showcases these airports' rankings at both European and global scales, highlighting that Europe's ten busiest airports also feature among the world's top fifty, underscoring their role in cementing Europe's preference for air travel for long distances.

Table 4.2: Busiest European airports per annual passenger movements - 2019 statistics (Eurostat, 2019)

Airport	PAX	Europe Rank	Global rank
Heathrow Airport (United Kingdom)	80,886,588	1	7
Charles de Gaulle Airport (France)	76,136,816	2	9
Amsterdam Airport Schiphol (Netherlands)	71,689,636	3	12
Frankfurt Airport (Germany)	70,435,867	4	15
Madrid Barajas Airport (Spain)	59,747,242	5	22
Barcelona–El Prat Airport (Spain)	51,734,144	6	27
Istanbul Airport (Turkey)	51,009,220	7	28
Sheremetyevo International Airport (Russia)	49,932,752	8	35
Munich Airport (Germany)	47,891,776	9	38
London Gatwick Airport (United Kingdom)	46,560,536	10	42

In addition to the countries hosting Europe's ten busiest airports, there are numerous others with high-traffic airports, as detailed in *Table 4.3*. Particularly, larger countries operate several airports that exceed the 10 million passenger mark, attributable to their substantial populations and multiple tourist attractions.

Table 4.3: Number of airports with more than 10 million passengers per country - 2019 statistics (Eurostat, 2019)

Country code	Airports	Country code	Airports	Country code	Airports
BE	1	FR	5	RO	1
CZ	1	IT	6	FI	1
DK	1	HU	1	SE	1
DE	8	NL	1	UK	7
IE	1	AT	1	TR	10
EL	1	PL	1	NO	1
ES	7	PT	2	CH	2

Consequently, these airports significantly contribute to the environmental impact of air travel, not just through the volume of long-distance flights they facilitate, but also due to the multitude of carbon-intensive short-haul feeder flights that converge on these hubs for transfers. As depicted in *Figure 4.2*, the surrounding airspace of these hubs is heavily loaded with air traffic, specifically from the numerous short-haul flights traversing the continent. Therefore, these airports are of vital importance regarding air traffic congestion.

Short-haul flights are a staple for European travel, connecting cities and neighbouring countries efficiently. They are particularly crucial for channelling passengers from regional airports to major international and intercontinental hubs, facilitating seamless transition between connecting flights. One of the key drivers of the short-haul flight market surge has been the growth of low-cost airlines, which make air travel for leisure or business purposes affordable for a broader range of passengers.

Figure 4.2: Air traffic snapshot over Europe - March 2019 (Eurocontrol, 2020)

The convenience of flying has triggered a significant increase in air travel, with passengers frequently opting to fly, even for short distances. Nevertheless, this surge in air traffic has led to congestion at major airport hubs in Europe, often operating at capacity limits, and consequently, the production of air pollutants has increased. For distances between 500 and 1500 km where most short-haul flights are classified, these flights have constituted about 40% of annual total flights in recent years, while contributing to a quarter of total flight-related CO_2 emissions, which is a significant share of pollution, despite their relatively short travel distances (Eurocontrol, 2021).

As previously mentioned, high-speed rail has emerged as a solution to these challenges, offering competitive travel times for similar distances to short-haul flying. Europe possesses one of the most extensive and advanced high-speed rail networks in the world, which has seen considerable growth and continues to expand under the Trans-European Transport Network (TEN-T) initiative. This initiative aims to develop a comprehensive transportation network and to improve the connectivity, efficiency, and sustainability of transportation systems across EU member states and beyond. Several Central and Western European countries have made significant investments in their rail infrastructure, resulting in highly competitive and advanced rail networks that are part of the TEN-T rail network.

The core network is comprised of key rail corridors and connections that are strategically vital for the efficient functioning of the European rail transportation system, with emphasis on high-speed rail corridors and cross-border links. In *Table 4.4*, countries with significant HSR network and their evaluation since the year 2000 are presented, while a list of countries with the most advanced HSR network and a brief reference to their respective services is given below.

Table 4.4: Countries with significant high-speed rail network and corresponding length in kilometres for years between 2000 and 2020 (European Commission 2021-b)

Year	BE	DE	DK	ES	FR	IT	NL	AT	PL	FI	SE	UK
2000	72	576	-	471	1290	238	-	24	-	156	187	-
2005	137	1089	-	1038	1549	238	-	105	-	882	187	74
2010	209	1178	-	2102	1912	856	90	121	-	1120	680	113
2015	209	1381	-	3002	2058	856	90	237	224	1120	860	113
2018	209	1571	-	3002	2734	896	90	254	224	1120	860	113
2019	209	1571	56	3297	2734	921	90	254	224	1120	860	113
2020	209	1571	56	3297	2734	921	90	254	224	1120	860	113

- Germany**:** Known for its efficient and extensive rail network with several technological advancements; operates the ICE (InterCity Express) network, connecting cities like Berlin, Frankfurt, Munich, and Cologne.
- France: Possesses the second largest network operated by TGV (Train à Grande Vitesse), which is known for its speed and accessibility, linking Paris with cities like Lyon, Marseille, and Bordeaux, as well as international destinations of neighbouring countries.
- Italy: The Frecciarossa and Frecciargento services operated by Trenitalia, connect cities such as Rome, Milan, Florence, and Naples, providing enhanced travel between major tourist destinations, as well as accessibility throughout the Italian peninsula.
- Spain: The AVE (Alta Velocidad Española) network is the largest network in terms of length, allowing multiple daily connections between Madrid, Barcelona, Seville, and Valencia.
- Belgium & Netherlands: Via the Thalys and Eurostar services, connections between the cities of Brussels, Amsterdam, Paris, and London are available.
- Switzerland: While not a member of the European Union, Switzerland has an extensive and efficient rail network, including high-speed services; the Swiss Federal Railways (SBB) connects major Swiss cities.

A visualization of the core railway network corridors in Europe is given in *Figure 4.3*, where railways are classified based on operating speed. When comparing airports and high-speed rail infrastructure, a clear correlation between high traffic airports and advanced high-speed rail network can be observed in large European cities.

Figure 4.3: Map of operational high-speed rail lines in Europe (Wikipedia, 2023)

4.3 Database Selection

Following the initial selection of countries and the statistical territorial units of FUAs, the NUTS 2021 maps and the databases for FUAs from Eurostat and OECD.stats were explored. The data were collected through Eurostat's Urban Audit database, regarding FUAs and specifically based on the annual population by age groups and sex. This is done in order to select the specific urban areas to analyse for each selected country. The analysis involves examining the highest population areas per country and selecting the ones that adhere to at least the 5% of the total country population, or that have over 500 thousands population. Out of this analysis, 119 urban areas are collected. This number is reduced based on the availability of rail station and airport in the area.

Railway stations linked to each urban area have been meticulously chosen based on the author's familiarity with the subject. In the initial phase, for smaller urban areas, only the larger and central stations offering intercity and long-distance services are considered, while later on they are excluded in the cases where air passenger movements are not significantly high.

To streamline computational demands, the identification process begins by filtering out pertinent commercial airports based on their annual passenger traffic, employing a minimum threshold of 5 million passengers per year. The relevant traffic data originates from the Eurostat database on air passenger transportation metrics (Eurostat, 2023). Specifically, data from the year 2019 is utilized to sidestep the disruptions in air travel resulting from the Covid-19 pandemic in 2020 and 2021, since air traffic is slowly returning to its pre-pandemic levels. Subsequently, these filtered airports are linked to each of the urban areas selected in the preceding step, utilizing the defined catchment areas. In certain instances where a significant airport is not found within a city's catchment area, airports in the surrounding area with passenger traffic falling below the threshold are included instead. Lastly, current operating lines on high-speed rail corridor are collected from a rail ticket provider affiliated with all high-speed train operators in Europe, and cross checked with multiple operators' websites, thus containing all relevant information for this study data, by checking high-speed train itineraries for each OD pair of the urban areas (Rail Europe, 2023). Conclusively, a final dataset of 69 urban areas is constructed, with their corresponding passenger movements and existing high-speed rail services, excluding night trains. A detailed overview of all the collected data is given in *Appendix A*.

4.4 Modelling Specifications

In *subsection 3.2.2,* the various parameters of the problem are defined, regarding the current HSR network situation, focusing on vertices, edges, lines, and demand and vehicle characteristics. These parameters are primarily computed based on the dataset used in this research, which includes information on vertex country and coordinates, and existing HSR services and air passenger movements between these vertices respectively. However, parameters regarding the characteristics of the utilized for this work train model, as well as parameters associated with the operator costs are selected based on insights from various authors.

Similarly, *subsection 3.2.5* details the problem constraints, which are crucial for network capacity, line design, and frequency planning. Some of these constraints ensure the model avoids physically impossible solutions, while others have a more practical application. An overview of the selected values for parameters and constraints are presented in *Tables 4.5* and *4.6*.

4.4.1. Parameter specifications

Vehicle specifications

In the context of high-speed trains, given that a variety of train models are operated by different providers across Europe, the task of selecting uniform vehicle parameters for a unified network presents unique challenges. To address this, a homogeneous fleet selection is adopted, drawing on insights from external expertise from RHDHV.

The choice has been made to standardize on the Frecciarossa 1000 model, which is currently in use on Italy's high-speed tracks. This train exemplifies the characteristics desired for a pan-European HSR network, as it combines speed, efficiency, and capacity in a manner that aligns with the overarching goals of a unified and efficient European rail system. Its selection indicates network standardization, ensuring that the system meets the needs of both operators and travelers. The relevant characteristics for this research are the vehicle seating capacity, load factor, and the operating speed.

The Frecciarossa 1000 has a maximum seating capacity of 457 seats, offering a range of classes including executive, business, premium, standard, and wheelchair-accessible seating. These trains can operate at speeds up to 300km/h, with a maximum design commercial speed of 360km/h, however, a simplified average operating speed of 220 km/h is selected for calculations to streamline the model by not accounting for variations in acceleration and deceleration. This simplification is followed by several authors with studies regarding rail networks (Campos & de Rus, 2009); Donners, 2016). Finally, high-speed trains typically operate with a design load factor between 70-80%. To maximize capacity utilization, a load factor of 80% has been chosen for this analysis. The selected parameters for the homogenous fleet (Trenitalia, 2018) are given in *Table 4.5*.

Cost specifications

The operator is responsible for the costs associated with the operation and maintenance of the network as outlined, driving the goal to minimize these expenses. Drawing on the study by Campos & de Rus (2009), which analyzed High-Speed Rail (HSR) systems worldwide, the research identifies three main cost categories: rolling stock acquisition, operational costs, and maintenance costs. For the purpose of this study, costs associated with the acquisition of rolling stock are excluded with the assumption that the rolling stock fleet already exists.

Focusing on current HSR systems in France (Thalys/TGV), Germany (ICE), Italy (ETR), and Spain (AVE), Jorik (2020) conducted a review of costs per passenger-kilometer. In this review, operational costs (C^{oper}) were found to range from 0.078 to 0.177 euros per passenger-kilometer, with an average of 0.130 euros, while maintenance costs (C^{main}) ranged from 0.0050 to 0.0230 euros, averaging at 0.0122 euros. Since a homogenous fleet is utilized in this work, the average cost values are selected, as presented in *Table 4.5*.

Emission specifications

The operator is also responsible for all emissions generated during the various stages of rail line design, similarly driving the goal of minimizing these pollutants. The International Union of Railways (UIC, 2011) study on the carbon footprint of HSR identifies three primary emission categories: manufacturing of rolling stock, operational emissions (including upstream emissions), and emissions from constructing tracks and heavy rail infrastructure. In this study, emissions from rolling stock manufacturing are excluded, assuming the use of an existing fleet. Similarly, construction-related emissions are omitted due to uncertainties about the extent of required new infrastructure for the modified network.

The UIC study analyzed heavy traffic HSR routes in France and China, including S-E Atlantic, LGV Mediterranée, Taipei-Kaohsiung, and Beijing-Tianjin. The analysis displayed an average of 5.7 grams of CO_2 per passenger-kilometer (E^{oper}) for French routes, while for Chinese routes, operational emissions ranged from 39.2 to 42.9 grams of CO_2 per passenger-kilometer annually. For this research, a daily average of these values is utilized, as shown in *Table 4.5*. Additionally, to incorporate emissions into the operator's cost objective function, emissions are converted from grams to euros using a Value of Carbon (VoC) metric for infrastructure. This metric is derived from an average of multiple studies (Bautista-Carrera, 2022; Dorband et al., 2022; OECD, 2022), and is given in *Table 4.5*.

Table 4.5: Parameter specifications

Category	Parameter	Value	Units
Vehicle	SC	457	[pax/veh]
	LF	0.8	[-]
	SP	220	[km/h]
Cost	C^{oper}	0.130	[euro/pax-km]
	C^{main}	0.0122	[euro/pax-km]
Emission	E^{oper}	0.0516	[gCO_2/pax-km]
	VoC	0.0005	[euro/gCO_2]

4.4.2. Constraint specifications

The constraints associated with the design of the lines in the model are tailored to ensure practicality and relevance. These constraints include setting minimum and maximum line lengths to prevent overlap with conventional train services and to avoid creating lines that exceed the typical travel distances of short-haul flights. Additionally, the model imposes limits on the number of stops per line. This is to ensure that each line includes at least two terminal stations while preventing an excessive number of stops that could increase overall travel times, making them less comparable to short-haul flights.

Furthermore, a minimum frequency for each line is established to guarantee operational viability. The model also takes into account line and frequency symmetries, ensuring a balanced and efficient network design. Finally, to maintain a focus on direct and efficient travel, the model restricts transfers to a single transfer per journey, aligning more closely with the convenience of short-haul flight travel times. These constraints presented in *Table 4.6*, prevent the model from creating a fragmented network of separate lines that would compete with conventional train networks, instead encouraging a holistic network perspective.

Table 4.6: Constraint specifications

Category	Constraint	Value	Units
Line Design	len_l^{min}	200	[km]
	len_l^{max}	1500	[km]
	$stops_l^{min}$	2	[stops]
	$stops_l^{max}$	5	[stops]
	$n_{pt}^{trf,max}$	1	[transfers]
Frequency	f_l^{min}	1	[veh/day]

4.4.3. Demand scenarios

The project's scenario selection is closely aligned with the global focus on sustainable transportation, particularly in aviation, as highlighted in the literature background. With increasing environmental concerns and the importance of addressing climate change, governments and transport authorities are actively seeking alternatives to air travel, especially for shorter distances. The scenarios developed in this study reflect these evolving dynamics, exploring various flight distances and geographical ranges. Each scenario indicates the degree of restriction on short-haul flights, thereby identifying the passengers that are considered as substitution passengers that are shifted to the existing HSR network. Consequently, these scenarios are characterized as demand scenarios, since different levels of influx demand is utilized to modify the networks.

The scenarios are shaped to encompass the diverse classifications of short-haul flight haul types, since literature reveals a disparity in defining the exact distance that qualifies as a short-haul flight. In response, this research adopts a flexible approach, embracing a wide range of definitions to cover the most pertinent and realistic scenarios for flight substitution. This methodology is in line with the policies and strategies of several EU Member States. Notable examples include Austria's ban on domestic flights that have a train alternative within 3 hours, and France's prohibition of flights where a direct rail service exists within 2.5 hours. By integrating these policy-influenced definitions, the demand scenarios are firmly rooted in the existing regulatory framework and practical considerations for replacing flights. For this reason, only demands between areas with distance of maximum 1000km is considered, to both emulate short-haul flights distances and maintain practical rail line properties. This ensures that the scenarios are not only relevant but also directly applicable to real-world situations.

Furthermore, the scenarios take into consideration the complex dynamics of modal shift. The focus on substituting short-haul flights with rail travel extends beyond mere distance considerations, since it critically involves assessing the availability and efficiency of alternative modes of transportation. The literature underscores the need to understand various factors that influence modal choice, including travel cost, duration, convenience, and environmental impact. Therefore, the demand scenarios are tailored to account for these elements, particularly within the diverse context of Europe's transportation infrastructure and the environmental footprint of different transport modes. They are attuned to the challenges associated with developing new infrastructure and the capacity of existing railway systems to absorb increased demand. Through this comprehensive approach, this study aims to offer a realistic evaluation of the feasibility of transitioning from air to rail travel, also contributing to the overarching objective of promoting sustainable mobility.

While the ideal scenario would be a 100% air-to-rail transition, achieving such a complete shift is not practically feasible. The complexity of, geographical constraints, travel desires and existing infrastructure limitations mean that a total replacement of air travel with rail is unrealistic. Therefore, the scenarios incorporate a range of demand distributions, from an optimistic 100% down to more realistic levels like 50%, to evaluate different degrees of modal shift. This approach allows for a comprehensive understanding of how varying levels of transition would impact the transportation ecosystem. Consequently, the scenarios are designed to realistically assess the potential for a partial but significant shift from air to rail, acknowledging that while a complete transition is the ultimate goal, a more gradual and feasible approach is necessary in practice. Below a detailed explanation of the two scenarios formulated in this study is provided. An overview of the separate urban areas datasets utilized for each scenario derived from the entire case study dataset, along with the main results are given in *Appendix B* and *Appendix C* respectively.

Scenario 1: Base case

The first scenario concentrates on the busiest airports in Central and Western Europe. This approach primarily aims to cater to the shift in demand of the largest number of passengers, by utilizing the existing coverage of the developed high-speed rail network of the broader area. More specifically, the base case encompasses the areas of London, Paris, Amsterdam, and Frankfurt, in which the four busiest European airports operate.

To broaden the scope and expand on this set to include flights to neighbouring countries, the feasibility of replacing short-haul flights within a 500km radius, as proposed by Baumeister & Leung (2021) and Eurocontrol (2021) is examined. Consequently, the areas of Brussels, Zurich and Milan are included in this scenario. These cities are geographically proximate to the initially selected areas, have airports with high passenger demand, and are situated in different countries, providing a broader perspective. A map of the existing connections between the areas included in the first scenario are illustrated in *Figure 4.4*.

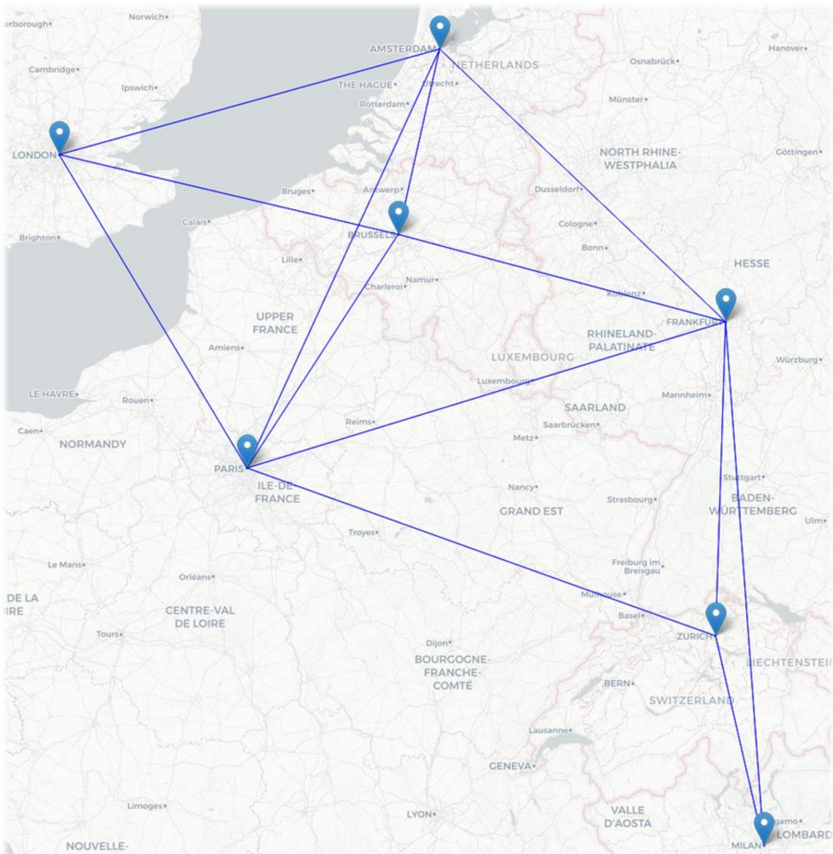

Figure 4.4: Scenario 1 current state map

<u>Scenario 2: Extended case</u>

The second scenario extends its focus to intra-European flights, aligning with the European Commission's 2050 vision, which foresees a significant transition of medium-distance passenger travel from air to rail. This scenario is particularly relevant in the context of ongoing discussions and policy initiatives aimed at reducing short-haul flights across Europe.

This scenario expands on the base case, incorporating a wider geographical spread that includes multiple regions adjacent to those covered in the first scenario. Notably, it incorporates Eastern European countries, along with regions in the southern part of the continent, particularly around the Mediterranean Sea. Key additions include Prague, Vienna, and Ljubljana, strategically positioned near Germany and Italy, which already possess advanced HSR networks. This expansion also encompasses southern cities like Barcelona, Madrid, and Lisbon, known for their efficient national and regional rail services.

Moreover, the scenario includes additional areas within countries already considered in the base case. For instance, Munich in Germany, Venice in Italy, and Toulouse in France are added, each representing significant urban centres with robust travel demand and potential for integration into the expanded HSR network. This comprehensive approach aims to create a more interconnected and sustainable travel infrastructure across Europe, in line with the broader goals of reducing carbon emissions and enhancing travel efficiency on the continent. A map of the existing connections between the areas included in the second scenario are illustrated in *Figure 4.5*.

Figure 4.5: Scenario 2 current state map

5

Results and Discussion

Following the collection of all necessary data for the selected case study, and the parameterisation of various model characteristics as described in the previous chapter, the supply-based model was developed and tested. This chapter asserts the results of the different scenarios for which a modified HSR network was designed. First, *section 5.1* presents the performance of the existing network for each scenario based on the analysis regarding the ability to serve the influx of short-haul travel passenger demand. Following, *section 5.2* describes the route possibilities of the selected scenario networks for demand overloaded FUAs, resulting from the design of new lines. Afterwards, the design characteristics of the modified networks are explained in *section 5.3*, based on the distribution of the passenger demand to the activated lines. Finally, the insights regarding the optimal solution outcomes where a balance between capacity utilization and operator costs can be achieved based on different stakeholder perspectives as well as the eventual performance of the networks are reported and discussed in *section 5.4*. The chapter concludes with a summary of the key findings that are extracted from the results.

The implementation of the model and its solution strategy was written in “Python 3.8.8” using the open-source development environment of “Spyder 5.1.5”, which was verified by continuous checks. A computer with the following characteristics was utilized for all performed tests:

- Processor: *Intel® Core™ i7-7700HQ CPU, 4/8 (Cores/Threads) with 6MB Cache, Base Frequency 2.80 GHz up to 3.80 GHz*
- GPU: *NVIDIA GeForce GTX 1060 with Max-Q Design, Pipelines: 1280, VRAM: 6GB GDDR5*
- RAM: *16 GB 2400 MHz*

5.1 Network Tolerance

The assessment of the network's ability to accommodate the passenger demand from short-haul flights is the first process in the Line Generation Algorithm. Since existing services have a current demand for HSR passengers, their operational capacity will not be able to satisfy both the present rail and the expected air traffic, and consequently, the overall network’s capacity is not sufficient. However, depending on the urban area and the size of rail stations, and hence, the number of trains that can be handled from each station within an operational day, it could be possible that with adjustments to the service itineraries certain areas could handle both existing and new passenger movements.

The demand associated with the influx of air passengers at each node is based on the total number of passengers that either board or align at the area, while its capacity can be computed based on the total number of vehicles of all the lines that operate in the area, and depending on their maximum possible seating availability, it can be expressed in total number of passengers during an operational day. Therefore, the difference between the demand of each node and its existing passenger capacity reveals whether there is a surplus or shortage of capacity at each node. Nodes where the demand surpasses the available capacity are of particular interest, as they indicate points in the network that are overloaded.

5.1.1. Scenario 1

In the first scenario, the overall existing vertex capacity is overloaded by 20% of its total ability to serve passengers based on the current operational HSR services, indicating that several nodes in the network are overloaded due to the increase in passenger traffic, as presented in *Table 5.1*.

Table 5.1: Network tolerance (Scenario 1)

Nodes	Demand (pax/day)	Capacity (pax/day)	Surplus/Shortage (%)
Amsterdam	33,140	19,194	-72.66
Brussels	13,610	21,022	35.26
Frankfurt am Main	28,394	26,506	-7.12
London	37,135	16,452	-125.72
Milan	19,137	10,054	-90.34
Paris	30,365	32,904	7.72
Zurich	22,263	21,022	-5.90
Total	**184,044**	**147,154**	**-20.04**

More specifically, three nodes (Amsterdam, London, and Milan) are overloaded with more than 70% of their total capacity, which can be attributed to both their high demand levels and their low operation of services towards the other destinations. This can be noticed when examining the possible destination nodes of the existing lines for these overloaded nodes, since they can either serve approximately only half of all the nodes in the network with a direct service. Moreover, this can also be observed when examining these nodes in terms of their location, as they are the furthest nodes in the network along with Frankfurt am Main which is also overloaded, yet in a significantly less percentage (~8%). As a result, this shortage in capacity indicates the necessity for the design of additional lines in order to increase total services in the network, and enable more direct and consequently transfer route options.

5.1.2. Scenario 2

In the second scenario, despite the network's larger size and wider spread, its ability to serve passengers based on the current operational HSR services is sufficient by approximately 18%, which is a major improvement compared to the first scenario. This suggests that the integration of new nodes, along with their associated demand and existing lines, is relatively well-balanced, allowing a significant portion of the new demand to be accommodated by the current lines in certain areas. The network's tolerance levels are detailed in *Table 5.2*.

Table 5.2: Network tolerance (Scenario 2)

Nodes	Demand (pax/day)	Capacity (pax/day)	Surplus/Shortage (%)
Amsterdam	64,408	26,506	-142.99
Barcelona	52,393	45,700	-14.65
Berlin	56,511	63,980	11.67
Brussels	29,951	52,098	42.51
Budapest	15,166	12,796	-18.52
Copenhagen	31,615	0	-
Frankfurt am Main	79,509	103,282	23.02
Lisbon	14,841	12,796	-15.99
Ljubljana	2,969	914	-224.84
London	55,828	26,506	-110.62
Luxembourg City	9,825	16,452	40.28
Madrid	33,306	63,066	47.19
Milan	39,828	108,766	63.38
Munich	61,803	89,572	31.00
Nice	22,638	6,398	-253.83
Paris	71,070	69,464	-2.31
Porto	15,385	12,796	-20.23
Prague	30,739	33,818	9.10
Rome	30,474	98,712	69.13
Seville	9,742	24,678	60.52
Toulouse	15,435	10,054	-53.52
Venice	21,160	57,582	63.25
Vienna	41,888	53,926	22.32
Warsaw	12,995	12,796	-1.56
Zurich	51,241	31,076	-64.89
Total	**870,720**	**1,039,218**	**18.30**

The results in this scenario display a few similarities compared to the first regarding the overloaded vertices, with Amsterdam, London, and Zurich still being unable to serve both and existing passengers through their current operations. Conversely, Frankfurt am Main and Milan which previously were also identified as overloaded, in this scenario, they sufficiently serve their respective demands, possibly due to their central location in the extended network, and the inclusion of multiple additional lines serving locations in close proximity. Notably, despite its also key location connecting multiple areas, Paris is slightly overloaded compared to the first scenario where it displayed small surplus in capacity, which can be attributed to the inclusion of areas in the Southern Europe. In contrast, Brussels retained sufficient capacity, and increased it by approximately 7%.

Regarding the newly included areas, most of them are identified as sufficient to supply their respective influx of passengers, with surplus percentages ranging from 5% to 69%. Instead, Barcelona, Budapest, Copenhagen, Ljubljana, Lisbon, Nice, Porto, Toulouse, and Warsaw are overloaded with demand, since they display a shortage in capacity ranging from 2% to 253%. These percentages indicate that for some areas, this shortage could be addressed by the satisfaction of demand through transfer paths, while for others, there is a clear need for the generation of new lines that would supply direct demands as well as create additional paths from transfer options. It is important to note that for Copenhagen, the shortage is infinite since no lines in the current state of the network exist, and thus, there are no possible connections to and from this area, indicating the certain creation of some lines to accommodate a part of its OD demand.

5.2 Generated Lines and Route Alternatives

The next process in the algorithm involves examining the nodes with excessive loads by first determining how to meet demand for destinations that lack direct services. This is achieved either by combining two lines of the existing network or by creating new ones. Depending on the OD demand pairs that cannot be currently met with the direct paths, all possible transfer paths for these pairs are generated in order to ensure complete connectivity for the entire network. These OD pairs are categorized into those served by direct paths, which use existing line services, and those needing a transfer between lines, thus using a transfer path. Finally, pairs that cannot be accommodated by either direct or transfer paths are filtered out, as these require the generation of new lines.

In the subsequent phase, the paths identified to serve the excluded pairs are analyzed and selected using Dijkstra's shortest path algorithm. These paths are incorporated into the network as new lines and are treated as direct paths, as they would have been recognized as potential transfer paths in the previous phase if applicable. Following this, all existing and newly constructed paths are compiled, forming the preliminary set of available route alternatives within the network.

However, since these routes are generated based on the overloaded nodes, it's essential to evaluate the preliminary set on how well it can satisfy the OD demand pairs for the rest of the nodes. This phase follows a similar approach, examining pairs that can be satisfied either through direct paths or through the newly generated shortest transfer paths. If there are still unsatisfied pairs, their reverse pairs are checked to see if they are already covered by the preliminary routes from the overloaded nodes, since if a pair is satisfied, its reverse pair is also considered satisfied. For such cases, the reverse path (whether direct or transfer) is constructed and added to the preliminary set of route alternatives.

If there are still unsatisfied pairs, the process of creating their shortest direct path is repeated, and a new line is constructed. This iterative process continues until a final set of route alternatives is established, ensuring comprehensive connectivity across the network.

5.2.1. Scenario 1

In the case of the first scenario where the existing network is denser, it is expected that adequate connectivity should be provided, at worst through a single transfer between the existing lines. This expectation is confirmed by the algorithm, which reveals that only one OD pair from the list of overloaded nodes cannot be accommodated by either a direct or a transfer path. More specifically, out of 30 pairs with overloaded nodes as the origin and all others as destinations, 17 are adequately served by direct paths, and 11 by a combination of lines. The “London - Milan” pair and its reverse are the only two identified as unserved, likely due to their geographical remoteness within the network, making existing services with up to a single transfer inadequate. The corresponding line that is created by Dijkstra's algorithm is a direct line (and its reverse) between these two nodes, without any intermediate stops, as shown in *Table 5.3*.

Table 5.3: Unserved pairs and new lines (Scenario 1)

Unserved Pair	New Line
London - Milan	[London - Milan]
Milan - London	[Milan - London]

The preliminary set of alternative routes now encompasses all 30 pairs associated with the overloaded vertices. The final assessment regarding the nodes without shortage in capacity, indicates that among the 12 pairs involving the remaining two nodes, the “Brussels - Milan” and “Paris - Milan” pairs cannot be served by the paths in the preliminary set. Consequently, their reverse pairs are examined, revealing that both are covered by different transfer paths. The reverse of all the identified paths are created as presented in *Table 5.4*, and stored in the new set of alternatives, to be utilized by these missing pairs.

Table 5.4: Missing pairs and new paths (Scenario 1)

Missing Pair	New path	Route
Brussels - Milan	Line4 & Line 7	Brussels - Frankfurt (*transfer*) - Milan
Paris - Milan	Line9 & RevLine10	Paris - Zurich (*transfer*) - Milan
	RevLine5 & Line7	Paris - Frankfurt (*transfer*) - Milan

Since there are no more unsatisfied pairs, the new set is the final set of path alternatives. It comprises a total of 77 paths, of which 22 are direct and the remaining are transfer paths.

5.2.2. Scenario 2

In the second scenario as explained in the previous subsection, the network's tolerance levels revealed insufficient connections in multiple areas. Notably, the combinations of existing lines were found to be inadequate, as 38 OD pairs associated with overloaded nodes remained unserved after generating all possible paths. Specifically, out of 312 pairs generated by these nodes, 98 are effectively served by direct paths and 176 by a combination of lines with a single transfer. It is important to note that for the overloaded areas of London and Paris, their corresponding paths towards all other destinations that could not be served by direct services, could be met by single transfer paths, and consequently, no new lines involving these areas were generated.

In contrast, for the area of Copenhagen, three new lines are generated connecting the city with five other locations, as expected. For the rest of the overloaded areas, the unserved pairs predominantly concern Lisbon, Ljubljana, Nice, Toulouse, and Warsaw with two pairs (and their reverse), while for the rest, single pairs are identified. The algorithm-generated lines corresponding to these findings are detailed in *Table 5.5*., where the unserved pairs (only for one direction) and their corresponding new lines are indicated, while unserved pairs that their reverse type is served by a transfer path from existing services, and thus, do not require a new line are not presented.

For the final assessment, the nodes without capacity shortage were examined, where out of the 288 pairs, 232 of them could be served by either direct of transfer paths, with the use of the existing services and the newly generated lines, while for the rest, their reverse counterparts where identified in the set of total possible paths. For them, the reverse paths were created and added to the set in order to be utilized to serve the 56 missing pairs, establishing the final set of possible paths that way.

Table 5.5: Unserved pairs and new lines (Scenario 2)

Unserved Pair	New Line
Amsterdam - Copenhagen	[Amsterdam - Copenhagen]
Barcelona - Milan	[Barcelona - Milan]
Budapest - Ljubljana	[Budapest - Ljubljana]
Copenhagen - Berlin	[Copenhagen - Berlin - Warsaw]
Copenhagen - Warsaw	
Copenhagen - Frankfurt am Main	[Copenhagen - Frankfurt am Main - Luxembourg City]
Copenhagen - Luxembourg City	
Lisbon - Barcelona	[Lisbon - Madrid - Barcelona]
Lisbon - Seville	[Lisbon - Seville]

Ljubljana - Munich	[Ljubljana - Munich]
Ljubljana - Venice	[Ljubljana - Venice]
Nice - Milan	[Nice - Milan]
Nice - Toulouse	[Nice - Toulouse]
Porto - Madrid	[Porto - Madrid]
Toulouse - Madrid	[Toulouse - Madrid]
Toulouse - Milan	[Toulouse - Milan]
Warsaw - Berlin	[Warsaw - Berlin - Copenhagen]
Warsaw - Frankfurt am Main	[Warsaw - Prague - Frankfurt am Main]
Zurich - Luxembourg City	[Zurich - Luxembourg City]

After the final evaluation of nodes without capacity shortages and their corresponding unserved pairs in the preliminary set of path alternatives and subsequent inclusion with reverse paths ore new lines, the final set was established, comprising 710 total paths. Among these, 174 are direct routes, while the rest involve transfers.

5.3 Modified Network Configuration

With the completion of the LGA, the set of route alternatives is inserted into the FSA along with the set of total available lines, as well as several parameters defined at the start of the model, such as the demand per OD pair and per node, the vehicle characteristics and the objective-related parameters.

The initial phase of the algorithm focuses on allocating demand among each node across all possible routes in the set, prioritizing paths with the shortest travel time. In the case where multiple paths share the same travel duration, the demand is evenly distributed among them. This process effectively determines the active lines and paths required to supply the network. Since these activated paths encompass both direct and transfer paths, distributed demand on transfer paths is counted twice, reflecting its distribution across the two lines that collectively form the transfer path. Therefore, the next phase of the algorithm, processes the path-level demands and converts them into line-level demands. This step is crucial for calculating the total demand on each active line, considering every serving edge. This includes edges not only directly served by a single line but also those that are part of a transfer path involving multiple lines.

Subsequently, the algorithm computes the passenger flow for each line based on the corresponding total line demands. This involves determining the number of passengers entering and exiting at each node along the line. The aim is to identify the node, and consequently, the OD pair within the line that experiences the highest passenger flow. In these calculations and due to the format of the line demand data, the algorithm accounts for passenger flows that are not directly served by a single line but are facilitated through transfers, as previously mentioned. This approach ensures that the frequencies set for each line are adequate to handle the segments with the heaviest traffic. These are computed in the subsequent process phase, based on the seat capacity and load factor of the vehicle as explained in the methodology chapter.

Finally, the frequency-dependent properties of the modified network regarding its capacity are computed by the algorithm before advancing to the final process phase. It is important to note that the line configurations discussed below are based on a specific optimal solution chosen from the list of solutions as identified in *section 5.4*. This approach is adopted to maintain coherence and continuity in the report's analysis.

5.3.1. Scenario 1

In the scenario of the smaller network, the algorithm activates 42 out of the total 77 paths for demand distribution. This set of activated paths encompasses all existing lines and all newly designed ones, amounting to a total of 22 lines, which are consequently all activated. This activation reflects the network's current adequate connectivity, indicating that the existing operational services are efficient enough to maintain a high service level, accommodating both the influx of new demand and the existing passenger flow.

Furthermore, the addition of only a single line and its reverse to the network underscores this observation. It also indicates that the modified network does not introduce many new routes in total. Among the activated paths, 14 are transfer paths, where the allocated demand is distributed across the combined lines that constitute each path.

Overall, the modified network consists of a variety of lines, each characterized by typical design properties such as the number of lines, their lengths, and the number of stops. Following the processes of passenger flow analysis and frequency calculation, varying frequencies are established for all activated lines. This is done while maintaining frequency symmetry to simplify the network's structure. The design properties of the network are illustrated in *Figure 5.1*.

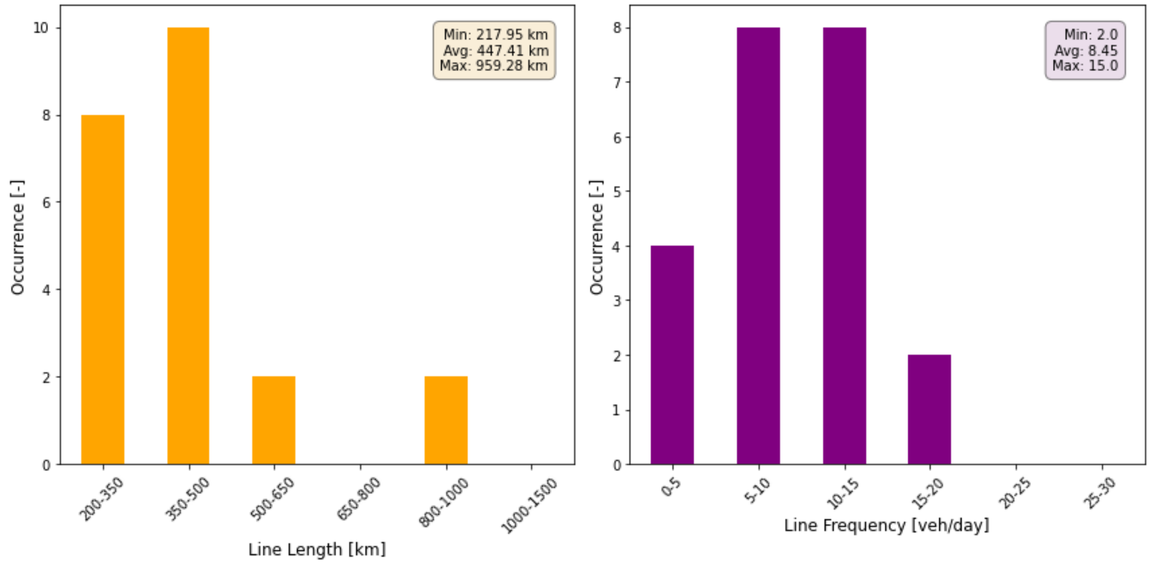

Figure 5.1: Network design properties' distributions and statistics: Line lengths (left), and Line frequencies (right) (Scenario 1 - Pareto optimal solution "P7")

From the analysis of the network's layout and line characteristics, it is evident that most lines cover short distances, reflecting the close proximity of the nodes. For these, two distinct types of recurring lines can be defined.

The first type includes a single line and its reverse counterpart, each stretching close to 1000km in total length. These lines play a strategic role by connecting to the core lines of the network and integrating new cities. This expansion is driven by the aggregate demand from these newly connected urban areas, leading to the creation of new, directly connected lines.

The second type comprises shorter lines (less than 500km), known as the core lines, which are a fundamental aspect of the network. Despite their relatively short length (ranging between 200 and 500km) and having just 2 or 3 stops, they offer frequent, bi-hourly services (around 9 vehicles per day). These lines cater to routes with high and stable demand at the areas they connect, thereby enabling large traffic flows along their paths.

The capacity-related properties of the network refer to the adjusted capacities of the vertices, which result from alterations and additions in line frequencies, as well as the inherent capacities of the lines themselves. The network's capacity properties are presented in *Figure 5.2*.

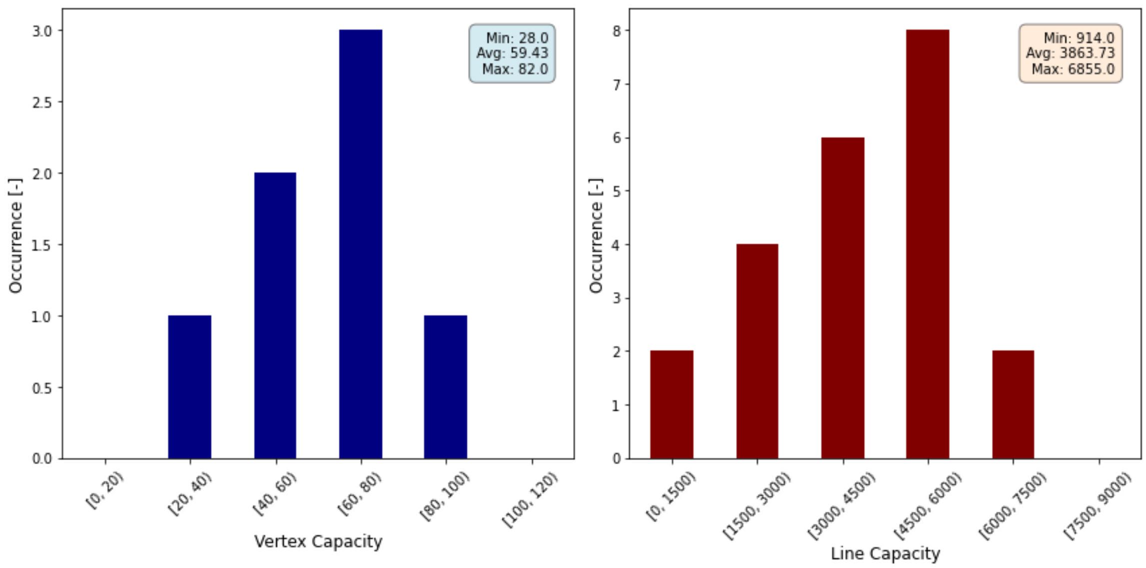

Figure 5.2: Network capacity properties' distributions and statistics: Vertex capacity (left), and Line capacity (right) (Scenario 1 - Pareto optimal solution "P7")

The network exhibits a well-balanced distribution of capacities across its nodes, with a high average of handling 60 high-speed trains during an operational day. Only a single node diverges from the rest, with a low capacity of 28 vehicles per day, indicating that the node might be situated at a more remote location within the network, primarily operating trains to a limited number of destinations where passengers then transfer to reach other parts of the network. Conversely, the node with the highest capacity supporting up to 82 vehicles per day, indicates that it acts as a central point in the network facilitating multiple transfers, thereby underscoring its extensive connectivity to various destination areas.

Analyzing the capacities of individual lines reveals that most are able to handle a daily passenger traffic ranging between 3000 and 6000. In contrast, there is a single line with a considerably lower passenger handling capacity (below 1000). This line, with its limited frequency of daily services, appears to primarily manage passenger movements between a single pair of destinations, without serving as an option for transfer passengers.

A map visualizing the configuration of the modified network with the corresponding vehicle movements per direction, on the edges between vertices served by direct services, is given in *Figure 5.3*. It can be observed that the only additional line between London and Milan enables the satisfaction of this pair's demand and although it can provide additional transfer options, due to length restrictions such paths are not deemed efficient.

The network's frequency adjustment reveals a relatively even distribution of vehicle operations. The Amsterdam-Brussels route is the busiest, with the highest number of vehicles above 20, while the London-Milan route has the least, reflecting different usage patterns. The Amsterdam-Brussels edge is busier because it includes two direct lines catering to passengers from Amsterdam traveling to various destinations. In contrast, the London-Milan edge is only used by passengers traveling specifically between these two cities. Furthermore, Paris and Frankfurt emerge as key central nodes in the network, facilitating passenger transfers to more distant locations like London and Milan. Some lines in these nodes operate up to 14 vehicles daily, underscoring their importance in the networks overall connectivity and efficiency.

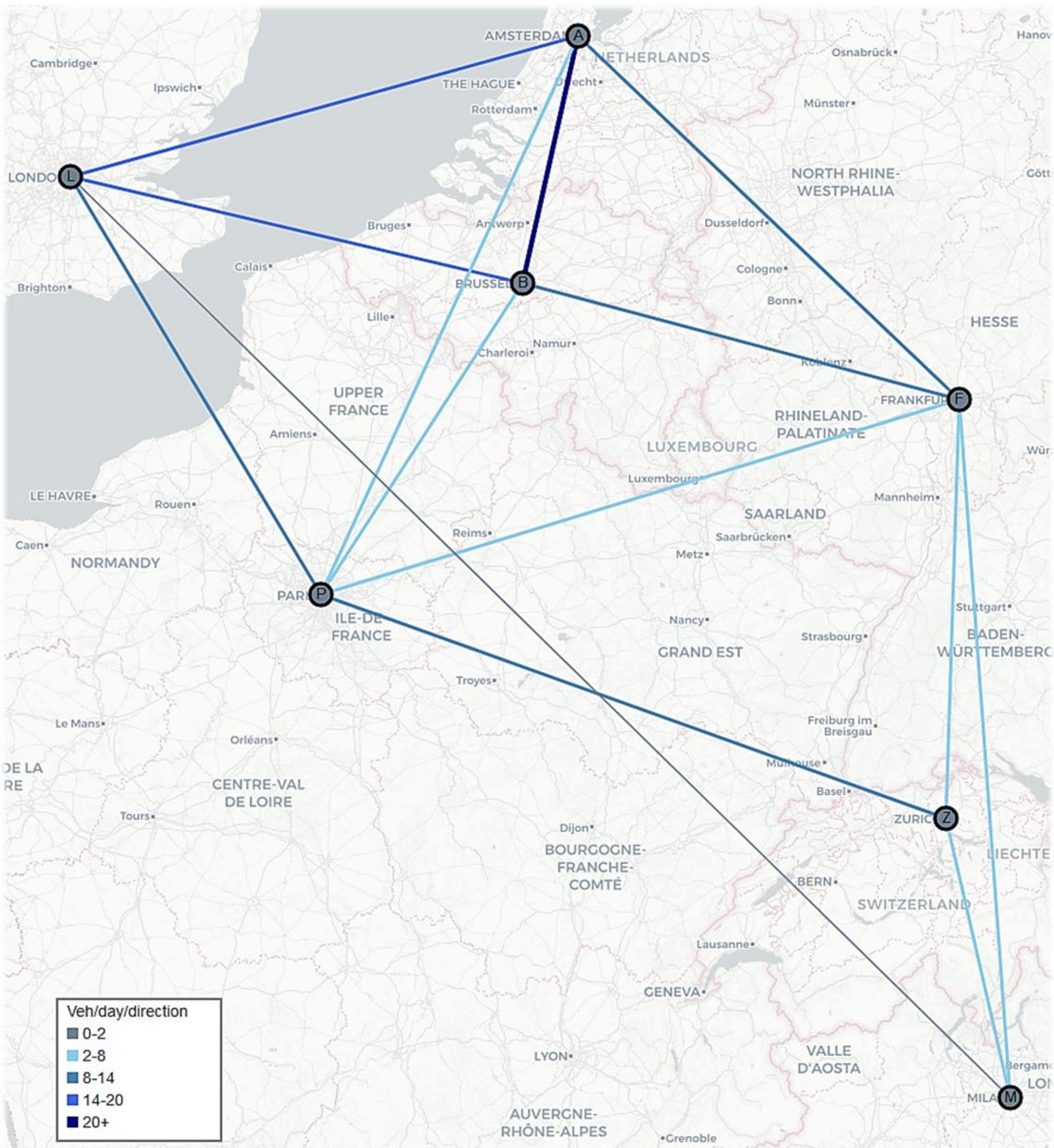

Figure 5.3: Modified network map (Scenario 1 - Pareto optimal solution “P7”)

5.3.2. Scenario 2

In the scenario of the extended network, the algorithm activates 86 out of the total 355 paths for demand distribution. This set of activated paths consists of mostly direct paths, encompassing all existing lines and all newly designed ones, which reflects the network's current adequate connectivity, as well as the necessity for the operation of the newly designed lines, in order to accommodate both the influx of new demand and the existing passenger flow.

In contrast to the first scenario, the second one resulted in the generation of significantly more lines, primarily due to the network's initial deficiency in operational services. The modified network in this scenario is characterized by a variety of lines, predominantly featuring low frequencies and moderate lengths. This is depicted through the network's design properties, distributions, and statistics, as illustrated in *Figure 5.4*.

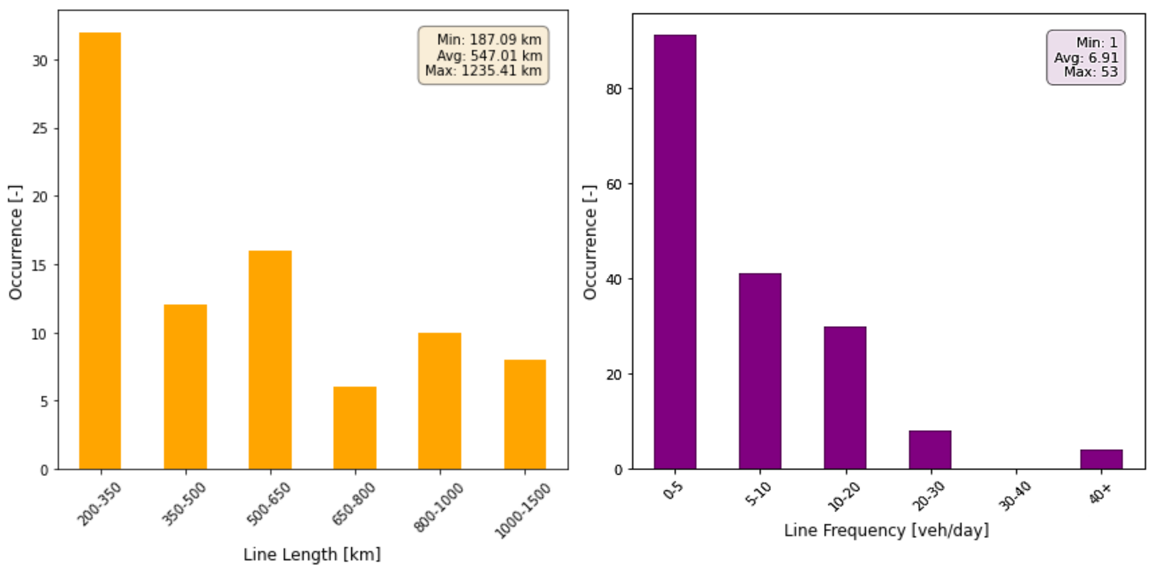

Figure 5.4: Network design properties' distributions and statistics: Line lengths (left), and Line frequencies (right) (Scenario 2 - Pareto optimal solution "P4")

In the analysis of the network's layout and line characteristics for the second scenario, most lines, similar to the first scenario, cover short distances, indicating the proximity of the nodes. The lines can be categorized into distinct types based on their characteristics. For these, the same distinct two line types of can be used to categorize the lines based on their characteristics.

The first type consists of 9 lines and their reverse counterparts, each extending over 800km. These lines are strategically important, connecting core lines of the network and integrating new cities. This expansion is driven by the combined demand from these newly connected urban areas, leading to the creation of new direct lines for distant destinations. The second type includes shorter lines, less than 500km in length. These core network lines operate with significantly low frequency per day hour, catering to routes with direct demand, and acting as starting or terminating points for transfer routes.

A third type can be defined, unique to this scenario, consisting of lines with medium lengths and average frequencies. These lines primarily offer direct services, with fewer long and medium-distance routes, mostly acting as transfer lines to reach the furthest points on the map and connect to short, single-stop lines. This is reflected in the comparative statistics of the two scenarios, where the average length of the network's lines in the second scenario has increased, but the average frequencies have decreased.

The capacity-related properties of the network show distinct differences between the simulated scenarios. The distributions and statistics of frequency-dependent node and line capacities are presented in *Figure 5.5*.

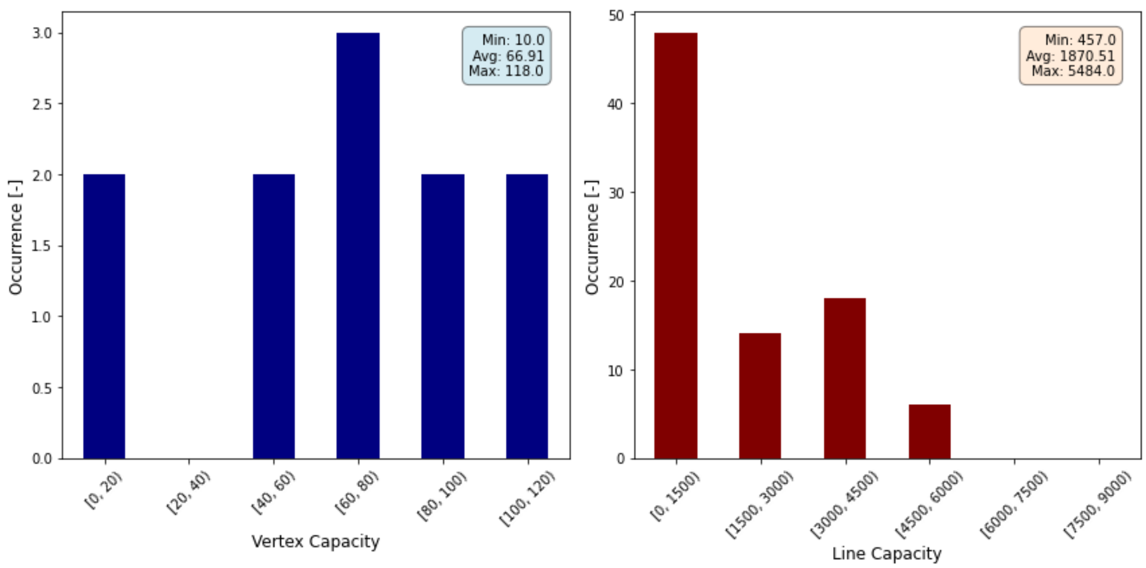

Figure 5.5: Network capacity properties distributions' and statistics: Vertex capacity (left), and Line capacity (right) (Scenario 2 - Pareto optimal solution "P4")

The network demonstrates a well-distributed capacity across its nodes, with a high average capacity to handle approximately 67 high-speed trains per operational day, marking a notable increase from the first scenario. An important observation is that two nodes manage considerably fewer trains, handling below 20 vehicles each. This suggests that the demand for these nodes is not fully met, highlighting the network's limitations in providing complete connectivity for all origin-destination passenger movements. In contrast, two nodes, Frankfurt am Main and Paris, emerge as central transfer hubs, with capacities of 100 and 118 respectively. These capacities translate to about 5 to 6 vehicles per hour, positioning them as pivotal nodes in the modified network. The increase in the maximum available node capacity, compared to the previous scenario, aligns with the overall rise in demand influx. A closer look at the capacities of individual lines shows that most can accommodate daily passenger traffic below 3000. This is a departure from the first scenario, where 3000 passengers represented the lower bound for average line capacity. However, this observed trend correlates with the line frequencies, which are notably lower, reflecting their specific usage purposes.

A map visualizing the configuration of the modified network with the corresponding vehicle movements per direction, on the edges between vertices served by direct services, is given in *Figure 5.6*.

The enhancement of the network through the addition of new lines, particularly in overloaded areas, has significantly improved connectivity across the entire network. This is especially evident in the southwest region of the continent, where locations are now better interconnected and also more effectively linked to the central hub of the network. Similarly in the north, cities like Copenhagen are now directly connected to multiple central locations, enhancing the overall network integration.

Overall, the central part of the network has become more robust, facilitating smoother and more diverse transfer options. This improvement is not limited to single-transfer scenarios, as examined in this study, but also extends to journeys requiring two transfers, especially beneficial for passengers traveling to more distant destinations.

In terms of network services, adjustments in frequency have led to a more balanced distribution. The central European connections, particularly in Germany and Italy, are the most active in terms of vehicle operations. Key German cities—Berlin, Frankfurt am Main, and Munich—see high traffic with at least 20 trains operating daily. A similar pattern is observed in Italy, with Milan, Venice, and Rome being major nodes due to both the volume of direct travel and their roles as transfer points for eastern and western European destinations. The Brussels-Paris connection also stands out, primarily serving as a conduit for nearby areas like Amsterdam and London, and facilitating southward travel.

Most other connections across the network maintain a moderate service frequency, with an average of 2 to 8 trains per day in each direction. However, several central-eastern connections offer sparse services, with a maximum of two trains per day, designating that cities in East Europe with smaller demands also require less services. This indicates a tailored approach to service provision, aligning with the varying demand levels across different regions of the network.

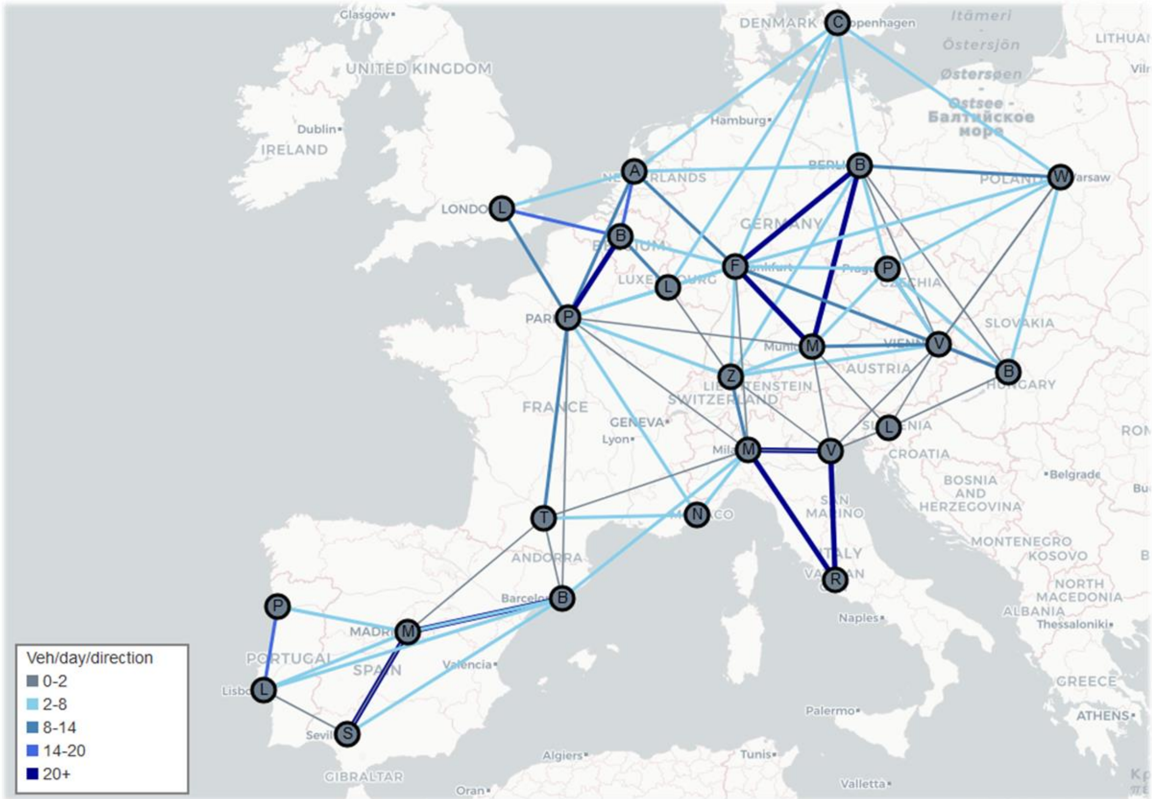

Figure 5.6: Modified network map (Scenario 2 - Pareto optimal solution “P4”)

5.4 Network Performance

Provided that the model's primary goal is to achieve a balanced solution that optimally maximizes and minimizes respectively the defined objectives, multiple set of values are computed for these objectives, employing various percentages of demand distribution. This approach allows for the exploration of different levels of demand satisfaction. The optimal solutions among these sets are then identified using Pareto front analysis. The percentages that are selected in this research start with a complete distribution of the expected demand starting at 100%, with all values for distributions up until 50% with a change of 1% with each iteration.

Once the network's design and capacity properties are successfully computed, the algorithm proceeds to calculate the individual components of the capacity utilization objective, as well as those related to the operator costs, before calculating the objective values in the final process. It is important to note that the capacity utilization for vertices and lines is expressed as percentages. Therefore, the total network utilization is also converted into a percentage format by dividing the values for vertices and lines by two.

Consequently, the algorithm computes all possible sets of objective solutions for each demand percentage. From these, it identifies a collection of optimal solutions for the entire network through Pareto front analysis. These findings are instrumental in making informed decisions about which percentages of demand distribution are optimal. This is based on the understanding that a complete shift of passengers from air to rail, from zero to one hundred percent, is not practically feasible. Finally, the employed performance indicators aim to identify the distinct performance characteristics of the modified network, in order to provide insights regarding its varying levels of efficiency and effectiveness.

5.4.1. Scenario 1

In the case of the first scenario, the objective values computed for varying demand percentages are depicted in *Figure 5.7*. The results show a predictable trend: operator costs decrease progressively as demand distribution is reduced. This trend is due to the nature of the operator cost minimization objective, which is influenced by the number of active lines, along with their length and frequency. Consequently, as demand decreases in each iteration, the required frequencies to meet this demand also decrease, correlating with the reduced number of passengers.

Conversely, the utilization percentage of the network’s capacity exhibits a notable variation as demand drops. Similarly to the costs which decrease when less demand is inserted to the network, capacity utilization increases with each successive reduction in passenger numbers. This increase is anticipated, given that line capacities are determined by multiplying the frequencies of active lines by the vehicles' full seat availability, which primarily results in capacity surplus. Since frequencies can only be integer values, at higher demand levels, some lines add an extra daily service to meet the needs of a small passenger group. This additional service typically operates below 50% capacity, catering to only a few passengers. Therefore, with each reduction in passenger numbers, certain lines stop requiring this additional service, leading to higher utilization due to reduced surplus capacity.

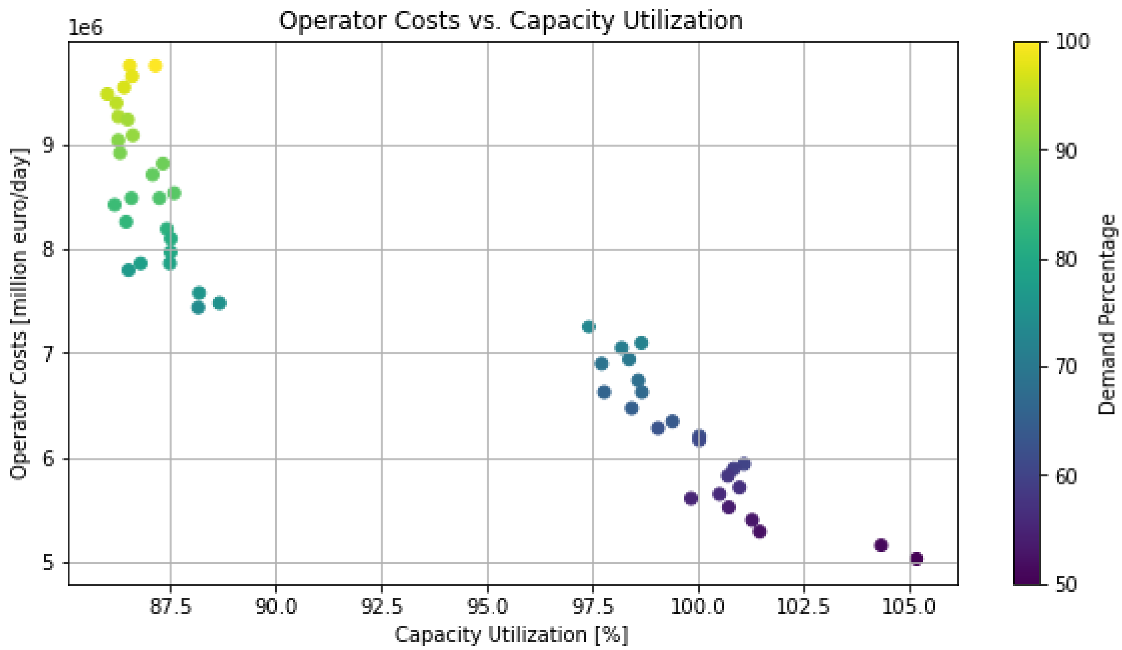

Figure 5.7: Objective solutions per demand distribution (Scenario 1)

Eventually, all excess capacity is eliminated, and lines reach 100% occupancy, signifying full capacity utilization. This point of transition is evident in the above figure, where fewer daily services lead to more efficient capacity usage. Beyond this point, utilization percentages exceeding 100% may suggest points of overloading in the network. Although, given the method of calculating line capacities, values above 100% cannot be achieved. However, the visualized values correspond to the complete network capacity, where vertex capacities is included.

From the computed values, 16 Pareto optimal solutions are identified within the 100-50% demand distribution range. These solutions are determined by assessing whether the capacity maximization value dominates the cost minimization value, aligning with the objective to design the network as efficiently as possible from a supply perspective, while balancing it through the operator costs. The Pareto front is illustrated in *Figure 5.8*, and detailed information about these optimal solutions is provided in *Appendix B*.

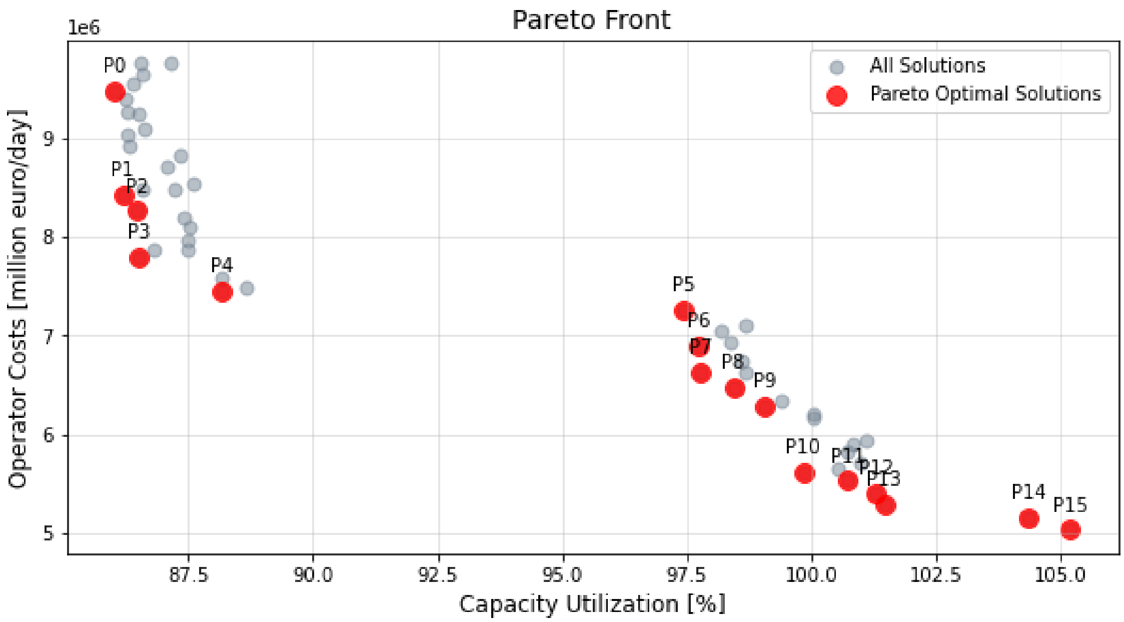

Figure 5.8: Pareto optimal solutions for capacity utilization maximization vs cost minimization (Scenario 1)

Analyzing the list of optimal solutions, it becomes evident that a balanced solution for creating a fully operational network without overloading nodes lies around the 97.5 mark in the spectrum of solutions. The design and capacity attributes of the network for the optimal solution "P7" were examined in the previous subsection. This solution, characterized by the values [97.784594, 6.625390e+06], demonstrates a capacity utilization nearing the ideal 100%. Adjacent solutions either show slightly higher utilization at increased costs or marginally lower utilization with a minor cost reduction, which may not justify the change.

Solutions to the left of the graph offer up to 10% higher utilization, yet, for a significant increase in costs. In contrast, solutions to the right present the lowest cost solutions, yet with a negative trade-off towards capacity utilization. Consequently, the network configuration for solution "P7" emerges as a prime candidate for implementation, striking an optimal balance between the dual objectives of maximizing network capacity and maintaining operational efficiency, nonetheless, dependent on the varying stakeholder perspectives.

5.4.2. Scenario 2

For the second scenario, the objective values computed for the varying demand percentages are illustrated in *Figure 5.9*. The results consistently show a decrease in operator costs with each successive reduction in demand distribution maintaining this predictable trend. Additionally, a smoother transition in capacity utilization is observed in this scenario, attributed to the more evenly distributed objective values in the graph, compared to first scenario's' clustered solutions.

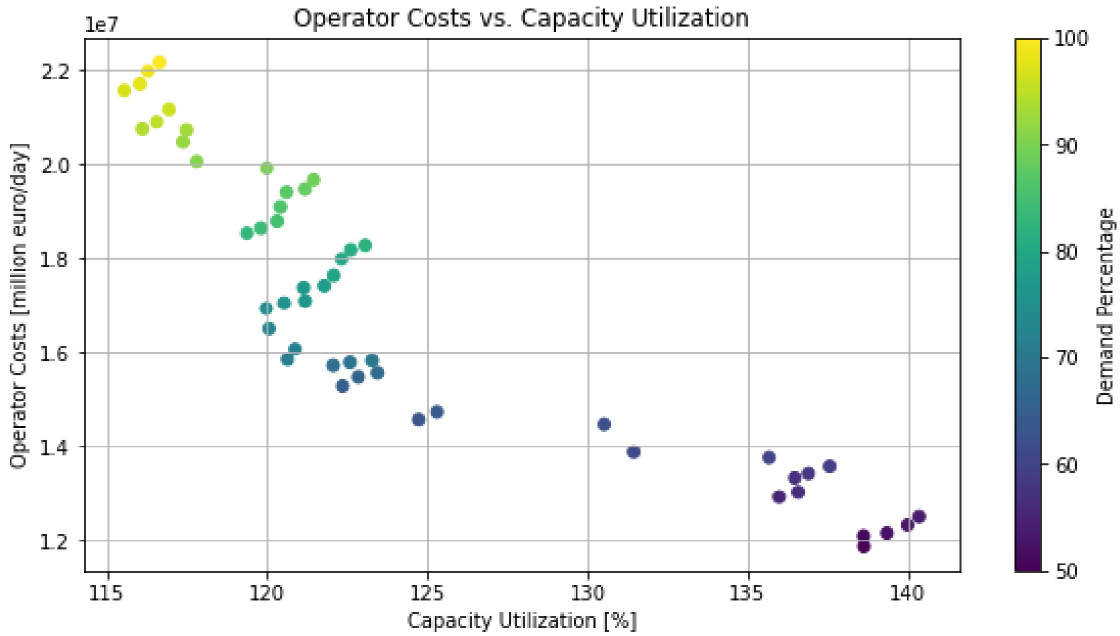

Figure 5.9: Objective solutions per demand distribution (Scenario 2)

A key observation in the objective solutions is that capacity utilization ranges approximately from 115 to 140, marking a notable increase from the first scenario. As capacity utilization for individual lines cannot exceed 100%, this significant change in the network's overall capacity is linked to the nodes' capacities. This indicates that while some nodes in the network are operating at full capacity, effectively maximizing utilization, there are others that lack the necessary supply to manage the demand of both arriving and departing passengers.

In this scenario, a total of 17 Pareto optimal solutions are identified within the 100-50% demand distribution range, spread out in a wider spectrum of values. Most of these optimal solutions are found at higher demand percentages, suggesting that the more extensive network, which faces higher demand levels than the simpler network, struggles with numerous unserved pairs. This leads to a requirement for more frequent and, consequently, more costly services to make the best use of the network's limited capacity. It is important to note that the costs associated with operating and maintaining these lines are higher due to the operation of a significantly larger number of lines as expected. The Pareto front is depicted in *Figure 5.10*, and detailed information about these optimal solutions is available in *Appendix C*.

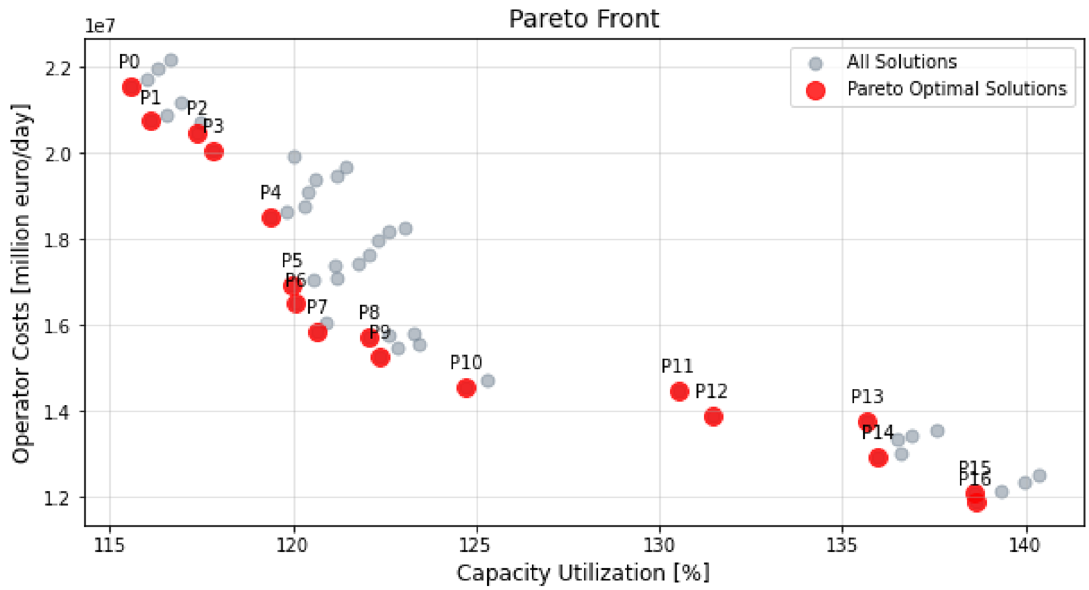

Figure 5.10: Pareto optimal solutions for capacity utilization maximization vs cost minimization (Scenario 2)

5.5 Summary of Key Findings

The simulation of the two scenarios led to the development of two distinct networks. These networks were evaluated based on their design characteristics and performance measurements.

Although both scenarios resulted in functional, high-level networks with similar overall structures, they exhibited notable differences in specific design details. As anticipated, the simpler scenario 1 displayed a relatively less developed network compared to the more advanced scenario 2. This difference is particularly evident in the significant increase in the number of lines, connected vertices, and reachable OD pairs in the more advanced scenario, which demonstrates the model's effectiveness in utilizing the network’s existing infrastructure to create a larger and more efficient network.

Despite the varying degrees of extensiveness, both scenarios maintains a similar layout, allowing for comparative analysis, with their network visualizations offering valuable insights into the network's shape, dimensions, and focal points. One of the key observations is the prevalence of lines that traverse few countries, highlighting the low interoperability and cross-border cooperation in the network's design for direct lines. However, that is expected due to the low number of vertices and as such, existing operational service with also a low number of stops. Nevertheless, both simulated scenarios successfully designed lines across the entire simulated area, ensuring that every part of the continent received some level of service. In the analysis of the network's design, three main behavioural aspects emerged from this analysis:

1. **Network Density:** There is a noticeable increase in network density towards the geographical center of the map, with Germany being a prime example. This centralization suggests a strategic focus on areas with potentially higher demand or connectivity needs.
2. **Unequal Distribution:** The network's extensiveness and density are somewhat skewed towards the west. This trend can be attributed to the lower demand in Eastern Europe compared to the western part of the continent. This geographical imbalance in demand has a direct impact on the network's layout, leading to a denser and more extensive network in the west.
3. **Selective Line Generation:** It was observed that cities with low proximity and lacking existing services often resulted in the generation of new lines, predominantly direct services, to cater to demand directly. With this approach, overloading risk is avoided for central nodes in the network, maintaining the efficiency and reliability of the network's core areas. However, the creation of these new, often lengthy lines leads to higher operational and maintenance costs, reflecting a trade-off between expanding service coverage and managing operational expenses.

These observations provide insights into the network's strategic design, highlighting a focus on areas with higher demand and the importance of city positioning in determining network coverage. The model's emphasis on key cities suggests a prioritization of efficiency and demand satisfaction, which may lead to certain areas being less serviced due to their lower demand or strategic positioning.

Furthermore, the developed networks exhibited differences and similarities in terms of performance based on the different performance indicators assessed. Concerning network coverage, the first scenario achieved complete coverage, serving all origin-destination pairs. This outcome underscores the effectiveness of targeted modifications in small-scale, high-demand networks in ensuring efficient supply throughout. Conversely, the second scenario, characterized by a large-scale network with uneven demand, was insufficient in terms of network coverage, since due to its expansive nature several OD pairs remained unserved, leading to unsatisfied demand.

In terms of network capacity utilization, the first scenario, with its simpler and more interconnected network design, showed superior performance. However, this advantage is somewhat double-edged. The network's capacity is tailored to current demand expectations, offering limited scope for accommodating future increases in passenger numbers.

In contrast, the second scenario's extended and more dispersed network faced excess demand on certain lines. However, this scenario has the potential to absorb additional demand beyond initial projections. This is possible because vehicles are more evenly distributed across the network, with some operating below full capacity. This suggests that networks with modifications focused on network configuration are more adaptable in meeting extra demand in specific areas, despite their limitations in serving all network locations.

Finally, from a sustainability perspective, the first scenario appears less efficient regarding financial implications, since the need for more operating vehicles leads to higher operational costs. Meanwhile, the second scenario mostly involves modifications related to physical infrastructure, entailing construction costs. However, these costs are not considered in of this study, as they vary based on multiple factors and are not directly affiliated with the network operators. Thus, in terms of operational cost-efficiency, the second scenario holds an advantage.

These findings highlight the complex dynamics among network design, capacity utilization, and economic sustainability within HSR networks, underlining the distinct strengths and weaknesses inherent in terms of network performance, since no alternative stands out. Therefore, findings regarding the performance of the networks can provide stakeholders with valuable guidance in making informed decisions about adopting particular network designs, along with the different demand distributions. This understanding is essential for optimizing the balance between operational efficiency, coverage, and cost-effectiveness in HSR networks.

6

Conclusions

This chapter concludes the research conducted in this thesis. The methodology developed within this study allowed to fill the gap identified at the start of the research, by answering the formulated sub-questions, and hence, the main research question, all of which are answered in *section 6.1*. Following, *section 6.2* provides insights on the practical and policy-related implications that can be extracted from the study's findings. Concluding, the limitations and challenges met in this study are addressed in *section 6.3,* along with recommendations for future research building upon the results of this work.

6.1 Research Questions

In the introductory chapter, four sub-questions were formulated that aided in addressing the main research question. The methodological process adopted in this study provided answers to each of these questions through various segments of the research. Below, a detailed explanation for each sub-question is provided, followed by a comprehensive response to the main research question.

- *What factors can influence the development of substitution scenarios that can effectively facilitate the air-to-rail transition?*

The first question is partially answered through the formulated demand scenarios in *section 4.4*, and is further supplemented by the results of the two simulated scenarios in this study, in which different demand distribution percentages were employed.

The literature findings that were utilized for the scenario development, revealed a multifaceted landscape, highlighting that the decision to replace short-haul air travel with alternative modes, particularly rail, is influenced by a diverse array of factors that range from practical considerations to policy-driven initiatives and socio-environmental concerns. The interaction of several factors was deemed critical, hence, their consideration during the formulation of the demand scenarios. The key factors identified are travel time and distance, environmental concerns and policies, service quality, availability of rail infrastructure, and economic considerations. These collectively determine the feasibility and appeal of rail as an alternative to short-haul air travel.

Regarding the development of a single pan-European scenario, practical constraints such as geographical limitations, travel desires, and existing infrastructure capacities make a complete air-to-rail transition of such magnitude unfeasible. Consequently, the scenarios were formulated to realistically assess the potential for a partial but significant shift from air to rail with the consideration of these factors.

The first scenario presents a network that, while basic, is densely populated with high-demand locations supported by substantial existing infrastructure. This scenario primarily focuses on the dynamics of travel characteristics, alongside the availability and quality of current physical infrastructure and operational services. In contrast, the second scenario envisages a more expansive network. It includes a variety of locations, some remote or with underdeveloped infrastructure, and places a greater emphasis on environmental and financial considerations across a broader area. With this approach, a comprehensive consideration of the various factors that are critical in developing substitution scenarios for implementation is ensured.

Furthermore, the scenarios encompass a spectrum of demand distributions, from an optimistic 100% transition to a more realistic 50%. From the outcomes, it can be observed that substitution is feasible at various levels, each corresponding to a different percentage in transition. This is due to the computation of diverse design alternatives and their modifications. However, it's crucial to note that not all proposed alternatives are viable, as some lack practical applicability. The identification of feasible options is facilitated through the Pareto optimal solutions, which aids in identifying the balanced and realistic designs. Consequently, the modified designs for each scenario, defined by their unique thresholds and influencing factors, embody the practical levels of substitution that can facilitate the transition from air-to-rail in a realistic and effective way.

- *What rail infrastructure elements of the strategic planning phase are critical for the redesign of a continental HSR network?*

In addressing the critical elements for the strategic planning phase of a continental HSR network redesign, this study, based on insights gained through the background research in *section 2.2*, which delves into the strategic aspects of railway transport planning, and by empirical data derived from the simulated scenarios, identifies two pivotal aspects. Specifically, these concern the physical infrastructure, encompassing rail tracks and stations, and the high-level operational elements including type and number of operational services).

These elements offer a comprehensive view of the network's configuration and operational framework and are essential for guiding infrastructure redesign. In the model, they are represented through the stations and lines of each scenario's network, along with their configuration properties, and they are both considered in the objective of maximizing network capacity utilization. However, it is observed that the capacity of lines plays a more critical role in network modifications. This is primarily due to the dependencies of the line and vertex capacities on the computed line frequencies, and the way in which frequency properties are defined, such as symmetry across corresponding lines.

A key observation is that line capacity utilization is significantly impacted by overestimated frequencies for certain lines. To maintain symmetry, additional, often underutilized trains are included, leading to excess capacity. Moreover, line-specific demand, varying based on demand distribution scenarios and line selection, also influences capacity. In contrast, station capacity utilization is solely influenced by modified capacities, based on the number of services and independent of other configuration properties. The model's outcomes illustrate these dynamics, as in the first scenario, a significant gap in capacity utilization is noted due to a sudden frequency drop, leading to the reduction of vehicles with excess capacity serving few passengers. Conversely, in the second scenario no such drop is noted, however, an overall worse capacity utilization due to demands not being fully satisfied can be observed.

Moreover, the strategic layout of the network which is primarily configured by the lines, has a direct impact on operation costs. This is evident in the first simulated scenario, which focused on frequency adjustments rather than the development of new lines, leading to higher costs. Conversely, the second scenario, which entailed the design of additional lines with more evenly distributed and less frequent services, resulted in lower operational costs. Furthermore, the strategic layout of the network, primarily determined by the lines, directly impacts operational costs. The first scenario, focusing on frequency adjustments, incurred higher costs. In contrast, the second scenario, involving the development of new lines with more evenly distributed and less frequent services, resulted in lower operational costs.

Overall, these findings indicate that given the nature of the capacity utilization calculation for the entire network, lines are more sensitive to changes in line frequencies, and thus, result in more significant modifications. This sensitivity underscores the importance of carefully considering line frequency adjustments in strategic planning. On the other hand, station capacity assumes a less critical role unless there are significant changes to the physical infrastructure, such as constructing new tracks or platforms to facilitate new lines. While this aspect is not the focus of the current study, it is important to acknowledge that for a viable redesign of a HSR network, these considerations are crucial. They are not only vital for the effective implementation of modifications during the strategic planning phase but also play a significant role in investment decisions related to network expansion. A balanced approach that considers both physical and operational infrastructure enhancements is crucial for the holistic development of the HSR network.

- *What are the key modifications to the design of HSR network infrastructure that overcome capacity limitations?*

The third question, is answered through the outcomes of two simulated scenarios, each leading to distinct network designs with unique modifications to overcome capacity limitations in HSR network infrastructure.

In the first scenario, the network's design closely mirrored the existing structure, with the primary modification being the addition of a single new operational line. This approach maintained the original network's layout while slightly expanding its capacity. In contrast, the second scenario introduced multiple new lines, leading to a significant redesign of the network. This involved replacing several existing routes with new ones, thereby altering the network's infrastructure to a greater extent. Regarding capacity and demand management, the first scenario's network can overcome capacity limitations, facilitating a complete shift from air to rail travel. The second scenario, while more extensive, faced challenges in meeting demand due to its less dense network, indicating a need for a more balanced approach between network coverage and density.

Moreover, the introduction of additional services and route options, both direct and through single transfers, emerged as a primary modification strategy in both scenarios. Adjustments in service volume were also crucial, as existing structures were often adequate but lacked service capacity. Consequently, networks became either denser or more extensive, optimizing capabilities or achieving a blend of efficiency and coverage.

Strategic design insights from the simulated networks revealed several key aspects. There was a noticeable increase in network density towards geographical centres, like Germany, indicating a strategic focus on high-demand areas. The network's extensiveness and density deteriorated towards the west, reflecting demand variations across Europe. Additionally, new lines, predominantly direct services, were created to cater to underserved cities, balancing the network's efficiency and operational costs.

Furthermore, operational implications of these findings suggest that more developed networks required fewer major design changes, focusing instead on operational adjustments like adding trains in low-service areas. In contrast, less developed networks needed significant modifications or even complete redesigns to meet the demand, especially for transitioning air passengers to rail.

In conclusion, the key modifications to HSR network infrastructure involve a strategic balance between expanding service coverage and managing operational expenses, with a focus on areas of higher demand and strategic city positioning. The modifications are informed by the type of demand and the existing network structure, ensuring alignment with the network's capacity and operational goals.

- *What is the performance of the redesigned networks in terms of transport efficiency and economic sustainability?*

The final question regarding the performance of the network can be answered through the insights gained when assessing the performance indicators in relation to the model results, along with the defined objectives for the development of a supply-based network design. Based on the model outputs, varying measurements applicable to a HSR environment and specifically regarding its infrastructure can be identified.

A critical aspect of this assessment is the operational and maintenance costs, which are fundamental to the economic sustainability of the HSR network. In the first scenario, the network's simpler and more interconnected design, while operationally efficient, leads to higher operational costs due to the necessity for more operating trains. In contrast, the second scenario, despite its expansive nature and reduced coverage, demonstrates an advantage in operational cost-efficiency. This is attributed to its focus on physical infrastructure modifications, which do not directly burden operational costs.

The network coverage and capacity utilization also play a significant role in assessing network modifications. The first scenario displays a complete network coverage, serving all origin-destination pairs, and highlights the effectiveness of targeted modifications in small-scale, high-demand networks. However, this scenario's capacity is closely tailored to the specific expected demand, offering limited scope for accommodating future increases in passenger numbers. On the other hand, the second scenario, with its large-scale network and uneven demand, fails to provide complete coverage, leaving several OD pairs unserved. Despite this, it possesses the potential to absorb additional demand, indicating a level of adaptability in meeting extra demand in specific areas.

In summary, the performance of the redesigned networks reveals a complex interplay between network design, capacity utilization, and economic sustainability. Each scenario exhibits distinct strengths and weaknesses, with no single alternative standing out across all metrics. These insights are crucial for stakeholders, offering valuable guidance in making informed decisions about network designs. They underscore the importance of balancing operational efficiency, coverage, and cost-effectiveness in the development and management of HSR networks.

- *What are the implications on network service capacity and economic sustainability at a strategic level, resulting from the redesign of Europe's rail network to substitute short-haul flights with high-speed rail?*

Having answered all the formulated sub-questions, a comprehensive answer to the main research question of this thesis concerning the implications of redesigning the rail network in Europe accordingly to replace short-haul flights with HSR can be provided. This transition encompasses not only infrastructure redesign but also the strategic considerations of service capacity and economic sustainability

Firstly, the shift from air to rail travel is influenced by a diverse array of factors, including environmental policies, infrastructure and service levels, and socio-economic considerations. The feasibility of this transition, constrained by geographical diversity, existing infrastructure, and regional travel preferences, necessitates tailored scenarios. These scenarios must realistically evaluate a partial yet significant shift, balancing potential modifications with realistic demand distributions to ensure an effective transition.

Following, strategic infrastructure elements highlight the importance of balancing physical infrastructure with high-level operational elements. Line frequency adjustments significantly impact network efficiency and operational costs, since their overestimation can lead to underutilization and excess capacity. Conversely, strategic line development and frequency distribution can optimize network performance and reduce costs. While station capacity is less critical unless major infrastructure changes are required, it remains an important factor for effective implementation and sustainable development in network planning.

Key modifications to the HSR network infrastructure focus on optimizing capacity and efficiently allocating resources and services to meet regional demands. This includes introducing additional services and adjusting existing route options, informed by demand types identified in simulated scenarios. The aim is to achieve a network that balances efficiency with expansion, optimizing capabilities while considering the network's physical layout and operational service levels.

Ultimately, the redesigned networks' performance, in terms of transport efficiency and economic sustainability, depends on balancing operational efficiency, network coverage, and maintenance costs. Networks with lower operational and maintenance costs due to fewer operating trains indicate greater economic sustainability. Additionally, transport KPIs regarding network coverage and expansion potential deriving from the configuration modifications, provide insights into their performance relative to their original state or other competitive networks. This comprehensive evaluation highlights the importance of strategic planning and adaptability in network design, ensuring that the solutions not only meet current transportation needs but are also sustainable and efficient in the long run.

In conclusion, the strategic implications of redesigning Europe's rail network to substitute short-haul flights with HSR are intricate and multi-dimensional. This process involves not only modifying services to align with varying demand levels but also fundamentally altering the network's structure. These modifications lead to networks that differ from their original configurations, both in terms of physical layout and operational service levels. This comprehensive approach ensures that the redesigned networks can effectively meet the expected air passenger demands, while supporting the broader goal of a more sustainable and efficient transportation system.

6.2 Implications for Practice and Policy Making

This study, aimed at developing a customized approach for high-speed rail HSR network design on a continental scale and based on the existing networks within Europe, offers significant implications for both practice and policy-making. By adopting a supply and operator perspective and integrating elements from traditional network design and frequency setting problems, this research has achieved key objectives. These include aligning HSR network infrastructure characteristics with mobility and sustainability goals, understanding the impact of factors like network capacities, operator-related costs, and line configurations, and identifying the optimal combination of these elements for diverse network objectives. The insights gained are set to enhance the current HSR system, making substantial contributions to the practical field of strategic-to-tactical HSR network design and the academic realm of TNDFSP research.

From a practical standpoint, the findings are particularly relevant in the context of long-distance travel. Acknowledging the environmental drawbacks and the mobility and social benefits of air travel, the study highlights the necessity of a viable alternative to naturally decrease air travel demand. Enhancing HSR infrastructure emerges as a competitive and appealing option for international travel, contributing to the transportation industry's sustainability. However, transitioning from air to rail heavily depends on the current state of the HSR network, especially the configurations of operating lines, as many are currently insufficient for such a transition due to capacity limitations. Thus, this research offers valuable guidance for efficient network improvements, addressing the challenges of limited capacity and the complexity and expense of related projects.

More specifically, the diversity in terms of infrastructure development levels and transition stages varies significantly by location Developed and smaller networks typically require fewer modifications in operating new lines, while larger networks with diverse infrastructures are more prone to changes. However, this is not universally applicable, as each area has unique characteristics such as demand patterns and passenger properties.

Furthermore, the findings from this study, while specific to the strategic planning of a continental HSR network, have broader implications for the development and optimization of HSR worldwide. The crucial role of line capacities and configurations in determining the efficiency and cost-effectiveness of HSR networks highlights a fundamental principle: strategic choices at the network design level, particularly those related to line layout and service frequency, are key determinants of the network's overall performance.

In a broader context, the findings from this study could be instrumental in guiding the development of HSR networks in various regions, optimizing their performance and adaptability. The research provides a framework for understanding the complex dynamics of HSR network planning and offers strategic insights that could be applied to future HSR projects, ensuring that these networks are not only competitive and efficient but also economically viable and adaptable to changing demands.

Furthermore, in terms of policy-making, the study's scenarios for different demand distributions following environmental concerns and policies within Europe, are particularly noteworthy. The computed solutions computed offer multiple alternatives, allowing stakeholders to select the most suitable one based on their priorities. This flexibility underscores the study's relevance in policy-making. It provides a framework for decision-makers to balance environmental objectives with the practicalities of HSR network design and operation, ensuring that policies are both environmentally sound and aligned with the realities of transportation needs and infrastructure capabilities.

The balance between network density, service coverage, and operational costs is vital for the sustainable development of unified HSR networks. These insights emphasize the need for adaptable and forward-thinking strategies in railway capacity planning, addressing the dynamic and diverse needs of modern mobility. This research underscores the potential of simulation models in aiding decision-makers to optimize network designs for current and future transportation challenges.

Overall, this research not only advances the academic understanding of HSR network design but also provides valuable insights for other researchers as well as stakeholders. It is important to highlight that the numerical outcomes of the study can be employed to further analyse more specific case studies and/or to tackle the problem from different perspectives highlighting some aspects that have been overlooked by this study.

6.3 Limitations and Recommendations

In this research, several limitations were encountered, each offering a direction for future exploration. These limitations not only highlight the complexities of simulating supply-based network design problems but also underscore the potential for even more holistic approaches in future studies.

Optimization

The primary limitation of this study was the challenge of using traditional optimization methods for simulating the supply-based network design problem. The initial model, intended to represent a linear optimization problem, faced complexities due to the non-linear relationship between decision variables and the objective function, particularly in the capacity utilization maximization. This complexity led to the development of the Frequency Setting Algorithm as a manual optimization approach. Future research could explore alternative optimization techniques that effectively manage such non-linear complexities.

Assumptions and Simplifications

Additionally, due to the nature of the problem regarding a continental-scale design, several assumptions where formulated in order to simplify both the methodology process as well as the selection and data collection for the case study. These assumptions, while necessary, limited the inclusion of detailed user characteristics and societal impacts. Since this work was conducted for the supply perspective of the network, no user-centric properties were included. Similarly, characteristics that could be used regarding the societal relevance of the network modifications were also excluded from this work since they are typically paired with user characteristics. Future studies could enrich the research by incorporating factors like access, egress, waiting and transfer times, along with user preferences and varying demand patterns, to provide a more comprehensive view of demand distribution and route selection.

Operational strategies and urban areas

Moreover, operational strategies common in traditional railway systems were not included in the modelling phase. Integrating these strategies in future models could offer deeper insights into the variations of train operations, particularly in the context of transfers and turnaround times, and how these affect the daily operational service of a line. Furthermore, the exclusion of urban areas with high short-haul flight demand due to due to the need for a manageable, yet complete dataset, is a notable limitation. Future research including these areas could yield substantial modifications to the scenarios, due to either their high short-haul flight demand and/or their respective limited connectivity with land-based transportation.

Computational limitations and network connectivity

The algorithms developed for this study faced limitations in handling large-scale design problems, primarily due to computational power constraints. This limitation is particularly relevant given the study's aim to design a continental-scale intra-European network. Refining these algorithms for large-scale applications or exploring new computational methods could be a focus for future research.

Moreover, the decision to enable only single transfer routes within the network emerged as a significant limitation. This constraint hindered the network's ability to meet demands for distant pairs, as a two-line connection network was insufficient for complete network coverage in extended examined areas. Allowing for multiple transfers in future simulations could not only yield more realistic results that mirror real-life operations but also contribute to a more interconnected network, aligning with the overarching goal of developing a unified continental HSR network.

Diverse case studies and additional planning factors

Based on the study's results, future research could contribute by exploring various case studies differing in size and location, incorporating additional perspectives on costs regarding users and/or society. This would allow for the development of design alternatives that consider a wider range of viewpoints, beyond the operator's focus on minimizing operating costs.

Additionally, including elements like timetabling and operational factors could further broaden the scope, enabling a comprehensive evaluation of results across the entire spectrum of planning, from high-level strategy to daily operations and implementation.

Environmental and social sustainability

Lastly, for a comprehensive assessment from a sustainability perspective should encompass environmental sustainability factors, particularly CO_2 emissions, and social sustainability factors such as congestion, accident rates, impact on surrounding habitats, and overall well-being. These aspects are crucial for understanding the broader social implications of the network's operation and design.

In summary, while this research faced various challenges and limitations, these challenges along with the actual findings of the research present opportunities for further exploration and innovation, potentially leading to more advanced and holistic solutions in the realm of HSR network design.

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Appendix A: Case Study Dataset

A1: Functional Urban Areas

Country	Code	Functional Urban Area	Airport	Station	PAX 2019	5M PAX
		EU Members				
Austria	AT	Vienna	YES	YES	31,634,898	YES
Belgium	BE	Brussels	YES	YES	26,287,166	YES
Bulgaria	BG	Sofia	YES	YES	7,078,183	YES
Croatia	HR	Zagreb	YES	YES	3,409,936	NO
Czechia	CZ	Prague	YES	YES	17,773,456	YES
Denmark	DK	Copenhagen	YES	YES	30,120,542	YES
Estonia	EE	Tallinn	YES	YES	3,258,003	NO
Finland	FI	Helsinki	YES	YES	22,049,170	YES
France	FR	Paris	YES	YES	76,136,816	YES
		Lyon	YES	YES	11,689,945	YES
		Marseille	YES	YES	10,117,073	YES
		Toulouse	YES	YES	9,616,912	YES
		Bordeaux	YES	YES	7,662,559	YES
		Nantes	YES	YES	7,189,067	YES
		Nice	YES	YES	14,467,269	YES
Germany	DE	Berlin	YES	YES	24,223,011	YES
		Hamburg	YES	YES	17,274,029	YES
		Munich	YES	YES	47,891,776	YES
		Frankfurt am Main	YES	YES	70,435,867	YES
		Stuttgart	YES	YES	12,700,428	YES
		Cologne/Bonn	YES	YES	12,350,829	YES
		Duesseldorf	YES	YES	25,476,454	YES
		Hannover	YES	YES	6,287,084	YES
Greece	EL	Athens	YES	YES	25,572,131	YES
		Thesalloniki	YES	YES	6,679,059	YES
Hungary	HU	Budapest	YES	YES	16,099,519	YES
Italy	IT	Milan	YES	YES	28,705,273	YES
		Rome	YES	YES	43,397,751	YES
		Napoli	YES	YES	10,834,496	YES
		Palermo	YES	YES	7,056,467	YES
		Bologna	YES	YES	9,460,393	YES
		Bari	YES	YES	5,574,041	YES
		Catania	YES	YES	10,200,929	YES
		Venice	YES	YES	11,541,290	YES
Latvia	LV	Riga	YES	YES	7,785,729	YES
Lithuania	LT	Vilnius	YES	YES	5,001,844	YES
Luxembourg	LU	Luxembourg City	YES	YES	4,364,168	NO
Netherlands	NL	Amsterdam	YES	YES	71,689,636	YES
		Eindhoven	YES	YES	6,784,607	YES
Poland	PL	Warsaw	YES	YES	18,867,506	YES
		Krakow	YES	YES	8,402,773	YES
		Gdansk	YES	YES	5,362,727	YES
Portugal	PT	Lisbon	YES	YES	31,190,125	YES
		Porto	YES	YES	13,192,791	YES
Romania	RO	Bucharest	YES	YES	14,697,239	YES
Slovakia	SK	Bratislava	YES	YES	2,284,735	NO
Slovenia	SI	Osrednjeslovenska (Ljubljana)	YES	YES	1,719,039	NO

Spain	ES	Madrid	YES	YES	59,747,242	YES
		Barcelona	YES	YES	51,734,144	YES
		Valencia	YES	YES	8,400,668	YES
		Seville	YES	YES	7,522,542	YES
		Bilbao	YES	YES	5,860,208	YES
		Malaga	YES	YES	19,597,999	YES
Sweden	SE	Stockholm	YES	YES	25,633,469	YES
		Gothenburg	YES	YES	6,671,515	YES
Connected to European Rail Networks						
United Kingdom	UK	London	YES	YES	80,886,588	YES
		Manchester	YES	YES	29,320,609	YES
		West Midlands (Birmingham)	YES	YES	12,646,456	YES
		Glasgow	YES	YES	8,833,503	YES
		Liverpool	YES	YES	5,013,742	YES
		Newcastle upon Tyne	YES	YES	5,194,407	YES
		Bristol	YES	YES	8,953,866	YES
		Edinburgh	YES	YES	14,733,966	YES
European Free Trade Association (EFTA)						
Norway	NO	Oslo	YES	YES	28,472,061	YES
		Bergen	YES	YES	6,213,531	YES
Switzerland	CH	Zurich	YES	YES	31,472,879	YES
		Geneva	YES	YES	17,826,513	YES
		Basel	YES	YES	8,386,211	YES
EU Candidate Countries						
Albania	AL	Tirana	YES	YES	3,338,147	NO
Bosnia and Herzegovina	BA	Sarajevo	YES	YES	1,143,680	NO
Moldova	MD	Chisinau	YES	YES	2,995,530	NO
Montenegro	ME	Podgorica	YES	YES	1,291,535	NO
North Macedonia	MK	Skopje	YES	YES	2,353,327	NO
Serbia	RS	Belgrade	YES	YES	6,159,018	YES
Turkiye	TR	Instanbul	YES	YES	52,009,220	YES
		Ankara	YES	YES	11,417,759	YES

A2: Vertex Coordinates

City	Code	Lat	Lon	City	Code	Lat	Lon
Vienna	AT	48.208176	16.373819	Riga	LV	56.949650	24.105186
Brussels	BE	50.850346	4.351721	Vilnius	LT	54.687157	25.279652
Sofia	BG	42.697708	23.321867	Luxembourg City	LU	49.611622	6.131935
Zagreb	HR	45.815010	15.981919	Amsterdam	NL	52.370216	4.895168
Prague	CZ	50.075539	14.437800	Eindhoven	NL	51.441643	5.469722
Copenhagen	DK	55.676098	12.568337	Warsaw	PL	52.229675	21.012230
Tallinn	EE	59.436962	24.753574	Krakow	PL	50.264893	19.023781
Helsinki	FI	60.169857	24.938379	Gdansk	PL	54.356030	18.646120
Paris	FR	48.856613	2.352222	Lisbon	PT	38.722252	-9.139337
Lyon	FR	45.764042	4.835659	Porto	PT	41.157944	-8.629105
Marseille	FR	43.296482	5.369780	Bucharest	RO	44.426765	26.102537
Toulouse	FR	43.604652	1.444209	Bratislava	SK	48.148598	17.107748
Bordeaux	FR	44.837788	-0.579180	Ljubljana	SI	46.056946	14.505752
Nantes	FR	47.218372	-1.553621	Madrid	ES	40.416775	-3.703790
Nice	FR	43.710175	7.261953	Barcelona	ES	41.385063	2.173404
Berlin	DE	52.520008	13.404954	Valencia	ES	39.469906	-0.376288
Hamburg	DE	53.551086	9.993682	Seville	ES	37.389091	-5.984459
Munich	DE	48.135124	11.581981	Bilbao	ES	43.263012	-2.934985
Frankfurt am Main	DE	50.110924	8.682127	Malaga	ES	36.721275	-4.421399
Stuttgart	DE	48.775845	9.182932	Stockholm	SE	59.329323	18.068581
Cologne/Bonn	DE	50.937531	6.960279	Gothenburg	SE	57.708870	11.974560
Düsseldorf	DE	51.224960	6.775670	London	UK	51.507351	-0.127758
Hanover	DE	52.375893	9.732010	Oslo	NO	59.913876	10.742282
Athens	EL	37.983810	23.727539	Bergen	NO	60.391262	5.322054
Thesalloniki	EL	40.640266	22.939524	Zurich	CH	47.376888	8.541694
Budapest	HU	47.497913	19.040236	Geneva	CH	46.204391	6.143158
Milan	IT	45.464203	9.189982	Basel	CH	47.559601	7.588576
Rome	IT	41.902782	12.496365	Tirana	AL	41.327545	19.818699
Napoli	IT	40.863900	14.228028	Sarajevo	BA	43.852813	18.386009
Palermo	IT	38.115688	13.361267	Chisinau	MD	47.018852	28.845686
Bologna	IT	44.494888	11.342616	Podgorica	ME	42.438061	19.265551
Bari	IT	41.117142	16.871872	Skopje	MK	41.997345	21.427996
Catania	IT	37.507877	15.083030	Belgrade	RS	44.803483	20.454550
Venice	IT	45.440845	12.315515	Instanbul	TR	41.008240	28.978359

A3: Passenger Demand (0001 - 0055) … (1835 - 1888)

Origin	Destination	Pax
Vienna	Brussels	454019
Vienna	Sofia	347250
Vienna	Zagreb	173171
Vienna	Prague	175742
Vienna	Copenhagen	455575
Vienna	Helsinki	194345
Vienna	Paris	944404
Vienna	Lyon	138750
Vienna	Nice	224219
Vienna	Berlin	966659
Vienna	Hamburg	720332
Vienna	Munich	531507
Vienna	Frankfurt am Main	1109585
Vienna	Stuttgart	556925
Vienna	Düsseldorf	771175
Vienna	Hanover	223481
Vienna	Athens	330018
Vienna	Thesalloniki	159367
Vienna	Budapest	107756
Vienna	Milan	447270
Vienna	Rome	558401
Vienna	Napoli	141845
Vienna	Bologna	182491
Vienna	Bari	89631
Vienna	Catania	104259
Vienna	Venice	181525
Vienna	Riga	133874
Vienna	Luxembourg City	124512
Vienna	Amsterdam	943705
Vienna	Warsaw	386021
Vienna	Krakow	127053
Vienna	Lisbon	335342
Vienna	Bucharest	634044
Vienna	Madrid	564199
Vienna	Barcelona	640052
Vienna	Valencia	150576
Vienna	Malaga	174201
Vienna	Stockholm	264672
Vienna	London	833930
Vienna	Oslo	172412
Vienna	Zurich	940410
Vienna	Geneva	289265
Vienna	Basel	196972
Vienna	Tirana	186878
Vienna	Sarajevo	159292
Vienna	Chisinau	77652
Vienna	Podgorica	86933
Vienna	Skopje	136072
Vienna	Belgrade	212412
Vienna	Instanbul	341727
Brussels	Vienna	486177
Brussels	Zagreb	119816
Brussels	Prague	333833
Belgrade	Sarajevo	40925
Belgrade	Podgorica	310662
Belgrade	Instanbul	203856
Instanbul	Vienna	333180
Instanbul	Brussels	303026
Instanbul	Sofia	158076
Instanbul	Zagreb	124279
Instanbul	Prague	218993
Instanbul	Copenhagen	263217
Instanbul	Helsinki	144355
Instanbul	Paris	771090
Instanbul	Lyon	148217
Instanbul	Marseille	122644
Instanbul	Nice	117083
Instanbul	Berlin	411087
Instanbul	Hamburg	329675
Instanbul	Munich	371468
Instanbul	Frankfurt am Main	700726
Instanbul	Stuttgart	295949
Instanbul	Cologne/Bonn	274255
Instanbul	Düsseldorf	535768
Instanbul	Hanover	231281
Instanbul	Athens	618406
Instanbul	Thesalloniki	114092
Instanbul	Budapest	210116
Instanbul	Milan	308756
Instanbul	Rome	288706
Instanbul	Napoli	108161
Instanbul	Bologna	152151
Instanbul	Venice	206118
Instanbul	Vilnius	75734
Instanbul	Amsterdam	694849
Instanbul	Warsaw	163658
Instanbul	Lisbon	150252
Instanbul	Porto	76651
Instanbul	Bucharest	359296
Instanbul	Ljubljana	122696
Instanbul	Madrid	312919
Instanbul	Barcelona	287726
Instanbul	Valencia	97254
Instanbul	Malaga	146130
Instanbul	Stockholm	241028
Instanbul	Gothenburg	128231
Instanbul	London	814561
Instanbul	Oslo	145428
Instanbul	Zurich	318335
Instanbul	Geneva	216224
Instanbul	Basel	128240
Instanbul	Tirana	108803
Instanbul	Sarajevo	166286
Instanbul	Chisinau	144952
Instanbul	Podgorica	106734
Instanbul	Skopje	117641
Instanbul	Belgrade	203001

A4: Existing HSR Lines (001 - 040) … (127 - 167)

Line	Frequency	Stops
Line1	4	Amsterdam,Brussels,London
Line2	11	Amsterdam,Brussels,Paris
Line3	1	Amsterdam,Düsseldorf
Line4	8	Amsterdam,Düsseldorf,Cologne/Bonn,Frankfurt am Main
Line5	1	Amsterdam,Düsseldorf,Cologne/Bonn,Frankfurt am Main,Basel
Line6	62	Amsterdam,Eindhoven
Line7	1	Amsterdam,Hanover
Line8	5	Amsterdam,Hanover,Berlin
Line9	5	Athens,Thesalloniki
Line10	1	Barcelona,Bilbao
Line11	2	Barcelona,Lyon,Paris
Line12	41	Barcelona,Madrid
Line13	3	Barcelona,Madrid,Seville
Line14	2	Barcelona,Madrid,Seville,Malaga
Line15	1	Barcelona,Toulouse
Line16	9	Barcelona,Valencia
Line17	8	Bari,Bologna,Milan
Line18	2	Bari,Bologna,Venice
Line19	4	Bari,Milan
Line20	1	Bari,Napoli
Line21	9	Bari,Rome
Line22	7	Basel,Berlin
Line23	2	Basel,Cologne/Bonn,Düsseldorf,Hamburg
Line24	5	Basel,Frankfurt am Main
Line25	5	Basel,Frankfurt am Main,Cologne/Bonn,Düsseldorf
Line26	4	Basel,Frankfurt am Main,Cologne/Bonn,Hamburg
Line27	7	Basel,Frankfurt am Main,Hamburg
Line28	7	Basel,Frankfurt am Main,Hanover
Line29	6	Basel,Paris
Line30	1	Basel,Stuttgart
Line31	1	Basel,Stuttgart,Munich
Line32	41	Basel,Zurich
Line33	2	Belgrade,Budapest,Vienna
Line34	2	Belgrade,Zagreb,Ljubljana
Line35	3	Bergen,Oslo
Line36	14	Berlin,Frankfurt am Main
Line37	10	Berlin,Frankfurt am Main,Stuttgart
Line38	4	Berlin,Frankfurt am Main,Zurich
Line39	1	Berlin,Gdansk

Line126	14	Lyon,Marseille
Line127	3	Lyon,Marseille,Nice
Line128	4	Lyon,Nantes
Line129	33	Lyon,Paris
Line130	3	Lyon,Toulouse
Line131	1	Madrid,Barcelona,Marseille
Line132	5	Madrid,Seville
Line133	15	Madrid,Seville,Malaga
Line134	22	Madrid,Valencia
Line135	11	Malaga,Seville
Line136	1	Marseille,Lyon,Nantes
Line137	6	Marseille,Nice
Line138	10	Marseille,Paris
Line139	1	Marseille,Toulouse
Line140	53	Milan,Bologna,Rome,Napoli
Line141	2	Milan,Lyon,Paris
Line142	25	Milan,Rome
Line143	28	Milan,Venice
Line144	8	Milan,Zurich
Line145	1	Munich,Paris
Line146	7	Munich,Prague
Line147	1	Munich,Venice
Line148	13	Munich,Vienna
Line149	6	Munich,Zurich
Line150	22	Nantes,Paris
Line151	21	Napoli,Rome
Line152	11	Napoli,Rome,Bologna,Venice
Line153	7	Nice,Marseille,Paris
Line154	4	Oslo,Stockholm
Line155	2	Palermo,Napoli,Rome
Line156	5	Paris,Stuttgart
Line157	10	Paris,Toulouse
Line158	6	Paris,Zurich
Line159	12	Prague,Vienna
Line160	2	Prague,Warsaw
Line161	19	Rome,Bologna,Venice
Line162	2	Seville,Madrid,Valencia
Line163	1	Venice,Milan,Zurich
Line164	2	Venice,Vienna
Line165	1	Vienna,Warsaw
Line166	4	Vienna,Zurich

Appendix B: Model Outputs - Scenario 1

B1: Cities for Scenario 1

City	Code	Lat	Lon
Amsterdam	NL	52.370216	4.895168
Brussels	BE	50.850346	4.351721
Frankfurt	DE	50.110924	8.682127
London	UK	51.507351	-0.127758
Milan	IT	45.464664	9.188540
Paris	FR	48.856613	2.352222
Zurich	CH	47.373878	8.545094

B2: Solutions for Scenario 1 (Pareto optimal in red)

Solution	Demand Percentage [%]	Capacity Utilization [%]	Operator Costs [€/day]
1	100	87.15	9748184.64
2	99	86.54	9748184.64
3	98	86.60	9646705.10
4	97	86.41	9541287.29
5	**96**	**86.02**	**9477818.86**
6	95	86.23	9390907.46
7	94	86.28	9259383.54
8	93	86.50	9231051.60
9	92	86.62	9081689.88
10	91	86.27	9034363.29
11	90	86.32	8913359.23
12	89	87.33	8811651.03
13	88	87.08	8706948.87
14	87	87.59	8530765.39
15	86	87.24	8483438.80
16	85	86.59	8483438.80
17	**84**	**86.19**	**8419970.37**
18	**83**	**86.46**	**8257732.58**
19	82	87.42	8189815.83
20	81	87.51	8097829.68
21	80	87.51	7970177.18
22	79	87.49	7861603.60
23	78	86.80	7861603.60
24	**77**	**86.52**	**7797419.52**
25	76	88.18	7579841.56

26	75	88.68	7483436.76
27	**74**	**88.16**	**7442203.03**
28	**73**	**97.42**	**7253317.87**
29	72	98.66	7094177.66
30	71	98.20	7046851.07
31	70	98.37	6938007.43
32	**69**	**97.72**	**6896773.70**
33	68	98.59	6736900.47
34	67	98.67	6625389.81
35	**66**	**97.78**	**6625389.81**
36	**65**	**98.43**	**6472156.67**
37	64	99.40	6346564.86
38	**63**	**99.06**	**6282380.78**
39	62	100.03	6206722.25
40	61	100.03	6167137.44
41	60	101.09	5941431.22
42	59	100.84	5896771.66
43	58	100.70	5829431.82
44	57	100.98	5717921.15
45	56	100.51	5654452.72
46	**55**	**99.84**	**5613218.99**
47	**54**	**100.72**	**5528974.61**
48	**53**	**101.28**	**5407970.56**
49	**52**	**101.46**	**5297175.54**
50	**51**	**104.34**	**5165486.48**
51	**50**	**105.18**	**5033962.56**

Appendix C: Model Outputs - Scenario 2

C1: Cities for Scenario 2

City	Code	Lat	Lon
Vienna	AT	48.208176	16.373819
Brussels	BE	50.850346	4.351721
Prague	CZ	50.075539	14.4378
Copenhagen	DK	55.676098	12.568337
Paris	FR	48.856613	2.352222
Toulouse	FR	43.604652	1.444209
Nice	FR	43.710175	7.261953
Berlin	DE	52.520008	13.404954
Munich	DE	48.135124	11.581981
Frankfurt am Main	DE	50.110924	8.682127
Budapest	HU	47.497913	19.040236
Milan	IT	45.464203	9.189982
Rome	IT	41.902782	12.496365
Venice	IT	45.440845	12.315515
Luxembourg City	LU	49.611622	6.131935
Amsterdam	NL	52.370216	4.895168
Warsaw	PL	52.229675	21.012230
Lisbon	PT	38.722252	-9.139337
Porto	PT	41.157944	-8.629105
Ljubljana	SI	46.056946	14.505752
Madrid	ES	40.416775	-3.703790
Barcelona	ES	41.385063	2.173404
Seville	ES	37.389091	-5.984459
London	UK	51.507351	-0.127758
Zurich	CH	47.376888	8.541694

C2: Solutions for Scenario 2 (Pareto optimal in red)

Solution	Demand Percentage [%]	Capacity Utilization [%]	Operator Costs [€/day]
1	100	116.64	22172434.68
2	99	116.29	21980677.46
3	98	116.03	21711756.87
4	**97**	**115.55**	**21571797.03**
5	96	116.94	21171204.61
6	95	116.56	20905953.48
7	**94**	**116.11**	**20752266.56**
8	93	117.49	20727945.83

9	**92**	**117.38**	**20479361.75**
10	**91**	**117.81**	**20066236.93**
11	90	119.99	19920854.09
12	89	121.46	19673830.53
13	88	121.19	19476768.98
14	87	120.61	19409421.47
15	86	120.42	19099267.14
16	85	120.32	18788373.31
17	84	119.81	18641812.18
18	**83**	**119.37**	**18535948.25**
19	82	123.06	18279761.45
20	81	122.62	18186355.15
21	80	122.32	17986313.89
22	79	122.08	17638129.01
23	78	121.79	17419102.23
24	77	121.14	17377422.38
25	76	121.19	17097184.02
26	75	120.53	17052524.46
27	**74**	**119.98**	**16937763.34**
28	**73**	**120.06**	**16507367.77**
29	72	120.88	16075211.54
30	**71**	**120.64**	**15852758.95**
31	70	123.28	15828438.22
32	69	122.59	15787204.48
33	**68**	**122.06**	**15723020.40**
34	67	123.45	15568463.40
35	66	122.85	15482123.98
36	**65**	**122.36**	**15290402.88**
37	64	125.31	14733033.90
38	**63**	**124.73**	**14572437.77**
39	**62**	**130.52**	**14472902.99**
40	**61**	**131.45**	**13884387.88**
41	**60**	**135.67**	**13764172.28**
42	59	137.56	13579272.10
43	58	136.90	13428784.73
44	57	136.47	13334131.55
45	56	136.58	13029435.29
46	**55**	**135.98**	**12930935.45**
47	54	140.35	12511612.35
48	53	139.99	12332667.16
49	52	139.35	12163634.01
50	**51**	**138.62**	**12101510.62**
51	**50**	**138.63**	**11876088.66**

Appendix D: Scientific Paper

A summary of this research in the form of a scientific paper is provided in this Appendix, starting on the next page.

Infrastructure implications of intra-European short-haul flight substitution with high-speed rail: A supply-based network design problem

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Delft, The Netherlands, December 2023

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Abstract - Short-haul flights, known for their high carbon intensity relative to distance, are increasingly challenged by high-speed rail (HSR), a viable and environmentally friendly alternative. This study develops a model adapting the "Transit Network Design and Frequency Setting Problem" to high-speed rail, focusing on optimizing existing networks rather than designing new ones. Two sequential algorithms are developed and integrated in the model, which initially generate the optimal paths in the network, and subsequently, set the appropriate frequencies to the existing and new lines. The model is applied to two scenarios within the European rail network, to assess the impact of network modifications on demand distribution, operational costs, and infrastructure development. The findings reveal that the impact of network modifications varies depending on the size and development level of the area. In smaller, well-developed networks, modifications mainly involve adjusting frequencies of existing services, while larger areas with diverse infrastructure levels necessitate new lines and modified configurations. The model offers varying implementation options, balancing capacity utilization and cost minimization, aiding stakeholders in making informed decisions. The potential of utilizing existing infrastructure for sustainable mobility is highlighted, suggesting that future endeavors should include diverse case studies and incorporate user and social cost perspectives, along with timetabling and operational factors for a more comprehensive evaluation.

Keywords - High-speed rail, Network design, Line configuration, Capacity utilization, Operator costs

I. INTRODUCTION

The aviation industry, despite strides towards sustainability, continues to have a substantial environmental footprint, necessitating more robust measures. Technological advancements, such as new aircraft designs, have improved efficiency and reduced emissions. However, the rapid increase in air travel signify that aviation remains a significant contributor to climate change, responsible for about 2% of global man-made CO_2 emissions and approximately 5% of total GHG emissions [1]. Short-haul flights are particularly concerning due to their high fuel consumption per passenger-kilometer as illustrated in Figure 1. In response, national and EU authorities are considering strategies to promote greener transportation alternatives, including the potential of banning short-haul flights where feasible.

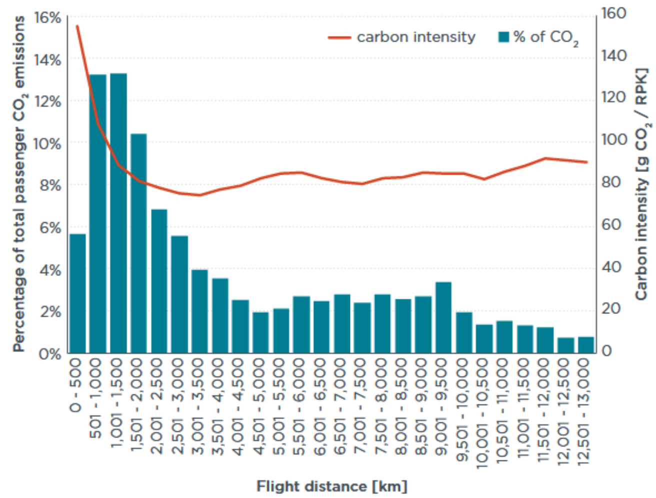

FIGURE 1: Share of passenger CO2 emissions and carbon intensity in 2018, by stage length [2]

Rail transport, especially high-speed rail, stands out as a sustainable option, aligning with the EU's environmental objectives of reducing transportation-related emissions by up to 90% by 2050 [3]. European railroads have already reduced by half their carbon footprint since 1990, while increasing passenger and freight volumes [4]. HSR, is a viable substitute for air travel specifically in short to medium-haul markets, but such a shift necessitates changes in both air and rail networks, affecting environmental and financial aspects of these industries.

This is due to the fact that rail and air travel are affected by distinct factors, necessitating a thorough analysis to fully grasp the pros and cons of such a shift [5]. Essentially, this change is likely to lead to more people using trains, increasing the need for enhanced train services and connections to substitute flight routes. However, considering this change is being contemplated at a continental level, it is anticipated that the overall rail network, which consists of various sub-networks with varying development levels, will require significant upgrades to its fundamental infrastructure [6]. These upgrades could be influenced by various performance metrics from both the aviation and railway sectors. Crucially, the nature of the substitution, particularly the scale of the modal shift – the specific flights being replaced and the resulting impact on passenger numbers – will play a major role.

The current understanding of designing fundamental HSR infrastructure for large-scale network substitution is limited. Scientifically, there's a gap in research on the capabilities and limitations of existing HSR network design and capacity planning in such a vast and complex network. Practically, there's a need for unified decision-making in HSR infrastructure design to enhance the efficiency of the European high-speed rail network. This includes a comprehensive understanding of the diverse factors impacting network infrastructure at a continental level and aligning them with policy objectives. The challenge is multidimensional, encompassing practical design considerations, capacity evaluation, and assessing the financial and environmental impacts of design changes.

The primary objective of this study is to bridge these gaps by exploring the potential impacts of enhancing HSR infrastructure and defining optimal network configurations that consider both physical attributes and sustainability aspects. This will be achieved by:

- ❖ Studying the substitutability of short-haul flights based on modal shift factors and flight classification.
- ❖ Examining the current state of HSR networks and analyzing different network designs in terms of capacity, economic and environmental effects.
- ❖ Identifying the necessary modifications to HSR infrastructure and services to facilitate a successful transition from short-haul flights to high-speed rail, tailored to specific substitution levels.

The aim is to provide a comprehensive analysis that will contribute to the strategic planning and development of HSR systems, particularly in the context of substituting short-haul flights, thereby aiding in the reduction of the environmental impact of transportation. This research holds significant relevance in advancing the field of HSR network design, by focusing on optimizing existing networks, contributing to evolving traditional demand-based network design approaches, and integrating existing infrastructure and capacity constraints. This approach offers a more holistic perspective on efficient railway planning, particularly in the complex HSR environment.

This paper is structured as follows. Section II presents findings of literature review, covering flight classification, modal shift for long-distance travel, and principles of railway network design optimization, particularly focusing on supply-based issues, while it also discusses performance indicators for transport networks. The employed methodology, including the formulation of the TNDFSP model for the HSR supply-based problem and the development of the algorithms, is detailed in Section III. Section IV focuses on applying the defined problem to a European region case study, detailing the selected database and information collection for model inputs, and introducing demand scenarios. In Section V, the results of the model are analyzed and discussed, evaluating alternative designs and examining performance metrics from the model outputs. The paper concludes with Section VI, which synthesizes insights from the analyses, critically assesses the research, acknowledges its limitations, and suggests future research directions and advancements in the field.

II. LITERATURE BACKGROUND

Several studies have highlighted the potential to decrease the environmental impact of highly-polluting short-haul flights by substituting them with greener transportation alternatives. Land-based transport options, particularly those matching the travel time of flights, are suitable substitutes [7]. Specifically, when comparing similar travel itineraries, high-speed trains demonstrate lower energy consumption per seat-kilometer compared to aircraft for short to medium distances, leading to reduced emissions. Additionally, a significant proportion of flights from major European international airports cover distances less than 750 km, a range where HSR can effectively compete with air travel. Furthermore, in a competitive long-distance transport market, railways could attract nearly 25% of passengers for journeys under 750 km, though this figure falls to 9% for longer trips [8].

Consequently, to successfully transition to a unified high-speed rail network, various aspects of both short-haul flights' classification and HSR planning need to be considered. These include the extent and method of replacing flights and the strategies to tackle this issue, taking into account relevant factors and evaluating the effectiveness of such solutions.

A. Short-Haul Flight Substitution

The categorization of flights is a critical aspect in understanding the dynamics of short-haul flight substitution. Flights are classified based on various factors, including route, operational purpose, aircraft type, and service level. When flight types are compared, travel distance and time are the main factors considered. The International Civil Aviation Organization [9] defines flight time as the total duration from the aircraft's initial movement for takeoff to its final rest at the end of the flight. Flight distance, typically measured along the great-circle distance, varies due to factors like weather conditions and air traffic. However, there is a lack of consensus on the specific distance thresholds, especially for short-haul flights, leading to different definitions across continents and airlines [2][7][9][10][11][12].

This research focuses on criteria related to rail travel times for potential air travel substitution, aligning with European initiatives to shift medium-distance passenger transport to rail by 2050 [13]. Additionally, Member States have initiated schemes to reduce short-haul flights, such as Austria's domestic flight ban for routes served by rail alternatives within 3 hours, and France's ban on domestic flights where direct rail services are available within 2.5 hours. These initiatives reflect a growing trend towards integrating rail travel as a sustainable alternative to short-haul flights.

European transport policy aims for a sustainable distribution of transportation modes, leading to modal competition as well as substitution. Modal shift, the process where one mode becomes more advantageous over another for the same route or market, is influenced by various factors including socio-demographic aspects, journey characteristics, and spatial patterns [14]. The shift between transportation modes is often driven by relative benefits such as travel cost, time, convenience, comfort, reliability, accessibility, environmental concerns, personal preferences, or social norms. However, the effects of modal substitution are context-dependent, with no general rule for its application [15]. Transportation planning and policy heavily rely on understanding these modal substitution factors to develop sustainable and efficient transportation systems.

The shift from air to rail involves new infrastructure and depends on geographical variations [16], since the availability of transport infrastructure varies, especially on corridors experiencing the highest modal competition. While new rail investments can lead to net GHG emission reductions, increased demand from an air-to-rail shift could undermine these benefits. Thus, assessing the railway system's capacity to accommodate additional demand is essential, considering short-term optimization, medium-term expansion, and long-term growth strategies [17].

B. Railway Transport Planning

Transportation is crucial for facilitating movement, but growing populations and travel demands have led to issues such as congestion and pollution. Public transportation systems, recommended for mitigating these drawbacks, require a balanced design considering service quality, cost-effectiveness, and overall system impact [18]. Transport planning, a complex process involving strategic, tactical, and operational decision-making, is extensively studied due to its multidimensional nature and varying stakeholder interests. The “Hierarchical Public Transport Planning Concept” [19] illustrates this process, encompassing tasks from high-level planning to implementation, with feedback loops for vertical dependencies.

The planning process begins with “Network & Infrastructure Planning,” focusing on developing or adjusting infrastructure based on transportation demand. “Line Planning” follows, determining routes, stopping policies, and frequencies. “Timetable Planning” involves setting specific arrival and departure times, while “Vehicle & Crew Scheduling” assigns vehicles and staff duties. The tactical phase aims to enhance system performance, aligning with profit generation or policy objectives. The operational level, or “Real-Time Management,” represents day-to-day activities.

The design of transport systems, due to significant interests and costs, has led to efforts to optimize this process. The “Transit Network Planning Problem” (TNPP) framework [19] structures the inherent challenges of transport planning, breaking them down into smaller sub-problems. These sub-problems often merge to address strategic and high-level tactical phases. This study focuses on the “Transit Network Design and Frequency Setting Problem” (TNDFSP), which involves route establishment and frequency determination, initiated with given demand and subject to various objectives and constraints as depicted in Figure 2.

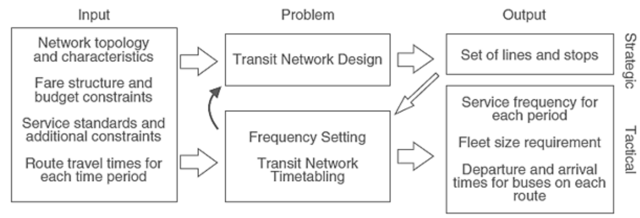

FIGURE 2: Interaction between strategic and tactical levels of the planning process

A key challenge in both problems is the limitation posed by the capacity of the existing infrastructure. Effectively optimizing infrastructure usage is a complicated and difficult task. It involves assessing how much additional traffic the current infrastructure can handle and determining the required investment for new infrastructure [20].

In railway, capacity planning, incorporated during strategic and tactical planning, involves different concepts, with “theoretical capacity” based on the maximum number of trains that can be scheduled, and “practical capacity” defined as the number of trains that can operate effectively while meeting quality requirements [21]. Practical capacity is often lower due to real-world limitations like train delays. Capacity planning methods range from stochastic models to optimization techniques, with TNDFSPs typically solved using mathematical optimization due to their complexity and the availability of computational power.

However, there is a variation in how transit network problems are defined, with capacity planning either incorporated as a constraint or ignored in network design. Most research focuses on user-centric, demand-driven network design, leaving a gap in supply-oriented studies. This study aims to address this gap, exploring demand-oriented TNDFSP structures to adapt these concepts to a large-scale network problem, particularly for high-speed rail at a continental level.

The TNDFSP is structured around key elements crucial for strategic transit network planning. It involves determining the optimal arrangement of transit infrastructure, including stations, lines, capacity, and frequency, to achieve efficient and effective transit operations [18]. Stations, lines, capacity, and frequency are interconnected, each playing a vital role in the network's overall performance and quality.

The TNDFSP also integrates mathematical and optimization techniques to solve the design problem. Mathematical models represent the relationships between network components, passenger demand, and performance metrics, while optimization algorithms identify the most favorable design solutions within set constraints and objectives [22]. This systematic approach aids planners and decision-makers in developing efficient, reliable, and sustainable transit systems. Due to its complex nature with multiple components, the characteristics of a TNDFSP optimization model are divided into objectives, decision variables, parameters, and constraints.

Objectives: The objective function in TNDFSP translates feasible line configurations into a quantifiable score for comparison. Traditional transit planning involves balancing the operator's cost reduction goals with the user's benefit maximization. These objectives often relate to route length for operators and deviation from shortest paths for users, with additional factors like external costs and travel time reduction also considered [23].

Decision Variables: These represent quantifiable choices within the parameters layer. In TNDFSP, the primary decision variables are the line plan and frequencies. Additional variables like fares, stop locations, capacities, and vehicle types are also considered, though less frequently [23].

Parameters: Divided into network and demand characteristics. Network characteristics include vertices (stops or stations), edges (direct connections), lines (passenger services), and paths (passenger routes). Network configurations vary from simplified radial and rectangular grids to more complex irregular grids. In HSR, factors like infrastructural limitations and investment costs are crucial, often leading to a focus on single corridors or lines for frequency and timetable planning [24].

Constraints: Constraints ensure realistic and attainable solutions, often specific to each case. Common constraints include financial considerations, capacity limitations, and connectivity requirements. Operational routes, express services, and time horizon specifications are also important, especially in practical applications [22][24].

In the context of high-speed rail, these components are adapted to address the unique challenges and limitations of rail infrastructure, emphasizing the interconnection between strategic planning and operational restrictions. An overview of the most frequently utilized components that could be employed and/or adapted to a supply-based problem are presented at the end in Table 2.

TABLE 1: Overview of frequently used TNDFSP components

Component	**Description**
Objectives	Vehicle capacity
	Infrastructure capacity
	Operator costs
	Total system and user cost
Decision Variables	Routes, frequencies
	Route spacing, headways
	Routes, stops
Constraints	Budget, Capacity, Lower/Higher node/edge frequency, Connected paths
	Infrastructure restrictions, Working Lines, Stretch capacity, Vehicle fleet size, Time horizon
	Route shape, Directness, Feasible frequencies, Load factor boundaries, Min/Max line length, Operational budgets
	Demand satisfaction, Vehicle capacity, Stop capacity, Link capacity

C. Transport Network Performance Measurement

Performance measures, both quantitative and qualitative, are essential for evaluating the effectiveness of transport systems or projects. The selection of appropriate indicators is crucial as they reflect various stakeholder perspectives and provide objective information for progress assessment, improvement identification, and informed decision-making. The complexity of evaluating transport network efficiency and effectiveness arises from differences in business models, network sizes, ownership structures, and geographical settings. High-speed rail, straddling conventional land-based transit and airlines, requires a review of performance indicators from both industries to define key performance indicators (KPIs) effectively.

In aviation, common KPIs at the strategic level include traffic-based and financial-based indicators, such as Available Seat Kilometres (ASK), Revenue Seat Kilometres (RPK), Cost per ASK (CASK), Revenue per ASK (RASK), and Yield. These indicators help determine operating profit by comparing expenses and earnings [25]. Similarly, these indicators are applicable to long-distance transport like HSR.

Strategic level transport indicators should align with strategic objectives for efficiency throughout planning phases and assess operating conditions and service levels from both transport and non-transport perspectives [26]. These indicators include network coverage, market share, intermodal integration, network expansion opportunities, and network resilience. Non-transport indicators relate to broader sustainability goals, covering social, economic, and environmental aspects.

Performance indicators can also be categorized into inputs (investments), outputs (direct achievements), and outcomes (effects on users and the community) [27]. Sustainability outcomes are subdivided into environmental, social, and economic aspects, with indicators like emissions, accidents, and travel costs [28].

Specifically for HSR, infrastructure performance indicators should focus on transport network or service supply. Metrics like maximum line frequency and line length are crucial for assessing rail network design capacity. Strategic-level KPIs regarding sustainability enable comparison between different design alternatives [29].

Environmental sustainability is commonly assessed through emissions, energy consumption, noise levels, air pollution, and land use. Carbon emissions are particularly significant, especially compared to carbon-intensive modes like flying. However, carbon footprint tools often overlook the environmental effects of infrastructure and rolling stock construction [30]. CO_2 emissions per passenger-km can measure the environmental impact of infrastructure construction and expansion.

Economic aspects, such as cost-effectiveness and efficiency, are quantified through capital costs, operational costs, maintenance expenses, energy consumption, and cost per passenger-km. Transport infrastructure costs include investments in new infrastructure, renewal costs, maintenance expenses, and operational expenditures [31]. Costs related to construction and expansion, measured in euros per passenger-kilometre, are combined with operational costs to assess the economic performance of a network at a high level.

III. METHODOLOGY

The main goal of this research is to identify the modifications to the strategic-level rail infrastructure required for the successful transition of passengers from short-haul flights to high-speed rail. Due to the size, complexity and lack of qualitative knowledge in the topic of HSR network design, a quantitative experiment was conducted. This experiment simulated the long-distance transport environment's transit planning process for HSR network designs, by performing different demand scenarios and interpreting the design alternatives outputs from a transport and a sustainability perspective.

A. General Approach

The methodology of this research is structured to emphasize its strategic focus, underpinned by several key modelling assumptions that influence network design. These assumptions cover various categories, including passenger demand, infrastructure, mode of transport, and technical and operational data. In addition, a static state of current short-haul flight demand as the sole influx to the rail network is assumed, without future changes. Finally, it presumes homogenous rolling stock and excludes operational strategies used in the operational level of design. The research methodology, from data collection and analysis to model development and algorithm formulation, is outlined in Figure 3, providing a roadmap of the research process.

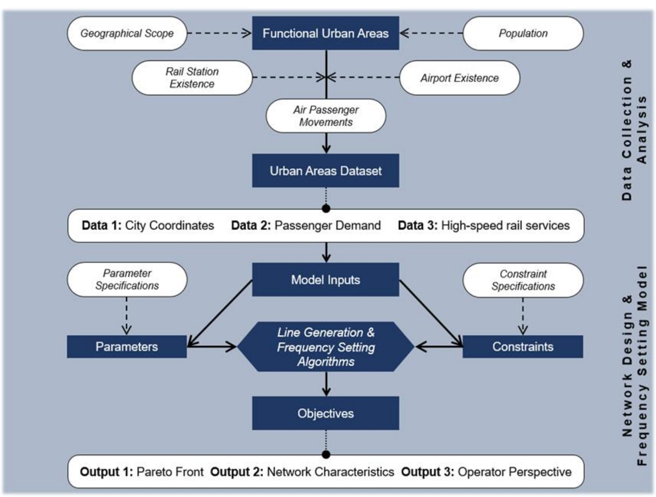

FIGURE 3: Methodology overview

The methodology encompasses gathering and analyzing necessary data, required to establish model parameters for the network design and frequency setting problem. The process begins by defining functional urban areas within the geographical scope of this research, as well as based on the population of the selected countries. This step includes identifying the main rail stations and airports in these areas, filtering out those lacking either facility. Subsequently, a data cleaning process is conducted based on airport passenger numbers, leading to the final selection of urban areas.

For these areas, three primary data types are collected for use as model inputs: the coordinates (latitude and longitude) of each urban area's main city, the air passenger demand between each urban area pair, and the existing high-speed rail services connecting two or more areas. These data inputs are crucial for defining and calculating the model's parameters and constraints, together with their respective specifications. These elements are then inserted into the developed algorithms, where network design modifications based on existing designs are calculated first, and then, the corresponding services to meet demand in the modified network are computed. Consequently, the objective values are derived from the algorithm-calculated elements.

The final step involves extracting the characteristics of the modified network, regarding the strategic infrastructure design and operational elements, along with the different objective-balanced solutions. These characteristics are crucial for evaluating the network modifications from both large-scale transport and economic sustainability perspectives.

B. Problem Characteristics

As identified in the literature, TNPPs quantitatively describe the search for optimal transit systems. Specifically, problems that involve selecting lines and their frequencies, and incorporate capacity planning, are known as TNDFSPs. This research defines a modified version of a TNDFSP to describe the design of a HSR system in a long-distance transport network, taking into account the existing network situation.

Transit network planning problems, due to their application-driven nature, use various notations across the literature. For this specific problem, the network is represented as an undirected and incomplete graph $G=[V,E]$, consisting of a finite set of cities (vertices) $V=[v1,v2,\ldots,vi]$, and a finite set of connections between these cities (edges) $E=[e1,e2,\ldots,ek]$. In this graph, a "line" is defined as a service that is a sequence of directly connected vertices. Multiple lines combine to form a set of lines $L=[l1,l2,\ldots,lm]$. Passengers traveling through the network on a single line follow a "direct path" p^d, while those requiring a transfer follow a "transfer path" p^t. These paths constitute the set of paths $P=[p1,p2,\ldots,p]$, where each origin-destination (OD) pair has either a direct or transfer path, with demand distributed to that specific path. Table 2 provides an overview of the indices and sets used in this model.

TABLE 2: Overview of the model's indices and sets

Notation	Description
$i,j \in V$	Vertex
$k \in E$	Edge
$m \in L$	Line
$d \subset P$	Direct path
$t \subset P$	Transfer path

As previously explained, the graph G of this network consists of vertices v, edges e and lines l. Within this graph, either direct paths p^d or indirect paths p^t using lines can be used to travel across vertices. The travel demand is given by the number of passengers originally served by short-haul flights that are now shifted to high-speed rail services. The services are operated by high-speed trains of the same properties in order to simulate a unified high-speed rail network. The characteristics of the five entities (vertices, edges, lines, demand, vehicles) provide the problem with its structural operating environment, for which a more detailed elaboration is provided below. An overview of the utilized parameters is provided in Table 3.

TABLE 3: Overview of the model's indices and sets

Notation	Description	Unit
Vertex parameters		
V	Number of vertices v	[-]
φ_v	Latitude of vertex v	[deg]
λ_v	Longitude of vertex v	[deg]
$Dist_{i,j}$	Distance between vertices v_i and v_j	[km]
Cap_v^{exs}	Existing maximum capacity of vertex v	[veh/day]
Edge parameters		
E	Number of edges e	[-]
$Existence_e(v_i, v_j)$	Existence of edge e between vertices v_i and v_j $(true = 1, false = 0)$	[-]
Len_e	Length of edge e	[km]
$Time_e$	Average travel time of edge e	[hr]
Line parameters		
Ω_l	Set of edges assigned to line l	[-]
$Stops_l^{exs}$	Existing stops of line l	[-]
Len_l^{exs}	Existing length of line l	[km]
Frq_l^{exs}	Existing frequency on line l	[veh/day]
Cap_l^{exs}	Existing maximum capacity of line l	[pax/day]
Demand parameters		
$D_{i,j}$	Demand between vertices v_i and v_j	[pax/day]
D_v	Demand on vertex v	[pax/day]
$D_{i,j}^{pd}$	Demand between vertices v_i and v_j along direct path pd_r	[pax/day]
$D_{i,j}^{pt}$	Demand between vertices v_i and v_j along transfer path pt_s	[pax/day]
D_l	Demand on line l	[pax/day]
Q_l	Maximum passenger flow on line l	[pax/day]
Vehicle parameters		
SC	Seating capacity	[pax/veh]
LF	Design passenger load factor	[-]
SP	Average travel speed	[km/h]

The TNDFSP is characterized by two decision variables: the selection of lines and the frequencies applied to these lines. In this research, the number of lines is optimally defined during the first algorithm phase, based on problem constraints, and subsequently used as an input for frequency determination. The line frequency frq_l is the dependent variable that computes capacities for vertices and lines, as shown in Equation 1. It is considered the single decision variable for this problem measured in vehicles per day.

$$frq_l = \left\lceil \frac{Q_l}{SC * LF} \right\rceil \tag{1}$$

The research problem is a bi-objective combinatorial optimization problem, aiming to improve and maximize the utilization of existing rail network infrastructure within feasible budget constraints. This falls under the TNDFSP, with the central objective of enhancing the overall capacity of the transit network through strategic resource allocation and utilization. Key considerations include the type of rolling stock, passenger demand accommodation, and the limitations posed by existing infrastructure.

The optimization question is expressed as: "Maximize the total capacity utilization while minimizing operational costs across all vertices and lines". This objective is twofold: firstly, to maximize capacity utilization by focusing on infrastructure capacity components; secondly, to minimize operator costs, ensuring that capacity expansion remains within logical financial limits.

Infrastructure Capacity Components (Max: Z1 = Vertex + Line): The infrastructural capacity includes both station and line capacities. The optimization aims to maximize the accommodation of air-to-rail substitution passengers within the redesigned infrastructure. The capacity utilization of stations and lines is influenced by the frequency of operating lines. Equations 2 and 3 express these capacity components:

$$Vertex = \sum_{v \in V} \left(\frac{D_v}{Cap_v * SC} \right) \tag{2}$$

$$Line = \sum_{l \in L} \left(\frac{D_l}{Cap_l} \right) \tag{3}$$

Operator Cost Components (Min: Z2 = Costs + Emissions): The operator aims to minimize expenses associated with service provision, including train personnel, energy consumption, administrative overhead, track usage fees, and station management. Additionally, environmental impact, specifically CO2 emissions, is considered as part of the operator-related costs. Equations 4 and 5 define these cost components:

$$Costs = \sum_{l \in L} (2 * len_l * frq_l * SC) * (C^{oper} + C^{main}) \tag{4}$$

$$Emissions = \sum_{l \in L} (2 * len_l * frq_l * SC) * (Em^{oper} * VoC) \tag{5}$$

To ensure feasible and computationally manageable results, the model incorporates a series of constraints, categorized into three main areas: Capacity, Line Design, and Frequency. These constraints are crucial for structuring the problem and are implemented and satisfied during the algorithmic steps, as detailed in the following sections.

Capacity constraints in the TNDFSP context manage passenger flows at vertices, edges, and lines, aiming to prevent capacity overruns and maintain transit network integrity. For this research, line capacities must exceed the maximum number of passengers within an operational day to ensure the network can accommodate the maximum passenger flow at any segment of a line.

Line design constraints influence the project in two ways: by setting parameters for line design (such as length and number of stops) to improve solution feasibility, and by limiting the number of potential lines through transfer restrictions to reduce computational load.

While many TNDFSP studies focus on establishing a range of viable line frequencies and vehicle headways, this research does not consider these factors due to the extended time horizon and infrequent nature of long-distance travel. However, three essential requirements are maintained, regarding the computation of integer frequencies, specific lower bounds and symmetry maintenance. All the above described constraints are listed below (Equations 6 - 15):

- Maximum passenger flow at each line should not exceed its capacity
  $$Q_l \leq Cap_l, \quad \forall \quad l \in L \qquad (6)$$
- Minimum line length
  $$len_l \geq len_l^{min}, \quad \forall \quad l \in L \qquad (7)$$
- Maximum line length
  $$len_l \leq len_l^{max}, \quad \forall \quad l \in L \qquad (8)$$
- Minimum number of stops
  $$stops_l \geq stops_l^{min}, \quad \forall \quad l \in L \qquad (9)$$
- Maximum number of stops
  $$stops_l \leq stops_l^{max}, \quad \forall \quad l \in L \qquad (10)$$
- Line symmetry
  $$l_{m(i,j)} = l_{m(j,i)}, \quad \forall \quad i,j \in V \qquad (11)$$
- Maximum number of transfers
  $$n_{p^t}^{trf} \leq n_{p^t}^{trf,max}, \quad \forall \quad p^t \in P \qquad (12)$$
- Integer frequencies
  $$frq_l = \mathbb{Z}, \quad \forall \quad l \in L \qquad (13)$$
- Minimum frequency
  $$frq_l \geq frq_l^{min}, \quad \forall \quad l \in L \qquad (14)$$
- Frequency symmetry
  $$frq_{l(i,j)} = frq_{l(j,i)}, \quad \forall \quad i,j \in V \qquad (15)$$

C. Model Formulation

The methodology involves using predefined parameters and constraints to operate developed algorithms. These algorithms help in determining decision variables and the problem's objective values. The model formulated to address this problem emulates a manual optimization process, consisting of a sequential, integrated use of two algorithms. The process begins with the construction of the modified network layout, including the design of new lines and potential transfer options, and is followed by the calculation of suitable frequencies for the network, and ultimately, the determination of the objective values. In conventional optimization problems, these steps are typically automated by an optimization solver. However, due to the interdependent nature of the first objective function components, an automated approach is not feasible since the problem is not linear. Therefore, the steps are executed through algorithms in this manual optimization process.

To achieve this, extensive data processing and adjustment of model parameters are necessary to meet the model's constraints, determine the decision variables, and compute the objectives. Initiating this process requires defining the parameters from the model's dataset, which paves the way for generating new lines as well as all the possible travel paths. Subsequently, these paths are analyzed to determine the frequency of both existing and new line services. This process is facilitated by two constructed algorithms: the Line Generation Algorithm (LGA) and the Frequency Setting Algorithm (FSA) respectively.

The LGA is designed to create a modified network layout for high-speed rail services, enhancing area connectivity. The algorithm's steps are briefly explained below, and illustrated in Figure 4.

1. Graph Creation: A graph is constructed with cities as nodes and existing line connections as edges. Travel times, calculated based on distance and average vehicle speed, are assigned as weights to these edges.
2. Existing Network Tolerance: The algorithm integrates demand data with existing network capacities, converting train frequencies into passenger capacities. It assesses each vertex for capacity surplus or shortage, identifying where demand exceeds capacity and necessitates service redesign.
3. Analysis of Overloaded Vertices: Overloaded vertices are analyzed for all potential direct and indirect paths. The algorithm differentiates between OD pairs served by existing direct paths and those that are not, setting the stage for new line generation.
4. New Edges and Lines Generation: Paths serving unserved transfers are identified, prioritizing direct paths when more efficient. New potential lines are generated to expand the network.
5. Analysis of Missing Edges: The algorithm searches for missing edges in the expanded network, including non-overloaded vertices, to enhance connectivity. It creates reverse paths for existing ones, finalizing the network model.

FIGURE 4: Line Generation Algorithm inputs and outputs per step

The algorithm methodically develops an enhanced high-speed rail network by leveraging existing capacities, demand, and connections. It strategically adds new lines and paths to optimize travel times and address capacity issues, resulting in a comprehensive model that effectively aligns service optimization with passenger needs.

Following this, the FSA uses the potential paths identified by the LGA to determine the frequencies for lines in the modified network. The FSA aims to optimize the frequency of high-speed rail lines, taking into account the demand distribution and the capacity of the train fleet. It functions as a programmed algorithm, incorporating various parameters such as demand data, percentage adjustments, and detailed path information provided by the LGA.

The primary objective of the function is to calculate objective functions tailored to various demand scenarios and to establish the optimal service frequency for each chosen line. To achieve this, the algorithm modifies the base demand data by applying different percentage levels, effectively simulating a range of demand scenarios. This approach enables the algorithm to prepare for varying levels of passenger usage. The sequential steps of this process are explained below and presented in Figure 5.

1. Demand Distribution: It calculates demand between each pair of vertices along every computed path, distributing the demand based on the shortest path or equally among paths of the same length.
2. Maximum Passenger Flow: The algorithm identifies the segments of each line with the highest passenger flow by examining demand changes at each vertex.
3. Frequency Setting: Frequencies for each line are calculated to handle the maximum passenger flow, considering load factor and seating capacity. The frequencies are adjusted for full coverage and line symmetry.
4. Capacity and Demand Calculation: Before calculating the objectives, all frequency-dependent variables like capacity and demand at each vertex and line are computed.
5. Objective Calculation: The objectives are computed to maximize capacity utilization and minimize operator costs.

FIGURE 5: Frequency Setting Algorithm inputs and outputs per step

Pareto front analysis is used to find optimal solutions for the bi-objective problem, balancing network capacity utilization and operator costs. This analysis identifies a set of non-dominated solutions, each representing a different trade-off between the objectives. The Pareto front is constructed by evaluating potential solutions based on demand percentage distribution, visualizing the optimal trade-offs between network capacity and operational costs. Decision-makers can select a solution from the Pareto front that aligns with their strategic goals, considering the balance between maximizing capacity and minimizing costs.

D. Model Outputs

The outputs of the model, stemming from algorithmic processes and network designs, are vital for evaluating performance and comparing scenarios. These outputs integrate key performance indicators (KPIs) from both airline and transit systems, tailored to the unique context of long-distance High-Speed Rail (HSR) travel.

Objective values from the Pareto front analysis provide insights into the effectiveness of each scenario, balancing network capacity and operational costs. These values, Z1 and Z2, offer a performance score across different demand distributions, highlighting trade-offs between maximizing capacity and minimizing costs. This information is crucial for decision-makers to align strategies with operational goals under varying demand conditions.

The HSR network characteristics output details the structure and performance of the proposed solution. It includes the number of active lines and key attributes like distance, stops, and frequency. Additionally, vertex and line capacities assess the infrastructure's ability to meet demand, while utilization KPIs highlight critical network components.

From the HSR operator's perspective, the focus is on minimizing costs, considering both immediate operational expenses and long-term sustainability impacts. The KPIs related to operator costs provide a comprehensive view of network efficiency, factoring in both financial and environmental aspects. This approach supports decision-making for high-quality, sustainable service provision, aligning with diverse stakeholder interests.

IV. CASE STUDY

The contextual analysis for the case study applied in this research, details the geographical scope, the market of short-haul flights and existing HSR network infrastructure in Europe, the selected dataset, and the parameterization of network components and demand scenarios.

A. General Context

The study focuses on the European continent to analyze the potential of air-to-rail substitution of short-haul flights by HSR. The selection of countries includes the 27 EU Member States, with additions and exclusions based on specific criteria. Countries part of the European Free Trade Association (EFTA), EU candidate countries, and nations connected to the European rail networks, such as Belarus, Russia, and the UK, are considered. Countries with small populations, island nations, and territories under other countries' dependency are excluded. Due to the Russo-Ukrainian war and data reliability issues, Belarus, Ukraine, and Russia are also excluded. The study narrows its scope to mainland territories, excluding overseas territories and islands.

The study requires a consistent dataset at the continental scale, leading to the selection of Functional Urban Areas (FUAs) as the primary focus. FUAs are chosen over city and greater city levels to avoid biases associated with administrative boundaries and to better represent the catchment areas of international transportation hubs. FUAs, as defined by Eurostat, encompass densely populated urban centers and their surrounding commuting zones.

Furthermore, several assumptions are made to streamline the focus and manage the scope of the research. The study concentrates on large Functional Urban Areas (FUAs) across Europe to balance computational feasibility with comprehensive continental coverage. It considers only existing infrastructure and near-term expansion plans, excluding speculative future developments and restrictive policies that might affect network modifications. Passenger movements are treated uniformly, without distinguishing between origin-destination and transfer passengers, and are assumed to be consistent throughout the year, disregarding seasonal fluctuations. The selection of airports and rail stations is based on high passenger traffic, focusing on major travel hubs and the main rail station in each urban area. The study excludes night trains classified as high-speed services and, for the UK, only includes London due to its key role in the rail network and connections to Europe. These assumptions are designed to simplify the examined area while ensuring the research remains aligned with its primary goal of exploring the potential for air-to-rail substitution of short-haul flights by HSR.

B. Long-distance Travel Market in Europe

In the context of Europe's evolving long-distance travel market, there has been a significant shift from air to rail travel, particularly in response to climate change concerns and the need for sustainable transportation. European airports, such as London Heathrow, Frankfurt, Amsterdam Schiphol, and Paris Charles de Gaulle, have traditionally dominated the travel landscape, facilitating extensive air travel across the continent. However, the rise in air traffic and associated environmental impacts have led to a growing emphasis on high-speed rail (HSR) networks as a viable alternative. The expansion of these networks, particularly under the Trans-European Transport Network (TEN-T) initiative, reflects a concerted effort to enhance connectivity and sustainability in European transportation. Countries like Germany, France, Italy, and Spain have notably advanced their HSR infrastructure, offering a competitive and eco-friendly option for distances typically covered by short-haul flights. This shift represents a key aspect of Europe's strategy to develop a more integrated and environmentally responsible transport network.

C. Database Selection

For the selection of study's database, the process begins with the selection of urban areas based on population data from Eurostat's Urban Audit database, leading to an initial list of 119 urban areas. This list is narrowed down by considering the presence of both a railway station and an airport in each area. Railway stations are selected for their capacity to offer intercity and long-distance services, while airports are chosen based on a minimum annual passenger traffic of 5 million, using 2019 data to avoid Covid-19 pandemic anomalies.

The final dataset is further refined by linking these airports to the corresponding urban areas and including significant airports outside city catchment areas when necessary. The high-speed rail lines are identified through Rail Europe and verified with various operators' websites, ensuring a comprehensive collection of high-speed train itineraries for each origin-destination pair. This meticulous selection process results in a final dataset of 69 urban areas, complete with passenger movements and existing HSR services, excluding night trains.

D. Modelling Specifications

The problem parameters are primarily computed based on the dataset used in this research, which includes information on vertex country and coordinates, and existing HSR services and air passenger movements between these vertices respectively. However, parameters regarding the characteristics of the utilized for this work train model, as well as parameters associated with the operator costs are selected based on insights from various authors.

The parameters for the study are based on the current state of Europe's HSR network as well as current operations. In the context of high-speed trains, given that a variety of train models are operated by different providers across Europe, the task of selecting uniform vehicle parameters for a unified network presents unique challenges. To address this, a homogeneous fleet selection is adopted.

The train model selected for the study is the Frecciarossa 1000, used on Italy's high-speed tracks, chosen for its speed, efficiency, and capacity. The vehicle specifications include a seating capacity of 457, an operating speed of 220 km/h, and a load factor of 80% [32][33].

Cost parameters are derived from studies on current HSR systems in Europe, focusing on operational and maintenance costs per passenger-kilometer, excluding costs associated with the acquisition of rolling stock, due to the assumption of an existing fleet. Operational costs range from 0.078 to 0.177 euros per passenger-kilometer, and maintenance costs from 0.0050 to 0.0230 euros, with average values adopted for this study [34][35]. Regarding emissions, the study focuses on operational emissions while excluding emissions from rolling stock manufacturing and construction. The operational emissions average 5.7 grams of CO_2 per passenger-kilometer for French routes and vary between 39.2 to 42.9 grams for Chinese routes [21]. These emissions are converted into euros using a Value of Carbon metric, integrating environmental costs into the overall operational cost framework [36][37][38].

For the model's constraints, various specifications are set to ensure the practicality and relevance of the high-speed rail network design. The constraints for line design include a minimum line length of 200 km and a maximum of 1500 km. This range is chosen to avoid overlap with conventional train services and to keep travel distances within the range of short-haul flights. The model also specifies a minimum of 2 stops and a maximum of 5 stops per line, balancing the need for accessibility with the goal of maintaining competitive travel times.

Furthermore, the model restricts the number of transfers per journey to a maximum of one, aligning the travel experience more closely with the convenience of short-haul flights. In terms of frequency, each line must have a minimum operational frequency of 1 vehicle per day. These constraints collectively aim to create a balanced and efficient network design, avoiding a fragmented network of separate lines and promoting a holistic network perspective.

The study's demand scenarios are shaped by varying definitions of short-haul flights and influenced by policies like Austria's 3-hour train alternative ban and France's 2.5-hour direct rail service prohibition. The scenarios focus on areas within a maximum distance of 1000km, reflecting practical short-haul flight distances and feasible rail line properties.

The first scenario which concerns a base case network, targets the busiest airports in Central and Western Europe, specifically London, Paris, Amsterdam, and Frankfurt. It expands to include Brussels, Zurich, and Milan, examining the feasibility of replacing flights within a 500km radius. This scenario leverages the existing HSR network and focuses on areas with high passenger demand and geographical proximity.

The second scenario concerning an extended case network, broadens the scope to include intra-European flights, in line with the European Commission's 2050 vision for a shift from air to rail travel. This scenario incorporates Eastern European countries and regions around the Mediterranean, such as Prague, Vienna, Ljubljana, Barcelona, Madrid, and Lisbon. It also includes additional areas within countries already considered in the Base case, like Munich, Venice, and Toulouse. This expansion aims to create a more interconnected and sustainable travel infrastructure across Europe.

Both scenarios are designed to assess the potential for a partial shift from air to rail, with demand distributions ranging from an optimistic 100% to more realistic levels like 50%. They aim to provide a realistic evaluation of the feasibility of transitioning from air to rail travel, contributing to the goal of promoting sustainable mobility.

V. RESULTS & DISCUSSION

Following the collection of all necessary data for the selected case study, and the parameterisation of various model characteristics as described in the previous chapter, the supply-based model was developed and tested. Firstly, the performance of the existing network for each scenario based on the analysis regarding the ability to serve the influx of short-haul travel passenger demand is examined. Following, the route possibilities of the selected scenario networks for demand overloaded FUAs are generated, resulting from the design of new lines. Afterwards, the design characteristics of the modified networks are explained, based on the distribution of the passenger demand to the activated lines. Finally, the insights regarding the optimal solution outcomes where a balance between capacity utilization and operator costs can be achieved based on different stakeholder perspectives as well as the eventual performance of the networks are analysed.

A. Network Tolerance

The study's assessment of network tolerance focuses on the network's capacity to accommodate passenger demand from short-haul flights, as the first step on the Line Generation Algorithm. Current rail services are insufficient to meet both existing and anticipated air traffic demands. However, adjustments to service itineraries in certain urban areas with larger rail stations might accommodate both demands. Passenger demand at each node is based on boarding or alighting passengers, while capacity is calculated from the total number of vehicles operating in the area and their seating capacity. The difference between node demand and capacity indicates capacity surplus or shortage, with overloaded nodes being of particular interest.

In the first scenario, the network is overloaded by 20%, with several nodes unable to handle the increased passenger traffic as presented in Table 3. Amsterdam, London, and Milan are particularly overloaded, exceeding their capacity by more than 70%. This overload is attributed to high demand levels and limited service operations to other destinations. The findings suggest a need for new lines to increase service options and facilitate more direct routes.

TABLE 3: Network tolerance (Scenario 1)

Nodes	**Surplus/Shortage (%)**
Amsterdam	-72.66
Brussels	35.26
Frankfurt am Main	-7.12
London	-125.72
Milan	-90.34
Paris	7.72
Zurich	-5.90
Total	**-20.04**

The network of the second scenario, despite being larger, has a sufficient capacity surplus of 18%. This indicates a well-balanced integration of new nodes and existing lines, allowing accommodation of new demand in certain areas. However, Amsterdam, London, and Zurich remain overloaded. In contrast, Frankfurt am Main and Milan, previously overloaded, now meet demand, likely due to their central location and additional lines. Paris shows a slight overload, while Brussels maintains sufficient capacity. Most newly included areas meet demand, but Barcelona, Budapest, Copenhagen, Ljubljana, Lisbon, Nice, Porto, Toulouse, and Warsaw show capacity shortages, indicating a need for new lines or transfer paths. Copenhagen, with no existing lines, requires new connections to meet demand. The network's tolerance levels are detailed in Table 4.

TABLE 4: Network tolerance (Scenario 2)

Nodes	Surplus/Shortage (%)
Amsterdam	-142.99
Barcelona	-14.65
Berlin	11.67
Brussels	42.51
Budapest	-18.52
Copenhagen	-
Frankfurt am Main	23.02
Lisbon	-15.99
Ljubljana	-224.84
London	-110.62
Luxembourg City	40.28
Madrid	47.19
Milan	63.38
Munich	31.00
Nice	-253.83
Paris	-2.31
Porto	-20.23
Prague	9.10
Rome	69.13
Seville	60.52
Toulouse	-53.52
Venice	63.25
Vienna	22.32
Warsaw	-1.56
Zurich	-64.89
Total	**18.30**

B. Generated Lines and Route Alternatives

In this stage, the algorithm addresses overloaded nodes by determining how to meet demand for destinations lacking direct services. This involves either combining two existing lines or creating new ones. OD demand pairs are categorized based on whether they are served by direct paths, need transfers, or require new lines. The next step involves using Dijkstra's shortest path algorithm to analyze paths for unserved pairs, incorporating these as new lines in the network. All paths, existing and new, form a preliminary set of route alternatives. This set is then evaluated to ensure it satisfies the OD demand pairs for all nodes, adding reverse paths or creating new lines as needed until a comprehensive set of route alternatives is established.

In the first scenario, the existing network is dense, and it's expected that most OD pairs with overloaded nodes can be served through direct paths or single transfers. The algorithm confirms this, with only one OD pair (London - Milan) unserved by either direct or transfer paths. Out of 30 pairs involving overloaded nodes, 17 are served by direct paths, and 11 by combinations of lines. The London - Milan pair and its reverse are the only unserved ones, requiring a new direct line. The final set of alternatives includes all 30 pairs associated with overloaded nodes. Further assessment of nodes without capacity shortage reveals two more unserved pairs (Brussels - Milan and Paris - Milan), whose reverse pairs are covered by different transfer paths. These reverse paths are added to the new set of alternatives, resulting in a total of 77 paths, including 22 direct and 55 transfer paths.

In the second scenario, the network's tolerance levels show insufficient connections in multiple areas. Despite generating all possible paths, 38 OD pairs associated with overloaded nodes remain unserved. Out of 312 pairs generated by these nodes, 98 are served by direct paths, and 176 by combinations of lines with single transfers. Notably, for London and Paris, all unserved paths could be met by single transfer paths, so no new lines involving these areas were generated. However, for Copenhagen, three new lines are generated. The unserved pairs mainly involve Lisbon, Ljubljana, Nice, Toulouse, and Warsaw, each with two pairs needing new lines. The created lines are presented in Table 6. The final assessment of nodes without capacity shortages shows that out of 288 pairs, 232 could be served by existing services and newly generated lines. The remaining 56 pairs are covered by creating reverse paths. The final set comprises 710 total paths, with 174 direct and 536 transfer paths.

C. Modified Network Configuration

The set of route alternatives generated by the LGA, is integrated into the FSA. This includes total available lines, demand per OD pair and per node, vehicle characteristics, and objective-related parameters. The algorithm allocates demand across nodes, prioritizing shortest travel time paths. It then converts path-level demands into line-level demands for calculating total demand on each active line and finally computes the network configurations and objective values for each demand distribution percentage. For the first scenario the following results are computed:

- Activated Paths and Lines: 42 out of 77 paths are activated, involving all 22 lines. This indicates efficient existing operational services.
- Network Characteristics: The addition of a single line and its reverse highlights minimal new routes. The network can be divided into two line types: (i) long lines (around 1000km), connecting core lines and integrating new cities, and (ii) shorter core lines (200-500km) with frequent, bi-hourly services.
- Capacity and Frequency Analysis: The network shows a balanced capacity, with most nodes handling around 60 trains per day. The busiest route is Amsterdam-Brussels. Paris and Frankfurt are key transfer nodes.

From Figure 6, where the characteristics of the networks for the solution with a demand distribution of 69% and a balanced combination of capacity utilization and operator costs (as calculated from the Pareto analysis) are depicted, it can be observed that most lines cover short distances, and that capacity is distributed fairly balanced across the network.

In the modified network, as visualized in Figure 7, the addition of a new line between London and Milan addresses direct demand between these cities but is inefficient for longer, indirect routes due to length restrictions. The network's frequency adjustment shows a balanced vehicle distribution, with the Amsterdam-Brussels route being the busiest, indicating high usage, and the London-Milan route having the least, reflecting its specific travel pattern. Central nodes like Paris and Frankfurt are crucial for facilitating transfers to distant locations, with some lines operating up to

14 vehicles daily, underscoring their importance in the network's overall connectivity and efficiency.

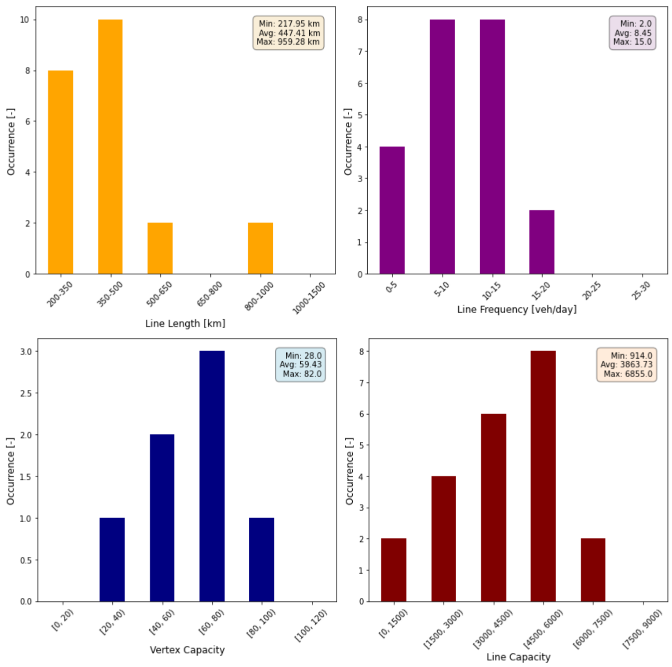

FIGURE 6: Network design and capacity properties (Scenario 1 - Pareto optimal solution "P7")

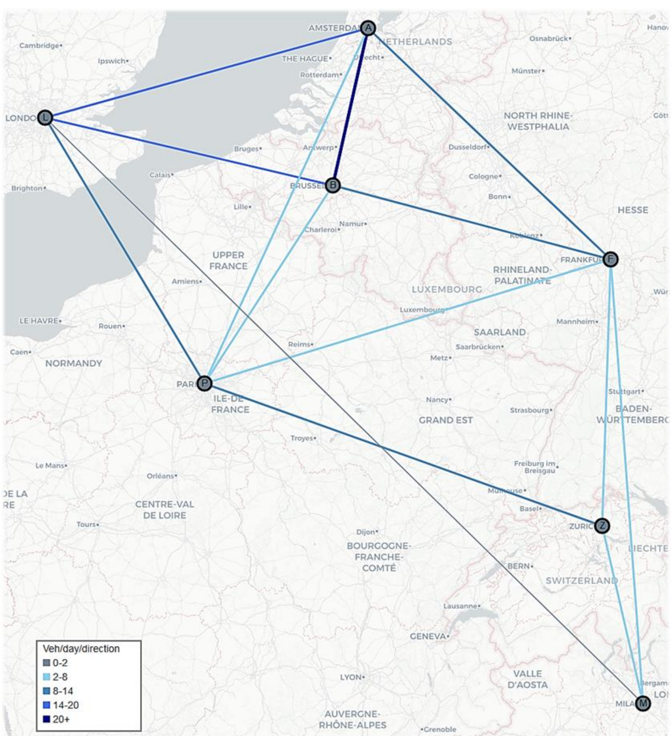

FIGURE 7: Modified network map (Scenario 1 - Pareto optimal solution "P7")

Similarly, the results from the simulation of the second scenario are the following:

- ❖ Activated Paths and Lines: 86 out of 355 paths are activated, mostly direct paths, reflecting the necessity for new lines.
- ❖ Network Characteristics: The network features a variety of lines, with a significant number of new lines due to initial service deficiencies. The network can be divided into three line types: (i) long lines (over 800km), connecting core lines and integrating new cities, (ii) medium length lines with average frequencies, offering direct services and acting as transfer lines, and (iii) shorter lines, less than 500km, operating with low frequency.
- ❖ Capacity and Frequency Analysis: The network shows a higher average capacity than Scenario 1, with Frankfurt am Main and Paris as central hubs. Central European connections are most active.

From Figure 8, where the characteristics of the networks for the solution with a demand distribution of 91% are depicted, it can be observed that most lines cover short distances, and that capacity is distributed fairly balanced across the network.

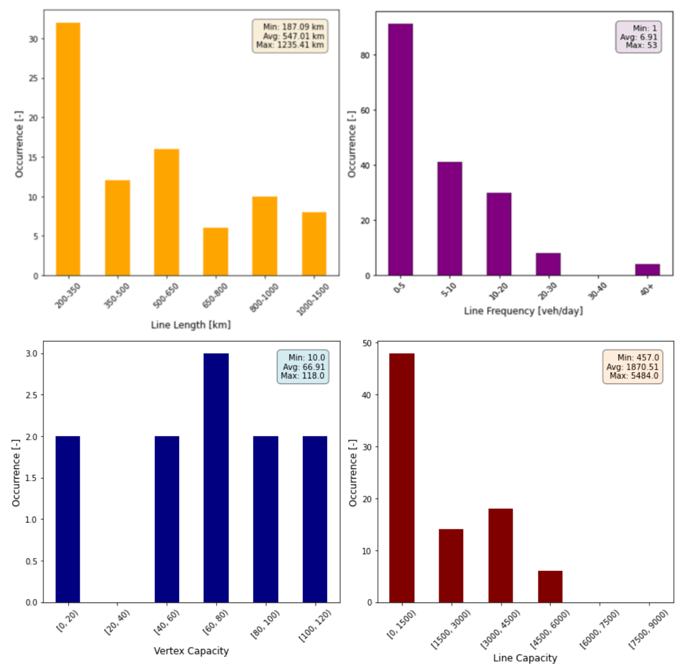

FIGURE 8: Network design and capacity properties (Scenario 2 - Pareto optimal solution "P4")

The modified network, as depicted in Figure 9, shows significant improvements in connectivity, particularly in overloaded areas, with new lines enhancing interconnections, especially in the southwest and northern regions of the continent. Cities like Copenhagen are now directly linked to multiple central locations, boosting network integration. The central network has become more robust, offering smoother and diverse transfer options, beneficial for both single and double-transfer journeys to distant destinations.

Network service adjustments have resulted in a more balanced vehicle operation distribution. Central European connections, especially in Germany and Italy, are highly active, with key cities like Berlin, Frankfurt, Munich, Milan, Venice, and Rome experiencing high traffic due to their roles in direct travel and as transfer points. The Brussels-Paris connection is notable for facilitating travel to nearby areas and southward routes.

While most network connections maintain a moderate service frequency, averaging 2 to 8 trains per day, central-eastern connections have sparser services, reflecting the lower demand in Eastern European cities. This indicates a tailored approach to service provision, aligning with the varying demand levels across different network regions.

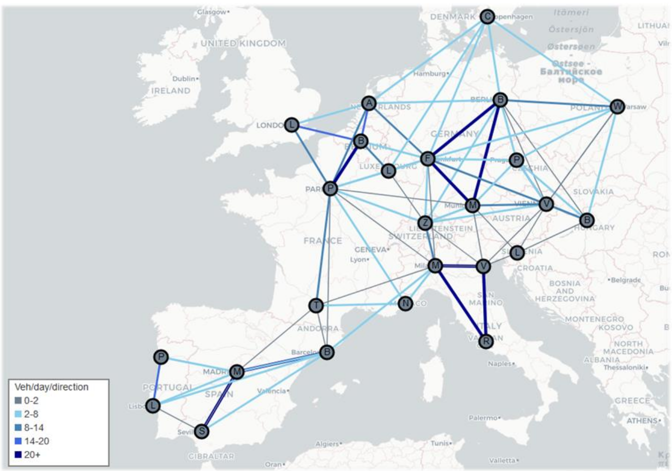

FIGURE 9: Modified network map
(Scenario 2 - Pareto optimal solution "P4")

D. Network Performance

The balanced solutions for the different set of solutions for each demand distribution percentage, are identified by the Pareto front analysis.

For the first scenario 16 Pareto optimal solutions are identified. Overall, it can be observed that operator costs decrease as demand distribution is reduced. This is due to fewer active lines and reduced frequencies needed to meet lower passenger numbers. Moreover, there's a notable increase in capacity utilization as demand drops. This is because line capacities, determined by multiplying frequencies by full seat availability, often result in surplus capacity. However, a sudden drop in capacity utilization is observed, which occurs when certain lines stop requiring additional services, leading to more efficient use of capacity. Figure 10 illustrates the Pareto front with the full set of computed solutions for this scenario.

For the second scenario, 17 Pareto optimal solutions are identified, mostly at higher demand percentages. These solutions reflect the network's challenge in balancing high demand with cost-effective service frequencies. Similarly to the first scenario, operator costs steadily decrease with reduced demand, while the transition in capacity utilization is smoother. Utilization ranges from 115 to 140, with a notable increase from Scenario 1. The sudden drop in capacity utilization is less pronounced in this scenario, attributed to the more extensive network and higher demand levels.

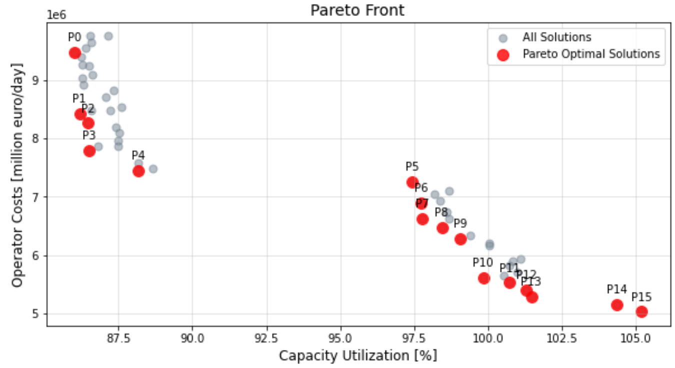

FIGURE 10: Pareto optimal solutions for capacity utilization maximization vs cost minimization (Scenario 1)

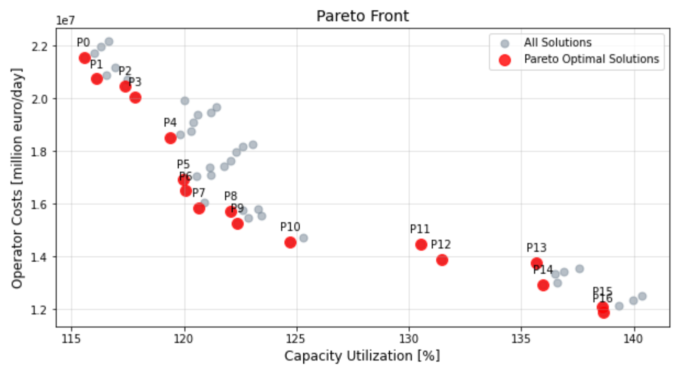

FIGURE 11: Pareto optimal solutions for capacity utilization maximization vs cost minimization (Scenario 2)

Ultimately, the study led to the development of two distinct high-level and functional networks, each with its unique design characteristics and performance measurements. Despite their similarities in overall structure, they displayed notable differences in specific design details. The simpler network in Scenario 1 was less developed compared to the more advanced network in Scenario 2. This advancement in Scenario 2 was particularly evident in the increased number of lines, connected vertices, and reachable OD pairs, showcasing the model's effectiveness in expanding the network's infrastructure.

Both networks, despite their varying degrees of complexity, maintained a similar layout, which allowed for a comparative analysis. Their visualizations offered insights into the network's shape, dimensions, and focal points. A key observation across both scenarios was the prevalence of lines that traverse a limited number of countries, highlighting low interoperability and cross-border cooperation in the network's design. This was expected due to the low number of vertices and existing operational services with a limited number of stops. However, both scenarios successfully designed lines across the entire simulated area, ensuring service coverage for every part of the continent.

In analyzing the network's design, three main behavioral aspects emerged: Firstly, there was an increase in network density towards the geographical center, with Germany being a prime example, suggesting a strategic focus on high-demand areas. Secondly, the network's extensiveness and density were skewed towards the west, attributed to the lower demand in Eastern Europe compared to the western part of the continent. This geographical imbalance impacted the network's layout, leading to a denser network in the west. Lastly, the selective generation of new lines was observed, especially for cities with low proximity and lacking existing services. This approach helped avoid overloading central nodes, maintaining network efficiency, but also led to higher operational and maintenance costs.

Performance-wise, the networks exhibited differences and similarities. In terms of network coverage, Scenario 1 achieved complete coverage, serving all OD pairs efficiently. In contrast, Scenario 2, characterized by a larger-scale network, was insufficient in network coverage due to several unserved OD pairs. Regarding network capacity utilization, Scenario 1, with its simpler design, showed superior performance but had limited scope for accommodating future increases in passenger numbers. On the other hand, Scenario 2's extended network faced excess demand on certain lines but had the potential to absorb additional demand, thanks to a more even distribution of vehicles across the network.

VI. CONCLUSIONS

This study developed a customized model adapting the TNDFSP in a long-distance transport environment for high-speed rail, focusing on optimizing existing infrastructure instead of designing networks from the start. This was achieved by analyzing the potential impacts of enhancing HSR infrastructure and defining optimal network configurations that consider both physical attributes and sustainability aspects.

The research reveals that the decision to replace short-haul air travel with rail is influenced by a diverse array of factors, including travel time, environmental concerns, service quality, availability of rail infrastructure, and economic considerations. These factors were crucial in developing realistic scenarios for the study, ranging from optimistic to more pragmatic transition levels. The findings indicate that while a complete air-to-rail transition on a continental scale is unfeasible due to practical constraints, significant shifts from air to rail are possible and can be effectively facilitated through carefully crafted scenarios.

In terms of the strategic planning phase for redesigning the continental HSR network, the study identifies two pivotal aspects: the physical infrastructure, including rail tracks and stations, and high-level operational elements like the type and number of services. The research underscores the importance of line capacity and frequency adjustments in network modifications, revealing that these elements have a more pronounced impact on network efficiency and operational costs compared to station capacity.

The key modifications necessary for overcoming capacity limitations in HSR network infrastructure were also examined. It presents two distinct scenarios: one with minimal expansion of the existing network and another with significant redesign, including the introduction of new lines. These scenarios demonstrate the importance of strategic network design, balancing efficiency with expansion to optimize capabilities and meet regional demands.

Evaluating the performance of the redesigned networks in terms of transport efficiency and economic sustainability, the study finds that networks with lower operational and maintenance costs due to fewer operating trains indicate greater economic sustainability. However, the performance of these networks is complex, with no single alternative excelling across all metrics. The first scenario, with its simpler design, incurs higher operational costs due to the necessity for more operating trains. In contrast, the second scenario, despite its expansive nature, shows an advantage in operational cost-efficiency.

Overall, the research provides a nuanced understanding of the challenges and opportunities in transitioning from air to rail travel in Europe. It highlights the need for strategic planning and adaptability in network design to create efficient, sustainable transportation systems. The study's insights are invaluable for stakeholders, offering guidance in making informed decisions about network designs and underscoring the importance of balancing operational efficiency, coverage, and cost-effectiveness in the development and management of HSR networks. The findings pave the way for future research, building upon the results to further explore and refine strategies for a sustainable and efficient transportation future in Europe.

From a practical standpoint, the study's findings are crucial for long-distance transportation, particularly in addressing the environmental drawbacks of air travel. The research underscores the necessity of enhancing HSR infrastructure as a competitive and appealing alternative for international travel, contributing to the transportation industry's sustainability. The transition from air to rail is heavily dependent on the current state of the HSR network, especially the configurations of operating lines. Many existing lines are currently insufficient for such a transition due to capacity limitations. This research provides valuable guidance for efficient network improvements, addressing challenges of limited capacity and the complexity and expense of related projects. The diversity in infrastructure development levels and transition stages across different locations necessitates tailored approaches. Developed and smaller networks typically require fewer modifications, while larger networks with diverse infrastructures are more prone to changes.

For policy-making, the study's scenarios, considering different demand distributions following environmental concerns and policies within Europe, are particularly noteworthy. The computed solutions offer multiple alternatives, allowing stakeholders to select the most suitable one based on their priorities. This flexibility is crucial for policy-making, providing a framework for decision-makers to balance environmental objectives with the practicalities of HSR network design and operation. The balance between network density, service coverage, and operational costs is vital for the sustainable development of unified HSR networks. These insights emphasize the need for adaptable and forward-thinking strategies in railway capacity planning, addressing the dynamic and diverse needs of modern mobility. The research underscores the potential of simulation models in aiding decision-makers to optimize network designs for current and future transportation challenges.

In this research, key limitations emerged, highlighting the complexities of simulating supply-based network design problems and pointing towards areas for future exploration. The primary challenge was applying traditional optimization methods to a non-linear problem, particularly in maximizing capacity utilization. This led to the development of the Frequency Setting Algorithm as a manual approach. Future research could explore more effective optimization techniques for handling such non-linear complexities. Additionally, the study's assumptions and simplifications, necessary for a continental-scale design, focused on the supply perspective, excluding detailed user characteristics and societal impacts. This suggests that future studies could enrich the research by incorporating a broader range of factors, including user preferences, operational strategies, and varying demand patterns, to provide a more comprehensive view of the network.

Furthermore, the algorithms developed faced computational limitations in handling large-scale design problems, particularly relevant given the study's aim to design a continental-scale intra-European network. Refining these algorithms or exploring new computational methods could be a focus for future research. The decision to enable only single transfer routes within the network also emerged as a significant limitation, hindering the network's ability to meet demands for distant pairs. Allowing multiple transfers in future simulations could yield more realistic results and contribute to a more interconnected network.

In summary, while this research faced various challenges, these limitations, coupled with the findings, present opportunities for further exploration and innovation in HSR network design, potentially leading to more advanced and holistic solutions.

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