A Unified Design of the European High-Speed Rail Network

Impacts of Design, Pricing and Governance Strategies

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A Unified Design of the European High-Speed Rail Network

Impacts of Design, Pricing and Governance Strategies

by

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Preface

Dear reader,

Before you lies my thesis on the design of line configurations for the European high-speed rail network; the final piece for the master's programme of Transport, Infrastructure and Logistics at Delft University of Technology. This report concludes the research that I have been working for the last months, but even more, my student time in Delft. A valuable experience on both academic and personal fields that I have had the chance to enjoy since September 2013.

Starting my time Delft with a bachelor in Civil Engineering, I developed a passion for the combination of technically challenging subjects that have a direct impact on society. Something that I found within the fascinating domain of transportation, which, for me, combines the best of both worlds. An excellent example of this concerns the topic of high-speed rail: A promising solution to connect the ever-shrinking world in a sustainable way - to make sure that future generations can enjoy this place as much as we do - but that also requires great efforts for its complexity.

This research was conducted at Royal HaskoningDHV and TU Delft, two institutions I experienced to have an excellent atmosphere. I want to thank all of the colleagues, educators and fellow students for their support I experienced during the process of this thesis. More specifically, my gratitude goes out to my graduation committee - Oded Cats, Mark Duinkerken, Jan Anne Annema and Barth Donners - who showed me the possible directions, were always happy to help, gave wise advice and guidance when necessary, but also allowed me the freedom to develop my individual work.

Finally, I would like to thank all the friends and family I feel happily surrounded by. Every day again, even in these extraordinary days. In this, a special word of thanks goes out to my dear grandparents Hans, Kick, Jaap and Heinke, mother Sandra, father Hans and sister Rosanne, whose hard work allowed me the opportunities I got and whose love and support helped me to make a strong basis for further steps.

I wish you a pleasant reading.

Delft, November 2020
Jorik Grolle

Abstract

High-speed rail (HSR) is frequently seen as a promising alternative for long-distance travel by air and road, given its environmental advantages whilst offering a competitive level of service. However, due to a lack of knowledge on the design of HSR specific line configurations and the prioritisation of national and railway company interests, no real European HSR network has been realised yet. Together, these lead to a sub-optimal performance from a user, operator and societal perspective.

This research is the first attempt to apply the more frequently used '*Transit Network Design and Frequency Setting Problem*' (TNDFSP) in an HSR setting, which searches the ideal set of lines and associated frequencies in a given network. To do so, this study developed a novel HSR generic model and solution algorithm, which were then parameterised for the European case. By benchmarking the current situation; analysing the relative importance of vehicle, passenger path and line design variables; evaluating pricing and governance strategies; and finally proposing improved settings; it was possible to assess impacts of improved design. The experiments showed that benefits for all stakeholders could be simultaneously enhanced when implementing a centralised governance and internalisation of external costs. This allowed the HSR market share to evolve from 14.7% to 29.9%, whilst also improving the societal cost-benefit ratio by 20.0%. The governmental investment which is required to fill the gap from the most economical to the most extensive solution equals € 2.2 billion per year, but also provides a positive rate of return of 1.8 for the combined user and societal benefits. Additionally, the model demonstrated the necessity of spilling unprofitable passengers and the importance of improved cooperation. These followed from the strong network integration with overlapping and border crossing lines of substantial lengths, the contradiction between national and international interests and the high number of critical infrastructural elements.

All in all, this study demonstrated the possibility of using the TNDFSP in an HSR setting, which opens ways for further understanding of HSR network design. For this specific research, it allowed the identification of substantial opportunities for mobility and sustainability. These can be reached by improved design choices, internalisation of external costs and by relaxation of the desires for a competitive railway market and national sovereignty; all newly underpinned arguments for the discussion on how to design a successful (European) HSR system. Future research could greatly contribute by incorporating the construction of infrastructure, including timetabling or operational aspects, assessing different case studies in size and geography or introducing new technologies.

Keywords
High-Speed Rail , Europe , Network Design , Line Configurations , TNDFSP , Pricing , Governance

Research article
For a more detailed summary, the research article associated to this thesis can be found in *appendix A*

Table of Contents

Preface i

Abstract iii

Table of Contents vi

List of Figures vii

List of Tables ix

1 Introduction 1
- 1.1 Background Exploration . . . 1
- 1.2 Problem Definition . . . 3
- 1.3 Research Characteristics . . . 4
- 1.4 Research and Report Architecture. . . . 7

2 Literature Review 9
- 2.1 Design of Transit Systems and Research Field Identification . . . 9
- 2.2 Definition of the TNDFSP . . . 11
- 2.3 Components of the TNDFSP . . . 13
- 2.4 Problem Solution Strategies . . . 17
- 2.5 Solution Performance Measurement . . . 22
- 2.6 Research Positioning and Contribution . . . 23

3 Methodology 27
- 3.1 Approach . . . 27
- 3.2 Problem Definition . . . 29
- 3.3 Model Formulation . . . 40
- 3.4 Experimental Set-Up . . . 54

4 Case Study of the European Network 57
- 4.1 Vertex Specifications . . . 57
- 4.2 Edge Specifications . . . 60
- 4.3 Mode Specifications . . . 63
- 4.4 Stakeholder Specifications. . . . 66
- 4.5 Constraint Specifications. . . . 67
- 4.6 Demand Estimations . . . 68

5 Validation 71
- 5.1 Model Implementation and Performance . . . 71
- 5.2 Model Behaviour and Necessity of Passenger Path Control . . . 75
- 5.3 Resulting Method Adjustments . . . 80

6 Results 81
- 6.1 Benchmarking the Initial Performance. . . . 81
- 6.2 Effects of Pricing and Governance Strategies . . . 82
- 6.3 Effects of HSR Vehicle, Line and Passenger Design Variables . . . 84
- 6.4 Potential Impacts and Characteristics of Improved Design. . . . 86

7 Conclusions 95
- 7.1 Key Findings of this Research . . . 95
- 7.2 Interpretations and Implications . . . 98
- 7.3 Limitations and Recommendations . . . 99

Bibliography **103**

A Research Article **III**

B Demand Estimation Methodology **XXI**

C Detailed Results of the Analysis on Governance and Pricing Strategies **XXIX**

D Detailed Results of the Analysis on High-Speed Rail Design Variables **XLV**

E Simulation Results of Initial and Synthesis Scenarios **LVII**

List of Figures

1.1 Trans-European High-Speed Rail network 2
1.2 The European High-Speed Rail network: a patchwork of smaller sub-networks 2

2.1 Hierarchical Public Transport Planning Concept 9
2.2 Framework of Transit Network Planning Problems (TNPP) 10
2.3 Schematic overview of high-level multi-sub-problem TNPP's 11
2.4 Three layer framework for the TNDFSP 13
2.5 Overview of problem solution strategies 18
2.6 Typical Line Generation & Configuration (LGP) scheme 19
2.7 Typical Line Construction and Improvement Scheme 21

3.2 Proposed high-level solution approach 41
3.3 Flowchart of the customised Line Generation Procedure (LGP) 42
3.4 Flowchart of the customised Line Configuration Procedure (LCP) 42
3.5 Flowchart of the customised the Network Analysis Procedure (NAP) 42
3.6 Legend for the flowchart components 42
3.7 Examplementary graph 43
3.8 Examplementary demand matrix 43
3.10 Example matrix shortest path 45
3.11 Example matrix estimated aggregated demand per edge 45
3.12 Example matrix estimated usage per edge/distance 45
3.13 Example normalised usage matrix 45
3.14 Example matrix inverted usage per edge/distance 46
3.15 Example matrix normalised riding times per edge 46
3.16 Example matrix combined edge weights 46
3.17 Example: Demand-Based Path matrix $DP^{ex.}$ 46
3.18 Line Configuration Procedure (LCP) in extended detail 47
3.19 Example of a Line Activation Operation (LAO) neighbourhood 48
3.20 Example of a Line Deactivation Operation (LDO) neighbourhood 49
3.21 Example of a Line Substitution Operation (LSO) neighbourhood 49
3.23 Flowchart of the Trip Demand Assignment operation 51
3.24 Overview of modelled pricing and governance scenarios 55
3.25 Overview of modelled HSR design variable scenarios 56

4.1 Map of the cities and airports that are considered in this study 58
4.2 Geographical location of the model's vertices 59
4.6 Visualisation of inner city access/egress modelling 60
4.7 Example: access/egress times for Berlin city-centre and surrounding airports 60
4.8 Example: Access/egress car paths for Berlin 60
4.9 Network of air connections between main European airports 61
4.10 Network of railway infrastructure between selected core cities 62
4.11 Visualised vehicle trip phases for air travel 63
4.12 Visualised vehicle trip phases for high-speed rail travel 65
4.13 Proposed demand estimation methodology 69

5.1 Resulting heuristic log process for the validation case 72
5.2 Performance comparison of heuristic and exhaustive search for validation case 73
5.3 Modal split per distance for long distance travel, determination of previous research . . 75
5.4 Development of separate island networks for not-adjusted simulations 76

5.5 Visualisation of different passenger detour paths 77
5.8 Visualised impacts of subsidisation measures 78
5.10 Visualised impacts of strategic pricing measures 80

6.3 Transit map of the ‘*Extensive*’ high-speed rail network 88
6.4 Distribution of typical line lengths 89
6.5 Distribution of typical line frequencies 89
6.6 Distribution of typical Number of stops per line 89
6.7 Map with vertex and edge characteristics of the ‘*Extensive*’ HSR network 90
6.8 Measured modal split per distance for different network strategies 92
6.9 Typical development of main cost components 93
6.10 Typical development of user cost components 93
6.11 Typical development of operator cost components 93
6.12 Typical development of societal cost components 93

B.2 Example case: City-Airport systems for London and Rotterdam XXIII

C.2 Map of vertex and edge characteristics for the base scenario XXX
C.3 Overview of developed networks for different policy scenario XXXI
C.9 Iteration development for the number of lines XXXII
C.10 Iteration development for the number of reachable OD’s XXXIII
C.11 Comparison of objective function and actual cost development XXXIV
C.13 Iteration development for the main costs components XXXIV
C.14 Iteration development for the user costs components XXXVI
C.15 Iteration development for the operator costs components XXXVI
C.16 Iteration development for the societal costs components XXXVI
C.17 Developed line plan overview with distance and occupation per line leg XXXVII
C.18 Iteration development for the operator’s efficiency XXXVIII
C.19 Distribution of line lengths XXXIX
C.20 Distribution of the number of stops per line XL
C.21 Distribution of the vehicle frequency per line XLI
C.22 Iteration development for the share of transfer passengers XLI
C.23 Iteration development for the modal split per trip XLII
C.24 Iteration development for the modal split per distance XLIII

D.2 Impacts of controlling the vehicle cruising speed XLVI
D.4 Impacts of controlling the vehicle seating capacity XLVII
D.6 Impacts of controlling the maximum number of transfers XLVIII
D.8 Impacts of controlling the average transfer time XLVIII
D.10 Impacts of controlling the geographically detouring passengers XLIX
D.12 Impacts of controlling the infrastructurally detouring passengers L
D.14 Impacts of controlling the minimum number of stops per line LI
D.16 Impacts of controlling the degree of demand-based line design LII
D.18 Impacts of controlling the allowable geographical line detour LIII
D.20 Impacts of controlling the allowable infrastructural line detour LIII

List of Tables

2.1 Review papers covering high-level Transit Network Planning Problems 12
2.2 Frequently used TNDFSP objective function cost components 14
2.3 Frequently used TNDFSP constraint type divisions 17
2.4 Frequently used airline KPIs 22
2.5 Frequently used transit KPIs 23
2.6 Scientific context of this research 24

3.1 Overview of this model’s indices and sets 30
3.2 Overview of this model’s vertex parameters 31
3.3 Overview of this model’s edge parameters 31
3.4 Overview of this model’s line parameters 32
3.5 Overview of this model’s mode parameters 33
3.6 Overview of this model’s demand parameters 34
3.7 Overview of this model’s decision variables 34
3.8 Overview of this model’s line design constraints 38
3.9 Overview of this model’s frequency and timetable Constraints 39
3.10 Overview of this model’s passenger path constraints 40
3.13 Overview of this model’s output parameters 54

4.1 Example values for measured in-vehicle travel time duration by car 62
4.3 Example values for estimated in-vehicle travel time duration by airplane 64
4.5 Travel time components and vehicle characteristics of air travel 64
4.6 Travel time components and vehicle characteristics of car travel 64
4.7 Travel time components and vehicle characteristics of high-speed train travel 65
4.8 User costs factors: Value of time for long distance travellers per trip component 66
4.9 Operator cost factors: Marginal operational and maintenance costs 66
4.10 Societal cost factors: Average external costs for transport per category and mode . . . 67
4.11 Overview of parameterised constraints 68

5.1 Resulting ‘*Pool of Lines*’ for the validation case 71
5.2 Final line configuration for the validation case 73
5.3 Selected 50 key-cities for computation control 74
5.4 Overview of proposed adjustments to the model, based on the method validation 80

6.1 Observed KPIs for the estimation of the initial network 81
6.2 Measured effects of pricing and governance strategies 83
6.3 Measured relations between HSR design variables and KPIs 85
6.4 Proposed synthesised scenarios and their associated settings 87
6.5 Descriptive characteristics of the developed synthesis networks 91
6.6 Stakeholder-financial characteristics of the developed synthesis networks 92

7.1 Overview of the research’s limitations 102

B.1 Example: Access / Egress times for London and Rotterdam airport system XXIII
B.3 Example: flight path possibilities and duration between London and Rotterdam XXIV
B.5 Example: estimated duration, probabilities and potential for London-Rotterdam XXVII

C.1 Developed policy scenarios: number of Lines XXXII
C.2 Developed policy scenarios: reachable OD’s XXXIII
C.3 Developed policy scenarios: main costs components XXXIV

C.4 Developed policy scenarios: societal costs XXXVI
C.5 Developed policy scenarios: operator’s efficiency KPIs XXXVIII
C.6 Developed policy scenarios: line length characteristics XXXIX
C.7 Developed policy scenarios: line stop characteristics XL
C.8 Developed policy scenarios: line frequency characteristics XLI
C.9 Developed policy scenarios: passenger transfer behaviour XLI
C.10 Developed policy scenarios: modal splits per trip XLII
C.11 Developed policy scenarios: modal split per distance XLIII

1

Introduction

High-speed rail, being part broader scientific and practical contextual region, can be assessed from a variety of perspectives. The goal of this introductory chapter is to present the perspectives taken by and underlying motives of this research. To get here, the chapter starts with a background exploration that is performed in *section 1.1*, which assess the current state on long-distance mobility and HSR practices on the European continent. *section 1.2* gives a continuation of this by defining the exact problems that require more profound research. Following this, *section 1.3* delineates the exact boundaries of this research by stating the knowledge gaps, objectives and research question that fill these gaps. To conclude, *section 1.4* finalises this chapter by providing an overview of the used structure.

1.1. Background Exploration

High-speed rail networks are part of a larger system that serves the demand for long-distance mobility, making them subject to a range of wider global developments. This section does the first search into this complicated playing field by performing an exploration of the relevant background areas.

Evolutionary growth of long-distance mobility

It is 2020, and the world is smaller than ever before. Over the last century, travelling over longer distances has become more and more common, a development that would not have been possible without aviation. Since its first commercial flights, the airline industry has experienced an impressive and almost constantly exponential growth (The World Bank, 2020).

This evolutionary growth of global mobility comes with its benefits and disadvantages. Contributing to multiple factors, the airline industry proved to be valuable in increasing social cohesion by providing accessibility, supporting economies and pushing technological advancements. (Caves, 1994). However, during the more recent years, society has become more aware of the negative impacts that this travel behaviour has on the environment. Externalities ranging from the depletion of finite natural resources, noise pollution and most of all the emission of greenhouse gasses that contribute to climate change (Janić, 1999), make that society has slowly started to re-evaluate its travel habits.

High-speed rail as a green alternative

Substituting passengers from air transport to high-speed rail is frequently seen as a promising alternative for short-haul flights (e.g. Albalate & Bel (2012) and Pagliara et al. (2012)), but also for long-distance car trips (Castillo-Manzano et al., 2015). The origin of this argumentation is two-fold, as (1) HSR promises competitive services to road travel ((Castillo-Manzano et al., 2015)) and air travel on distances of up to 750 km (Donners & Heufke Kantelaar, 2019; Pijnappels, 2020); and (2) a relative improvement on the environmental impact of long-distance travel due to its relatively low externalities (Givoni, 2006).

Starting with the first argument on competitiveness (1), it is identified that a large share of flights from international hub airports in Europe do not travel further than 750 km, a distance range for which it is generally accepted that HSR options can compete with air travel. It was shown by Donners & Heufke Kantelaar (2019) that for Amsterdam Airport Schiphol (AMS) approximately 40% of all flights do not surpass this distance. Something that was confirmed by Pijnappels (2020), who stated similar shares of very short flights (ranging from 34% to 52%) for other meaningful European airports like Munich (MUC), Frankfurt (FRA), Paris (CDG) and Madrid (MAD).

Bringing a lower environmental impact - by for example offering the possibility of using green electricity (Li et al., 2013; Prussi & Lonza, 2018) - and combining this with competitive levels of service when considering travel times, ease of access & egress and seating comfort (Pagliara et al., 2012), the high-speed train shows a clear potential in the challenge of reducing the environmental impact of long-distance travel. It makes that, amongst other factors, the development of this mode is often advocated by numerous parties, such as governments, NGO's, railway companies, but also airlines and airports.

Historical network development and current performance of HSR

In the 1990s, a framework for a future European transport network was introduced by the European Commission, in which a vision for the development of core infrastructure for all main modes of transport was provided (European commission, 2020b). This '*Trans-European Transport Network*', of which the core rail and air infrastructure is given in *Figure 1.1*, connects the continent in a strategic order to enhance social cohesion within the union and encourage the use of the most appropriate mode of transport for each stage of a journey (European commission, 2020b). On the map, airports are indicated by the airplane symbol, conventional rail infrastructure is indicated in green and HSR infrastructure in purple, with non-finished lines (in 2013) being dashed.

Since the initiation of these plans, substantial progress has been realised in the development of the European HSR network. *Figure 1.2* shows that by 2019, a considerable number of HSR lines are already constructed and operated via one or more services. In this 30-year time span, a range of HSR projects have proven to be effective. The introduction of the HSR line between Madrid and Barcelona resulted in a passenger air/rail modal split shift from 11:89% to 46:54% (Pagliara et al., 2012). Similarly, the number of air-passengers and flights between Brussels-London and Brussels-Paris greatly decreased due to the introduction HSR, whereas, a complete discontinuation of air services between Paris and Metz/Nancy was observed in the period from 1991 to 2010 after the introduction of HSR (Dobruszkes, 2011). However, it should be accounted for that these shifts in model splits cannot directly be assigned to a substitution of passengers, as these improvements of accessibility typically also come with the generation of new traffic.

Nevertheless, despite the combination of seemingly favourable circumstances, the active promotion by governments and promising modal shifts results for existing lines, a strong and constant shift towards the HSR has not been realised yet. Air travel is still growing faster than ever before whilst travelling longer distances by train is still mostly a non-efficient practice (European Court of Auditors, 2018).

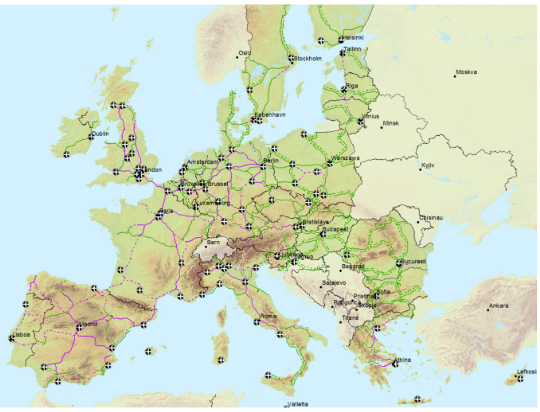

Figure 1.1: Trans-European High-Speed Rail network as composed by the European commission (2013)

Figure 1.2: European sub-networks based on data from European operators as gathered by Wikipedia (2020)

1.2. Problem Definition

This thesis focuses on the performance of high-speed rail in a network context. From that perspective, two fundamental problems can be identified: (1) a lack of knowledge on efficient line configurations given an existing HSR infrastructure and (2) the prioritisation of national and company interests leading to poorly connecting networks, which are due to many national parties that are operating only within their part of the network. In the paragraphs below, each of these problems are further discussed.

Problem 1: lack of knowledge on the design of HSR line configurations
Requiring high investments and long-term solutions, much effort is generally made in the design of public transport systems. When doing this, it is essential to understand how passengers travel and on which factors they base choices, as this allows for well-founded decisions along with the transit network planning phases. In earlier days, this topic was already studied for the Trans-European (conventional) railway network by Janić (1996), who determined that travel speed, frequency and travel costs were the most important service attributes for that in that setting.

Putting this knowledge into use and evaluating the transport market for specific regions allowed to support the decision making in the construction of infrastructure. Something that was for example done as a predictive tool by Allard & Moura (2014), as an evaluation tool by Adler et al. (2010) and of course the proposed network of the European Union (European commission, 2013), which resulted in the proposed European network of HSR infrastructure.

Having this (planned) infrastructure, the next step is to decide on how to use it by the determination of services to offer exactly. A lot of research has been done in the field of transit network design optimisation (Kepaptsoglou & Karlaftis, 2009; Farahani et al., 2013; Ibarra-Rojas et al., 2015). These types of models enable the search to a set of performing lines their associated frequencies having a strong contribution to the defined goals whilst respecting the infrastructural limitations. Researches on this have been done in a variety of contexts, such as bus lines in urban environments (Heyken Soares et al., 2019), railway lines in national networks (Ghoseiri et al., 2004; Jin et al., 2013) and multi-modal regional networks (Chien & Schonfeld, 1998). However, the knowledge of this last step starts to become thinner when asking the same questions for international or continental HSR line configurations.

Having an existing HSR infrastructure on continental scale, there are currently no methods available for how to configure efficient lines on this, as will be underpinned more thoroughly in literature review on '*Transit Network Optimisation*' in *chapter 2*. The studies, as mentioned above, show parallels to what could be expected when optimising line configurations for high-speed rail. However, working with less frequent travel compared to the urban environment, longer travel times in general, other motives to travel and modal competition with the unique characteristics of a complete long-distance transport, it is found that these unique characters of cannot be captured by existing models.

This being unknown, it cannot be said what the importance is of factors like route lengths, the number of stops and line frequencies, but it is also not possible to indicate potential hub stations, crucial links and the trade-offs in network completeness. Furthermore, it is not known what model requirements come along with the characteristics of long-distance travel. Gaining knowledge in these fields could contribute to the effectivity of HSR on a network scale and therewith extrapolate the promising results of single lines and corridors to a whole HSR system.

Problem 2: reduced network integration by prioritisation of national and company interests
The second main problem (2), as briefly stated before, is the way the network is currently used. Traditionally, most railway undertakers work in a nationally orientated and monopolistic model (Laperrouza & Finger, 2009). One of the fundamental believes of the European Union, however, is that opening the national railway markets to cross-border competition is an essential step in building an integrated European railway area (European commission, 2020a). In reality, though, it turns out that privatising national railway markets is a very complex task since almost every country has a unique railway governance structure (Finger, 2014). Combining this with the fact that railway

infrastructure is generally still provided by national governments, makes a mix which is ineffective in reaching the policy goals of social cohesion, increased mobility and appropriate mode choice as formulated by the EU (European Court of Auditors, 2018).

The above-derived findings separated network operations were also observed by other parties, such as Vickerman (1996). In this work, the development of HSR in the first years after the introduction of the TEN-T was analysed. The author identifies the failure to provide an integrated framework, which causes a lack of a genuine international network function. An excellent example of this is the different approach as used in France and Germany. The French worked towards a radial network using Paris as a centre, constructing HSR lines on their already major routes. At the same moment, however, Germany had mainly invested in solving problematic bottlenecks, often between less significant cities, making a more “flattened” network.

More than two decades later, in a report from the European Court of Auditors (2018) on the HSR network, it is stated that the EU’s long-term plans lack a credible analysis, are unlikely to be achieved and miss an EU-wide approach. Combining this with the previously stated governance factors and national interests makes that the current European network is only a patchwork of smaller networks without good coordination across borders. A statement that can be confirmed when recalling *Figure 1.2* again, where it is seen that most high-speed railway undertakers focus on their national markets.

The above findings imply that the European line configuration is not ideally designed for international travel, as it unnecessarily raises hindrances at national borders and is not designed from a single and European perspective. However, using the same infrastructure but in a different way, might open chances for improvement.

1.3. Research Characteristics

The research of this thesis is positioned in such a way that it is able to contribute to the problems as defined in *section 1.2*. In describing the specific characteristics of this research, *subsection 1.3.1* uses the defined problems to pin-point the deficiency in current knowledge. Following this, the objectives that contribute to the filling of these gaps are presented in *subsection 1.3.2*, after which the research question and its sub-questions that meet these objectives are stated in *subsection 1.3.3*. Finally, an overview of the relevance to multiple factors is discussed in *subsection 1.3.4*.

1.3.1. Knowledge gaps

The problem definition of *section 1.2* shows that there is still insufficient knowledge within the design of HSR line configurations and that an overall strategy is lacking. The knowledge gaps that are defined can be distinguished as both practical as scientific. Below, both of these are briefly addressed. The scientific knowledge gap will be further defined in the conclusion of the literature review of *section 2.6*.

Practical gap: potential contribution and design characteristics of an improved HSR network
Summarising the problem definition above, it can be said that there is a chance for improving the effectivity of the European high-speed rail network when making more integrated decisions on line configurations. At this moment, it is not yet known how to design these integrated services on a continental level, such that this could be used for a contribution to policy goals. This regards the actual design decisions, on for example which type of lines should be used, how they should interconnect and what type of network they should form, but also the governance structures and pricing policies that are required for such a network are still unexplored. Moreover, it is not yet known what the potential of an integrated and continental HSR network could be concerning the potential benefits that this brings for users, operators and society as a whole.

Scientific gap: quantitative problem and model describing HSR line configuration design
Because of the complexity and size of this problem, the use of an automated tool is unavoidable when undertaking the search for a quantitative fill of the practical knowledge gap. Similar questions for urban transit systems are typically described by the use of ‘*Transit Network Design and Frequency Setting Problems*’ (TNDFSP) - as will be discussed more elaborately in the literature review of *chapter*

2 - that concerns the selection of lines and their associated frequency for a given network. It will be shown that an abundance of literature covering these problems is available, just like general literature on HSR systems. However, none of these researches have studied a line configuration problem for an integrated continental high-speed rail environment. Because of this, it is not yet known what requirements the unique characteristics of this integrated continental HSR environment (such as the previously mentioned in-frequent travel, longer travel times, deviating travel motives and competition with airlines) impose on a model that is able to address this problem. This research is the first attempt this TNDFSP in an HSR setting.

1.3.2. Research objectives

The ultimate goal of this research is to find the potential impact that can be made by improved line configurations and to find how these configurations should look like, both from a physical perspective as well as a pricing & governance perspective. To get here, a further division of four sub-objectives was made, such that they allow for a filling of the practical knowledge gap in a step-wise manner.

The first (1) research sub-objective is to gain more insights into the design characteristics of HSR networks that provide a high contribution to mobility- and sustainability-related policy goals. Following this, the second (2) sub-objective is to find the relative importance of different design variables in vehicle characteristics, passenger paths restrictions and line design features. Thirdly (3), it is aimed to find the impacts of different pricing policies and governance structures. Finally, the fourth (4) sub-objective is to learn about ideal combinations of the previously mentioned aspects, such that they can be used in pursuing the previously mentioned policy goals. Successfully achieving these sub-objectives should allow meeting the overall objective.

1.3.3. Research questions

To be able to reach the above stated (sub-)objectives, the following research question and associated sub-questions are formulated:

Main research question

The main research question addresses the central topic of this thesis in such a way that a concrete answer can be given. Combining the problem definition with the knowledge gaps and objectives, the following research question is formulated:

”To what extent can the user, operator and societal performance of a European high-speed rail network be improved by centrally designed line configurations as well as pricing policies and how would such networks look like?”

Sub-questions

This research question will be answered by the use of sub-questions. To provide a structured framework in organising these, they are divided into two phases: The first (1) phase considers the analysis of the current scientific and practical fields and works towards the development of a quantitative tool that can be used to perform the experiments for this study. The second (2) phase requires the actual developed to perform the experiments which allow this research to meet its (sub-)objectives.

Phase I: towards a quantitative model

- 01: What is the state of the current HSR practices on the European continent?
- 02: Who are the stakeholders, how are they involved, and what are their objectives within the network?
- 03: What is the current state of transit optimisation?
- 04: What is the current state of HSR line configuration optimisation?
- 05: What requirements do the unique characteristics of HSR travel impose on an optimisation tool?

- 06: How can the reality be simplified to find a balance between the realism and solvability of a problem?
- 07: How is the problem of centrally optimising line configurations for an HSR network defined?
- 08: How should the performance of an HSR network be assessed?
- 09: How does a model look like that is able to design optimal HSR route configurations?
- 10: What is the transport demand between European cities and how can this be determined?
- 11: Which parameters accurately represent the HSR environment?

Phase II: Application of the quantitative model

- 12: To what extent are the current HSR settings able to construct a feasible network; and if not, which adjustments should be made?
- 13: What is the achievable network performance withing the current pricing policy, governance structure and technologies available?
- 14: What is the relative impact of different pricing and governance strategies and how can they be used for certain goals?
- 15: What is the relative importance of different design variables and how can they be used for certain goals?
- 16: What combination of policy and design adjustments should be made, relative to the current settings, to improve the current network performance?
- 17: How would the resulting networks look like and which guides to the provide for the design of the European HSR network and networks in general?
- 18: How would these improved settings and resulting networks perform for user, operator and societal interests; and how would these performances compare to the current situation?

1.3.4. Research relevance

The research topic of this thesis can contribute up to multiple goals. Below, an overview of the relevant aspects has been given from a social, scientific and company perspective.

Social relevance

As briefly explained in the introduction, long-distance transport has substantial negative impacts on the environment, but it also comes with benefits for mobility and social cohesion. Combining this knowledge with humankind being used to travel all over the world within hours and great monetary interests involved, it is not realistic to believe that air travel demand can be reduced by a counter-constructive discussion in which it is argued that we should ‘just fly less’.

In order to naturally decrease the demand for air travel, a good alternative has to be offered. HSR is currently one of the only options that could potentially compete with air travel, making that it becomes an interesting field of research for this topic. Contributing to the knowledge in this field can help with the efficient use of HSR and therewith contribute to societal goals.

Scientific relevance

In chapter 2, it is found that current knowledge on transit route network design problems does not reach the field of high-speed rail or long-distance transport in general. Expanding the current modelling techniques to this, a new field with very specific properties and characteristics is opened. This contributes to both the understanding of HSR potential performance as well as the possibilities of translating the transit route network design problem to out-of-the-box ideas.

Company relevance
Royal HaskoningDHV sees a wish from governments to further enhance HSR corridors. Currently, the knowledge on how to efficiently design these corridors is not available at governmental or company level. Being an independent engineering consultancy company, Royal HaskoningDHV sees opportunities in providing governments with underpinned advice.

1.4. Research and Report Architecture

The main goal of this research is to contribute to the objectives as formulated *subsection 1.3.2*, which will be done by answering the main research question and its sub-questions. To do this, the following research architecture was applied in this study:

Methodological approach
Given the size, complexity and limited qualitative knowledge in the topic of HSR network design, it was chosen to perform a quantitative experiment that is performed on the European continent with the currently available technologies. In this experiment, a simulation of the transit planning process for HSR line configurations in a long-distance transport environment is made. By performing different scenarios and interpreting the trade-offs in the quality of service (e.g. network coverage and directness), but also the economic profitability and societal impact, lessons are to be extracted on a variety of governance, policy and design aspects.

The above-mentioned experiment is based on the '*Transit Network Design and Frequency Setting Problem*' (TNDFSP), which is concerned with the strategic design of transit networks and which is typically used for urban transit systems. This study is the first attempt to transform and solve this problem for an HSR environment. Solving this specific problem comes with two main challenges: first (1) the newly introduced aspects of the HSR environment, which require to be modelled accurately; and secondly (2) the inherent complexity of TNDFSPs, which brings the necessity of advanced solution methodologies that respect the problem's characteristics whilst maintaining a reasonable computation time and result accuracy.

Report structure
The report is based on the research question and its sub-questions whilst maintaining a classical chapter division. This means that it will first work towards a model that describes the general problem, after which this will be used for experiments. The remainder of this report is organised in the following structure: Starting, *chapter 2* reviews literature that is concerned with the research field that optimises network design and frequency setting problems, the wider field of HSR research and the interface between this. This, such that it is possible to define which adaptions have to be made for the standard problem and which difficulties these impose in further developments. Following this, *chapter 3* presents the exact method that was used. This holds a detailed methodological approach, a definition of the customised TNDFSP for an HSR setting, a novel heuristic formulation and the presentation of the four exact experiments that are to be performed. This is then continued by *chapter 4*, which operationalises the newly defined problem to the European context and currently available technologies.

Having everything set to simulate, the model is first validated on heuristic performance and solution quality in *chapter 5*. After ensuring this quality, the results are extracted in *chapter 6* by performing the four previously mentioned experiments and analysing their outcomes. Following this, conclusions are drawn in *chapter 7* using the lessons of all previous analyses, after which the same chapter also sheds a critical light on the performed research and provides views for future steps.

For an encapsulated overview of this research, the reader is advised to consult *appendix A*, which contains the article that is associated with this study,

2

Literature Review

In this chapter, a thorough assessment of the current knowledge within the field of transit network optimisation is performed. This assessment is divided into multiple stages, as can be seen in the chapter outline below. First, a general framework for the design of public transport systems, associated optimisation problems and the problem specifically interesting for this research will be presented in *sections 2.1* and *2.2*. This is followed by a deeper exploration of the main components as found in line design and frequency setting problems in *section 2.3*. The complexity involved in the optimisation of line configurations requires specific solution approaches, of which an analysis is presented in *section 2.4*. Following this, *section 2.5* discusses the importance to select key performance indicators that allow for a proper interpretation and makes an inventory of relevant items for this research. Finally, an overview of the relevant study fields, a scientific gap definition and a thesis positioning are given in *section 2.6*.

2.1. Design of Transit Systems and Research Field Identification

Transportation finds its importance in allowing people to move between their activities. With growing population size and travel demands, an increase of mobility-related issues such as congestion and pollution are created. Forms of public transport are often advocated as they can potentially reduce the impact of these disadvantages. However, to reach an effective state for this, the design of a public transport network has to be balanced between the quality of service for users, the costs minimisation for operators and the impact on the system's surroundings (Guihaire & Hao, 2008; Farahani et al., 2013). Designing and planning public transport systems is a subject that has been assessed in plentiful scientific researches and practical analyses. In the subsections below, this research field is examined more thoroughly.

2.1.1. Hierarchical public transport planning scheme

The design process of a public transport network comprises all steps that have to be taken before a system is operated. Due to the highly complex working environment and stakeholder considerations as explained above, the problem is frequently divided into smaller sub-problems which cover strategic, tactical and operational decision making phases (Desaulniers & Hickman, 2007; Ibarra-Rojas et al., 2015). The so-called '*Hierarchical Public Transport Planning Concept*', as depicted in *Figure 2.1*, indicates the sequence of executed tasks. In principle, the planning process flows from top to bottom, though feedback loops are included to ensure for vertical dependencies.

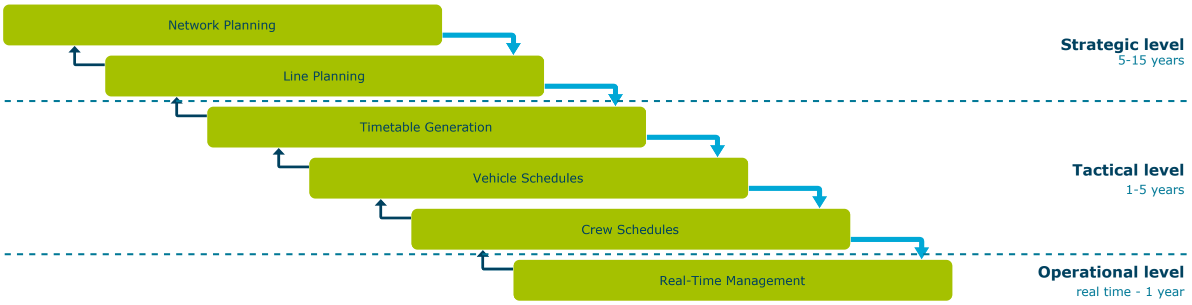

Figure 2.1: Frequently used Hierarchical Public Transport Planning Concept (Bussieck, 1998; Lindner, 2000; Lusby et al., 2011)

The stages of Hierarchical Public Transport Planning Concept are described by multiple authors over a longer time-span. (Bussieck, 1998; Lindner, 2000; Lusby et al., 2011). Despite small formulation differences, the essence is always similar. The first stage of *Network Planning* is mostly focused on analysing the transport demand, such that it is known which OD-traffic can be expected. Based on these traffic demands, lines (also called routes or services), stop locations and frequencies are designed in the *Line Planning* stage. Depending on the exact problem, the high-level infrastructural investments can also be determined on this strategic level.

On a shorter time horizon, a more tactical approach is applied. In the *Timetable Generation*, all arrival- and departure times are fixed, for which the specific vehicles are assigned in the *Rolling Stock Schedules*. This phase is ended by the *Crew Schedules*, in which crews are assigned scheduled operations. Characteristic for the tactical phase is the goal of maximising the performance of the system, whether that is based on making a profit or the compliance with policy goals. Complexity in this phase can be found in the non-linear constraints regarding, for example, the wages of personnel.

Finally, the lowest level of the public transport planning scheme is the operational level, which deals with the day-to-day operations, thus the *Real-Time Management*. Even though the division between the three levels may look quite rigid, it has to be noted that that the exact position of stages within the levels is flexible and open for problem-specific interpretation, which makes that also different explanations of this framework can be found across the literature.

2.1.2. Optimising public transport networks

Following the great interests and costs associated with public transport design, numerous optimisation efforts have been made. Based on the hierarchical public transport planning concept of *Figure 2.1*, Ibarra-Rojas et al. (2015) constructed a framework which provides an outline for the problems that quantitatively describe this puzzle. Encompassing, the overall subject is named a '*Transit Network Planning Problem*' (TNPP). This problem is then subdivided into smaller sub-problems that go parallel to the preceding public transport planning division. The schematic overview of these sub-problems, their inputs and outputs is given in *Figure 2.2*.

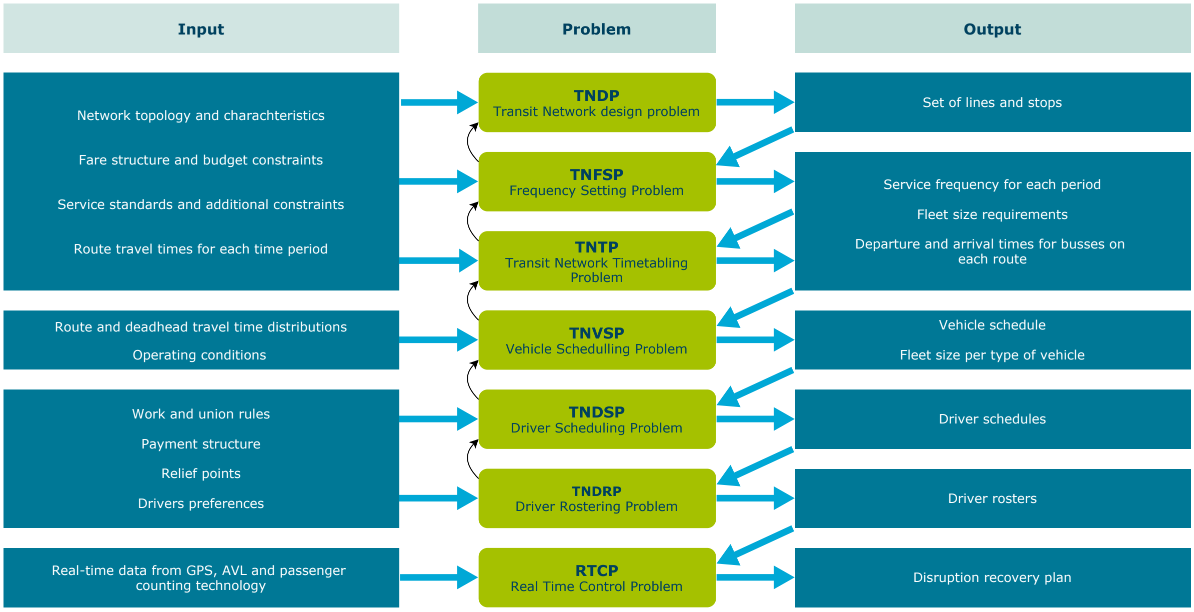

Figure 2.2: Framework of Transit Network Planning Problems (TNPP) (Ibarra-Rojas et al., 2015)

Due to cross-level relations between the sub-problems of *Figure 2.2*, it is often favoured to combine several sub-problems into one. Something that was recognised by Guihaire & Hao (2008), who presented an overview of multi-level problems. In this framework, as depicted in *Figure 2.3*, it is seen that three multi-level problems are defined for the strategic and high-level tactical phases. Here, the '*TNDFSTP*' covers all three sub-problems (design, frequency setting and timetabling), whilst the '*TNDFSP*' and '*TNFSTP*' only cover two out of three problems.

2.1.3. Identification of the relevant problem

The research question of this thesis (see *subsection 1.3.3*) concerns the impact of centrally optimised HSR line configurations, thus the line design and frequency setting. Pairing this knowledge to the framework of Guihaire & Hao (2008), it is established that the problem of this research can be classified in the category of '*Transit Network Design and Frequency Setting Problems*' (TNDFSP). This TNDFSP is positioned in the strategic decision-making level and is highlighted in *Figure 2.3*. Further steps of this literature study focus specifically on the TNDFSP research field but do also consider the four partially relevant problems (TNDP, TNFSP, TNDFSTP and TNFSTP) to explore the wider possibilities.

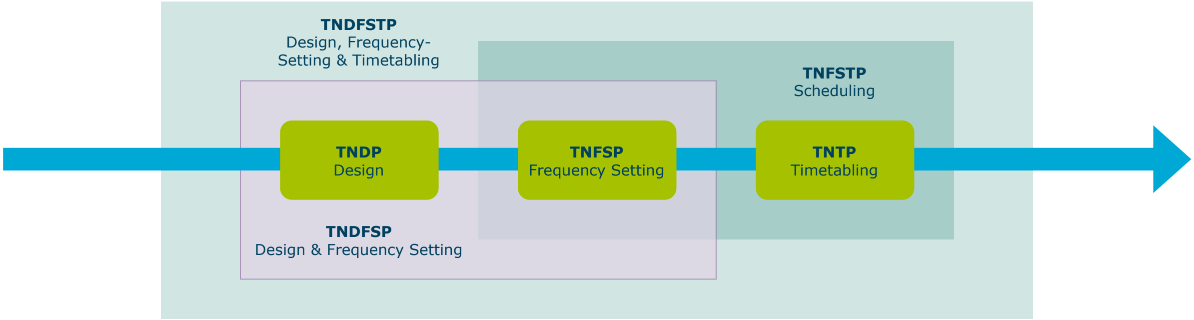

Figure 2.3: Schematic Overview of high-level multi-sub-problem TNPP's (Guihaire & Hao, 2008)

2.2. Definition of the TNDFSP

According to the definition of Guihaire & Hao (2008), a TNDFSP combines the (1) design problem (which determines a set of lines, consisting of terminal stations and intermediate stops, for an area's topological characteristics) with a (2) frequency setting problem (that finds adequate frequencies for a specific time period). Both of these problems start from a given demand and work under a combination of objectives and constraints. The first problem (design) tries to balance user interest (e.g. direct lines, large service area, demand satisfaction) against operators interest (reducing costs). The second problem (frequency), is more operator focused and combines resource limitations (e.g. the number of vehicles) whilst maintaining a level of service for users.

The resulting output of the two combined problems is a set of routes and associated frequencies, which are sometimes supplemented with vehicle types (Kepaptsoglou & Karlaftis, 2009). Corresponding to this finding, Schöbel (2012) defines these three main output elements as a '*line plan*' consisting of chosen lines and '*frequencies*' that are applied on these lines. Together, they form the '*Line Configuration*'. This terminology will be used in this report when describing the output of the TNDFSP.

2.2.1. Complexity of the TNDFSP

The problem, as described above, is generally seen as relatively complex, something that was also identified by Baaj (1990) and Fan & Machemehl (2004). In these works, six main factors that build complexity in finding a unique and optimal solution were given. Starting, (1) it is seen that the definition of decision variables and expression of objective functions bring great difficulties and that (2) the costs associated to the network configuration are often non-convex and non-linear. As a third reason, it is explained that (3) the route design problem has a discrete nature bringing combinatorial complexity, hence making the problem NP-hard. Following this, (4) the great variety of important trade-offs and conflicting objectives makes this a multi-objective problem. The fifth argument describes that (5) the spatial layout of routes makes it hard to make a set of routes which obeys the design criteria and is operationally feasible. Finally, (6) the nature of the variable transit demand brings an extra complication.

2.2.2. Reviewing literature providing a framework of the research field

Across the literature, numerous researches covering one or more of the relevant problems can be found. However, given the application-driven character of this problem, the problem descriptions often stated in an informal way and lacking a clear description (Schöbel, 2012). This leads to a large variety of problem formulations, solving strategies, proposed heuristics and used formulations. To provide the research field with more structure, several review papers have been written. An overview of these can be found in *Table 2.1*.

Table 2.1: Review papers covering high-level Transit Network Planning Problems (TNPP)

Year	Author	Title	Description
2008	Guihaire & Hao	Transit network design and scheduling: A global review	Unification of the research field, specifically focused on high-level strategic problems and the combination of these problems
2009	Kepaptsoglou & Karlaftis	Transit Route Network Design Problem: Review	General overview of more practical applications and strategies including route construction
2012	Schöbel	Line planning in public transport: models and methods	Unification of the research field, specifically focused on mathematical problem formulation
2013	Farahani et al.	A review of urban transportation network design problems	Provide a bigger picture of transportation network design problems, encourage cross-fertilisation within the field
2014	López-Ramos	Integrating network design and frequency setting in public transportation networks: a survey	modelling features: objective cost components, constraints, algorithmic aspects
2015	Ibarra-Rojas et al.	Planning, operation, and control of bus transport systems: A literature review	Planning processes and real-time control strategies for recent and not addressed research works
2019	Iliopoulou et al.	Metaheuristics for the transit route network design problem: a review and comparative analysis	Metaheuristic solving techniques

Despite working from overarching views, the review papers do still define many aspects of transit network problems differently. These differences can primarily be explained by two factors: (1) a perspective which is either more scientific or practical oriented and (2) a transport type (mode and scale) specific perspective versus a more normalised perspective. Regarding the second factor, it is observed that almost all transport type orientated researches are focused on urban bus and rail systems. The research question of this thesis, however, is situated on a higher scale-level (continental) using different modes (airplane, high-speed train and car). In the remaining parts of this literature study, the review papers as stated in *Table 2.1* are used as a basis to inventory available techniques and translate these finding to relevant information regarding a potential HSR problem.

2.2.3. Structure of the TNDFSP

When defining the TNDFSP (*section 2.2*), a consensus regarding the ongoing processes and the resulting output (line plan, frequencies and line configuration) were found. It is seen however, that this consensus is not true concerning the input of the model. Something that mainly finds its origin in the different perspectives ranging between the normalised scientific and specified practical point of views.

The more classical form of the TNDFSP, as described by amongst others Schöbel (2012) and Guihaire & Hao (2008) uses a given set of already available lines to select from. However, applying this problem for real-life and more practical oriented models, Kepaptsoglou & Karlaftis (2009) found that these set of lines are usually not available. Because of this, it is seen that many works incorporate an extra problem that concerns the production of candidate lines. Furthermore, truly existing situations often require way more realistic and specified input concerning parameter characteristics or constraints. Given the more practical perspective of this specific thesis, it is therefore chosen to follow the structure of Kepaptsoglou & Karlaftis (2009) in the further decomposition of the TNDFSP.

In order to reveal the key characteristics of the TNDFSP,Kepaptsoglou & Karlaftis (2009) separate the problem into a so-called '*three-layer structure*'. In this framework, as projected in *Figure 2.4*, all three layers represent one or more typical characteristics of the problem. The first layer of '*objectives*', gives insights in the goal of the problem, the second layer of '*parameters*' defines the operating environment that covers both the decision variables as well as the operational parameters and constraints. The third layer of '*methodology*' includes the mathematical framework and the algorithmic techniques applied in solving the problem. The structure of this three-layer framework will function - in a slightly changed sequence - as a thread for the following sections of this chapter, in which the TNDFSP will be further decomposed.

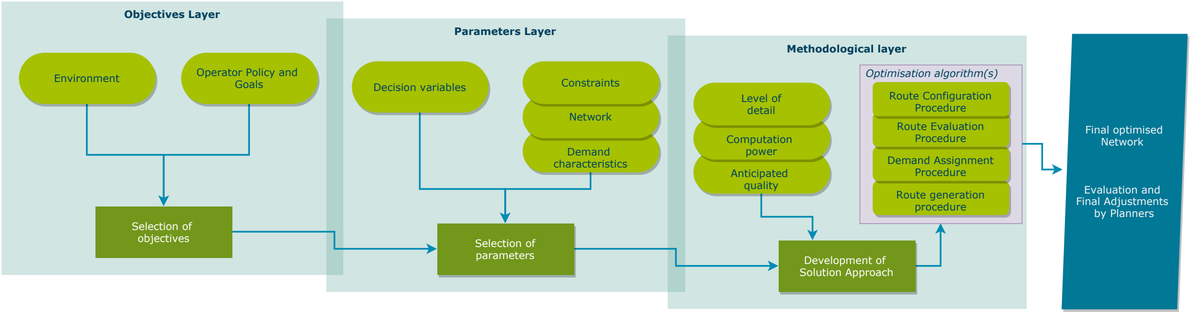

Figure 2.4: Three layer framework for the TNDFSP (Kepaptsoglou & Karlaftis, 2009)

2.3. Components of the TNDFSP

Being a complex problem with many elements, the TNDFSP is frequently divided into several parts: the objectives, decision variables, parameter environment and constraints. Each of these is discussed in the subsections below.

2.3.1. Problem objectives

In optimisation problems in general, the objective function is the mathematical expression based on the decision variables that reflects an objective that can either be minimised or maximised (Hillier & Lieberman, 2015). For a TNDFSP, this means that the objective function translates the potential decisions (comprised as possible line configurations) to a score that can be compared. As previously mentioned in *subsection 2.2.1*, the TNDFSP comes with multiple characteristic complexities: a difficulty in expression, non-convex and non-linear costs and the variable interests which inherently induce multi-objective character. Below, three main elements of the problem's objective are discussed.

Objective function types

Transit planning classically has two main partners involved: the operator wishing to minimise its costs and the user desiring a maximisation of its benefits. Both of these can be expressed in different ways, but usually, the operator's costs are formulated based on the total length of the routes, whereas the user's costs are mostly defined as the deviation from the shortest paths (Owais et al., 2016). This finding is confirmed by the work of Kepaptsoglou & Karlaftis (2009), who however also found that many pieces of research deviate from this by incorporating other factors such as external costs, total (societal) welfare, transfer minimisation, capacity maximisation, travel time minimisation or fuel consumption minimisation.

These more specific objectives can be used separately to investigate very detailed questions within the problem, but they can also be combined into a multi-objective formulation that potentially covers a broader field. A very common example of this the total welfare objective, that tries to incorporate the different perspectives in order to find a compromise. For this, however, it is necessary to attach weights to each of the sub-objectives, which can be a challenging aspect Kepaptsoglou & Karlaftis (2009).

Objective function costs components

An objective function, even for a singular goal, is often formulated by multiple costs components. Assessing objective functions for a wide variety of TNPP's, López-Ramos (2014) came to the conclusion that the majority of functions find their structural origin from the same cost elements. These costs can be divided into costs related to the operator and costs related to the user. An overview is given in *Table 2.2*.

Table 2.2: Frequently used TNDFSP objective function cost components (López-Ramos, 2014)

Operator cost components	User cost components	
- Infrastructure resources	- Unsatisfied demand	- Transfer time
- Planning resources	- Travel times	- Vehicle occupation
	- At station waiting	- Mode disutility
	- In-vehicle time	

Translation to HSR:

Concerning the objectives, the HSR problem shows several parallels to the more frequently found bus planning problem. Regarding the classical single-objectives, it is seen in Yue et al. (2016), that the operator's perspective is optimised by maximising the profit for the total fleet of trains. Similarly, Gallo et al. (2011) applies a somewhat extended view of using four separate objective functions, namely operator costs, transit user costs, car user costs and external costs.

Building towards more integrated views, it is seen that Li et al. (2013) focuses on a green perspective by formulating a multi-objective function that covers both minimising energy use and carbon emission costs, as well as passenger-travel-time. An operators perspective is added to this by Sun et al. (2014), who also incorporate the minimisation of train travel times.

2.3.2. Problem decision variables

Decision variables, as explained by Hillier & Lieberman (2015), are the representations of quantifiable decisions to be made, of which the values are to be determined by solving the problem. In the framework of 2.4, it can be seen that these are located in parameters layer. The authors of this framework (Kepaptsoglou & Karlaftis, 2009) find that in general, two main decision variables are used for the TNDFSP: the line plan and frequencies (as previously mentioned in *section 2.2*).

However, as also recognised by Fan & Machemehl (2008), implicitly many more decision variables are taken into account. This follows from the fact that the selection of a specific line comes with its own characteristics, such as covered lengths, stop locations, directness or the lack of that. Furthermore, the combination of lines and frequencies also indirectly decides how many passengers are actually transported. Following the two main decision variables, it is also seen that a some less frequently specifically mentioned options are used in literature. Examples of these are fares, stop locations and vehicle types (Kepaptsoglou & Karlaftis, 2009).

Translation to HSR:
From the perspective of HSR, it can be deduced that many resemblances with other transit modes can be found. This, because the mentioned decision variables are all focused on the high-level network and passenger flows, rather than operational factors. It makes that the decision variables for this are not further expanded.

2.3.3. Problem parameter environment

The parameter environment 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 network of a TNDFSP consists of several key elements: the '*vertices*' (stops or stations), '*edges*' (direct connection between vertices), '*lines*' (passenger service residing a sequence of connected edges) and '*paths*' (passenger course between two vertices following one or more lines) (Schöbel, 2012). According to Kepaptsoglou & Karlaftis (2009), three general network structures can be defined: simplified radial structures, simplified rectangular grid structures - both widely used from around the 1980's - and in later times more often realistic irregular grid structures.

Translation to HSR:
Translating the above to the HSR situation, no works using a true rectangular or radial structure are found for rail-related problems. The spatial geography on the larger distances is not as much designed into reoccurring shapes compared to urban regions. Next to that, the more recent character of this topic means that the computational possibilities have been mostly available from the beginning on. In Allard & Moura (2014), a radial-like network is used, though this is more a result of the Iberian peninsula and especially Madrid-focused scope. Furthermore, this problem is not a true TNPP, as it comes closer to a multi-commodity flow problem for air and rail competition. The research of Lovett et al. (2013) already comes a lot closer to a TNPP for High-Speed Rail, where nine hypothetical nodes are structured as an irregular complete network.

Characteristic for rail problems – including HSR – is that the infrastructural limitations and high investment costs often make that it is also interesting to analyse only one corridor or line, in which a focus is laid upon the frequency and stopping locations, including the construction of a feasible timetable. This combination means that it is a bi-level problem, that combines both strategic line planning (the frequency planning part), as well as tactical timetable generation. An example of where this is seen is Jong et al. (2012) for Taiwan's HSR corridor running from the north to the south side of the island.

The analysis of network structures reveals that, despite different possibilities for a full network analysis, no such research has been done before. Lovett et al. (2013) did come close to this, but their model was only able to capture a relatively small network in a close to linear form. Additionally, this research was a lot more focused on a supply perspective regarding infrastructure and network planning, rather than taking passenger demand into account.

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. A search through studies close to the TNDFSP field shows that distinctions can be made on three key modelling decisions: (1) '*spatial pattern*', (2) '*time scope*' and (3) '*dynamic demand aspects*'.

In the work of Kepaptsoglou & Karlaftis (2009), two main types of spatial demand patterns for the TNDFSP are identified. A one-to-many demand, which could be found in researches that focus on a specific hub station or attraction centres (such as Chien et al. (2003)), or many-to-many demand patterns emphasising networks where flows occur between multiple origins and destinations (such as Zhao & Zeng (2007) and Hassan et al. (2019)).

The second key modelling decision concerns the time scope to be chosen, as the demand can be highly variable over the time (Farahani et al., 2013). Across the overarching transit network planning problems (TNPP), it is observed that this scope ranges from years to minutes. On the one hand, highly discrete problems concerning infrastructure construction - like the TNDP - are mostly interested in averaged flows that justify an investment. On the other hand, on a tactical timetabling level (TNTP) the level of detail reaches up to minutes (Farahani et al., 2013; Ibarra-Rojas et al., 2015) as this is crucial for the provision of dynamic capacity. This together makes that the TNDFSP, being on the strategic side of the frequency problem, is located somewhere between these extremes but with an accent to the strategic a long-term time-scopes.

The third factor relates to the dynamic demand aspects. One of the main principles in transport sciences is the interaction between demand and supply. Across literature on transit network planning and the topic of air-rail competition, two recurring impacts (Givoni & Dobruszkes, 2013) of increasing the supply (or level of service) can be identified: (1) mode substitution (Janić, 1993; Janić, 1996) and (2) demand growth due to both increased level of service (Cervero, 2002; Beaudoin & Lin Lawell, 2018) and network effects (Laird et al., 2005; Di Giacinto et al., 2012).

In the review paper of Kepaptsoglou & Karlaftis (2009), it is seen that TNDFSPs often vary in their strategy to cover for these elasticity effects, as incorporating this in a model brings extra complexity. Especially the older works often used a simplification in which they assumed all types of demand to be fixed. If however chosen to do so, including these effects can be done in two ways according to Lee & Vuchic (2005). The first only covers for demand shifts between modes, whilst the other also takes into account the effects of demand generation for the whole network.

Translation to HSR:

An essential difference between many of the urban region oriented TNDFSPs and one that would describe a high-speed rail network is the origin that passengers come from. In the classical problem, it is often assumed that passengers find their origin in certain neighbourhoods of a residential area that are modelled as zones or centroids (e.g. Fan & Machemehl (2008) or Heyken Soares et al. (2019)). However, for the scenario of HSR competing with AT, it is important to realise that distances are a lot greater, access and egress times are experienced differently, and catchment areas of airports could differ or overlap on other scales.

2.3.4. Problem constraints

Imposing constraints on any optimisation problem is used as a way to ensure feasible and realistic solutions are found, but it also contributes in reducing the computational burden by reducing the solution space (Bussieck, 1998). Depending on the exact problem, these constraints are usually case-specific. However, frequently utilised constraint types can be recognised when analysing researches in the transit planning field. Several pieces of research have addressed this categorisation of constraints. An overview of this is given in *Table 2.3*.

In her search for a unification of line planning models from a fundamental perspective, Schöbel (2012) formulated seven basic constraints (see column 1). It is seen that these primarily concern broad budget, capacity and connectivity constraints. Another overview, but then from a more practical point of view, was given my López-Ramos (2014) (see column 2). In this overview, more specific constraints are defined. Examples of these are working lines (respecting already existing lines), express services (allowing to not stop at every station along the line) or time horizon (max. amount of time per vehicle to finish all services).

Searching specifically towards constraints in classical bus systems, a third overview was composed by Zhao & Zeng (2006). The list as defined in this article (see column 3) indicates an already further specified range of possibilities on, for example, the line design, vehicle loading and budgets. Other

Table 2.3: Frequently used TNDFSP constraint type divisions

Schöbel (2012)	**López-Ramos (2014)**	**Zhao & Zeng (2006)**
- Budget constraints	- Infrastructure restrictions	- Route shape
- Capacity constraints	- Working Lines	- Directness
- Lower edge frequency requirements	- Express services	- Feasible frequencies
- Higher edge frequency requirements	- Stretch capacity	- Load factor boundaries
- Lower node frequency requirements	- Vehicle fleet size	- Min. and max. line length
- Upper node frequency requirements	- Time horizon	- No. of routes
- Connected path for every OD-pair		- Fleet size
		- Operational budgets

interesting constraints in urban-context researches were found in Gallo et al. (2011), who bounds the total kilometres per vehicle to account for public administration subsidies or maintenance time and in Heyken Soares et al. (2019), who works with pre-specified terminal stations from a practical point of view.

Translation to HSR:
Many of the constraint types as mentioned in *Table 2.3* could be considered applicable for a high-speed rail scenario, though one could also imagine that this mode of transport brings a lot of new and case-specific constraints. Characteristic for rail infrastructure is the strong link between strategic planning and operational constraints, as a rail system is relatively dependent on its infrastructure. This is underpinned and expanded by Bussieck (1998), who notes that operational and political constraints often play an important role in conventional railway systems, but that it is not always possible to quantify them into a mathematical model.

The above-mentioned types of constraints are especially interesting for the HSR problem, as both operational and political differences are likely to occur in cross-national transport. Operational constraint examples on this could be, for example, physical interoperability and safety systems, more complex station or edge capacities and difficulties in overtaking (Ahuja et al., 2005; Yue et al., 2016). On the political field, divergent governance or international political conflicts can be expected. An important - not specifically HSR related.

2.4. Problem Solution Strategies

Reaching on the final layer of the three-layer framework (*Figure 2.4*), a light will be shed on methodological solution strategies. As previously mentioned and explained by Schöbel (2012), the application-driven character of line planning problems makes that they are usually described in an informal way. It also means that for this layer, numerous approaches can be found in the literature. In this section, these approaches are discussed and combined into the comprehensive overview of *Figure 2.5*. Below, each of these components will be further discussed.

Before breaking down the elements of *Figure 2.5*, it is important that an even more fundamentally different approach can be used in the search for an ideal line configuration. This division is formulated by Kepaptsoglou & Karlaftis (2009), whose work mainly focuses on the practical implementation of TNDFSP, including the creation of lines to be chosen from. As these two steps go hand-in-hand, the authors propose two possible methods: the '*Line Generation & Configuration*' approach (also LGC; see *Figure 2.6*) and the '*Line Construction & Improvement*' approach (also LCI; see *Figure 2.7*). Both of these procedures require the same input, which was earlier defined as the '*parameters layer*' of *Figure 2.4*. From this moment on, the strategies start to diverge as their characteristics bring different solving difficulties. The break down of possible solution strategies, as depicted in *Figure 2.5*, will be done in *subsection 2.4.1*, *subsection 2.4.2* and *subsection 2.4.3* on the basis of these two fundamental approaches.

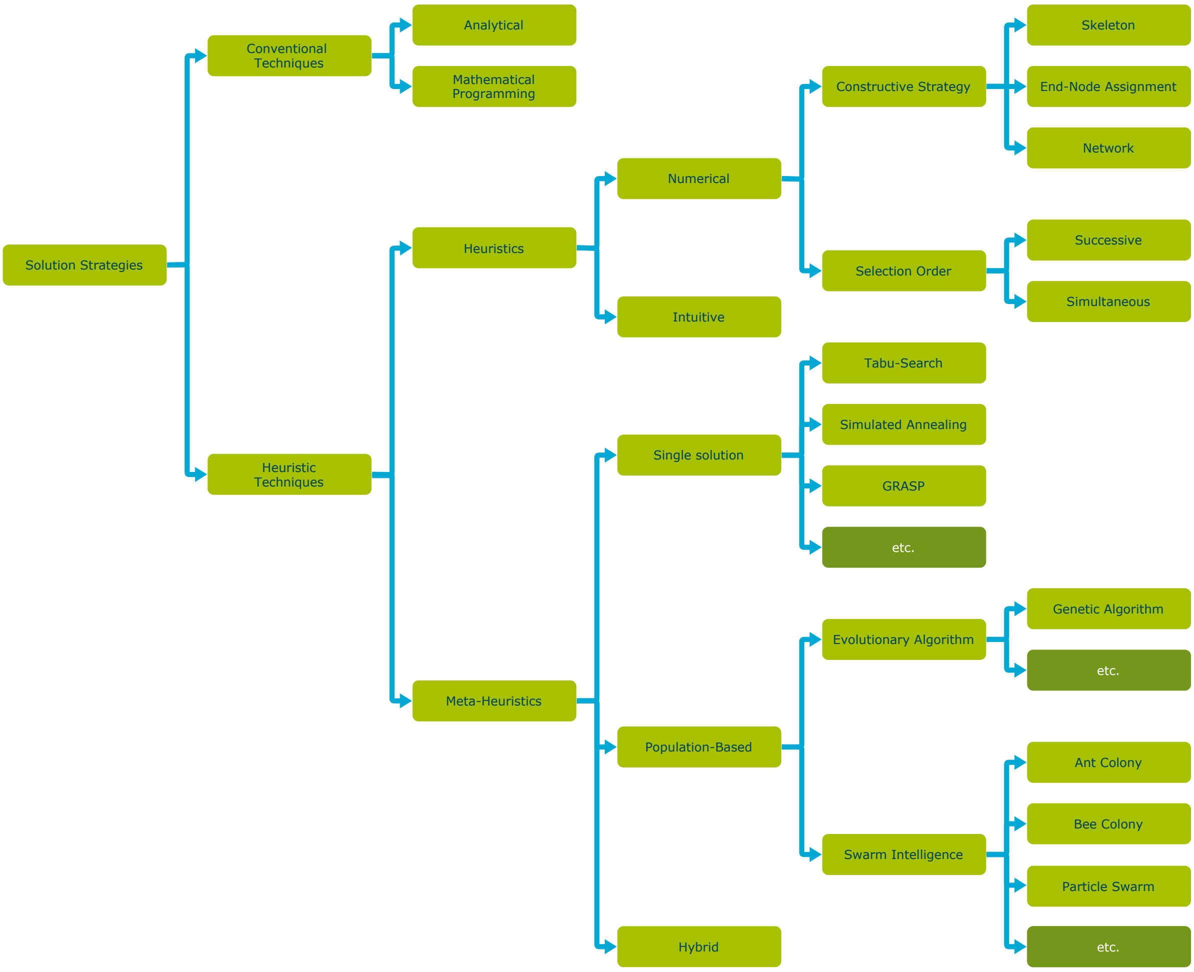

Figure 2.5: Overview of problem solution strategies (based on Iliopoulou et al. (2019))

2.4.1. Solving methods

Moving on from the fundamental division of LGC and LCI, Kepaptsoglou & Karlaftis (2009) defines two main types of solving strategies that can be used for both approaches: '*conventional techniques*' and '*heuristic techniques*'. This definition is further expanded by Iliopoulou et al. (2019), who classified four sub-categories on this: '*Analytical*', '*Mathematical*', '*Heuristic*' and '*Meta-Heuristic*' methods. These four categories can be seen in the third column of *Figure 2.5*.

Conventional techniques

The literature review of Iliopoulou et al. (2019) gave that the analytical methods were mainly used to determine specific line attributes only for an already existing network, making that they were fairly limited in their possibilities whilst being slightly opaque when interpreting the overall results. A conclusion that was followed by the finding that mathematical programming techniques failed for regular TNDFSPs due to their inability of realistically representing structures of routes. Earlier on, in *section 2.1* on the optimisation of the line design and frequency setting, it was already explained that there are six main factors that bring complexity to the TNDFSP. It is commonly accepted that these traditional solving techniques cannot be applied efficiently to nowadays questions, as they are not able to effectively work around the difficulties. Something that was also already found by Ceder (2001), Youssef et al. (2001) and Fan & Machemehl (2004).

Heuristic techniques
Following the alternative route to heuristic techniques, (Iliopoulou et al., 2019) finds that regular heuristics are mostly found in earlier literature, whereas the improved computational possibilities allowed for the use of more advanced meta-heuristics in more recent years. In the current situation, both of these techniques can be used depending on the exact problem characteristics. Being explained more thoroughly later on (*subsection 2.4.2* and *subsection 2.4.3*), using the LGC approach comes with a relatively large solution space compared to using LCI approach. This makes that the former benefits more from meta-heuristics, whereas it is more sensible to solve the latter by the use of regular heuristics. In the following subsections, both of the fundamental methods (LGC and LCI) will be further discussed.

2.4.2. Line generation and configuration approach

The first approach (LGC) is based on the principle of generating a large set of candidate lines for the network and finding the optimal sub-selection of these lines. This search is performed by strategically presenting multiple possible line sets to a Network Analysis Procedure (NAP), where the performance is calculated by assigning the traffic and determining the frequency, such that the best option can be found. The main challenge in this process comes from the large solution space, which makes that an optimal solution is often approached by the use of meta-heuristic techniques, as these are generally strong in efficiently searching this space. A typical schematic overview of the '*Line Generation and Configuration*' approach was constructed by Kepaptsoglou & Karlaftis (2009) and can be found in *Figure 2.6*.

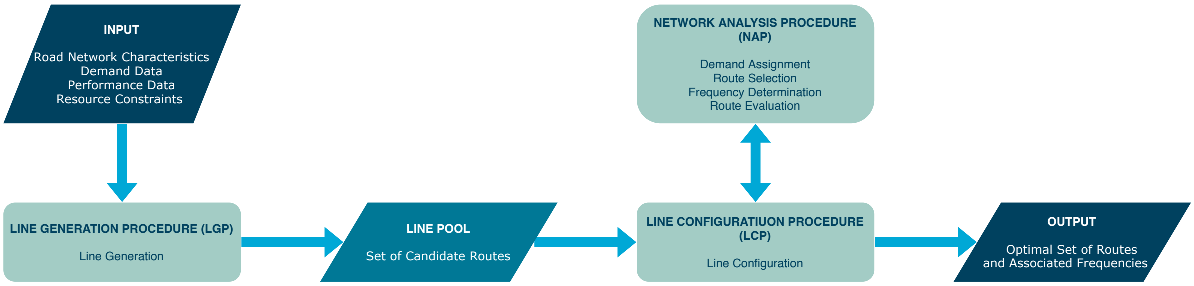

Figure 2.6: Typical Line Generation & Configuration (LGP) scheme (Kepaptsoglou & Karlaftis, 2009)

Line Generation Procedure (LGP)
The first typical step in this process – the '*Line Generation Procedure*' (LGP) – is also a very important one. In this phase, it is key to find a balance between the size of the line pool, as this has a great impact on realism and effectivity. Finding this balance correctly results in a strong performance regarding the objective function, but also a manageable computation time given the limited pool size (López-Ramos, 2014).

The exact implementation of the LGP as described above, varies significantly over the literature, as these problems usually require customised approaches for each problem. The review work of Kepaptsoglou & Karlaftis (2009) identified that most methods are shortest-path based algorithms that are subject to a range of constraints. Examples mentioned are Fan & Machemehl (2004), where a combination of Dijkstra shortest path algorithm and yen's k-shortest path algorithm are used and the work of Ngamchai & Lovell (2003), in which a selection of neighbouring nodes algorithm is applied.

An alternative way to build more realism within the line generation is by taking the knowledge on-demand already into account, as explained by Kepaptsoglou & Karlaftis (2009). Here, it can be seen that some researches combine the shortest-paths with the demand data in search to minimise the difference between these demands, whilst other only use the shortest-paths as a starting point and perform multiple procedures to filter their final set of routes. One of the latest strategies for this phase was applied by Heyken Soares et al. (2019), who built a shortest path based map from a passenger perspective. With this procedure, passenger demand is projected by an all-or-nothing assignment to their shortest possible infrastructural path in the network - assuming every passenger prefers this - such that it becomes clear which links are used most. Based on the knowledge of these links, a series of routes are constructed that try to cover those links.

Line Configuration Procedure (LCP)
The Line Configuration Procedure (LCP) is responsible for the strategic selection of line sets from the '*Pool of Lines*' and sending these to the '*Network Analysis Procedure*' (NAP). Based on the network descriptors calculated by the NAP, the performance (objective value) of the suggested solutions is determined. Following the result of this step, the LCP suggests new solutions until an optimum or certain threshold has been reached. Given the size and complexity of the problem, this step can be either solved analytically or with the use of (meta-) heuristic techniques that are able to strategically search the solution space. In practice, for real-life problems, Iliopoulou et al. (2019) find that most research applies meta-heuristics - regularly in combination with heuristics - for this.

Meta-heuristics
According to Iliopoulou et al. (2019), three types of meta-heuristics can found: so-called '*single-solution-based*','*population-based*' and '*hybrid*' techniques (see *Figure 2.5*). From their assessment, the authors find that single-solution-based methods are rarely independently used. Instead, they are more frequently applied in a hybrid form with other techniques. On the other side, it is seen that population-based techniques, such as '*evolutionary algorithm*' and '*swarm intelligence*', occur more widely for solving TNDFSPs.

The group of evolutionary algorithms is part of the population-based techniques and imitates what is known from biological evolution, for which the most commonly known variant is called '*Genetic Algorithm*' (GA). With this strategy, it is possible to handle complex constraints, elaborate multi-objective functions and large solution spaces. Another family of population-based techniques is called swarm intelligence, which is influenced by the ability of simple agents to locally interact and therewith contribute to a greater goal. For this, frequently used techniques are '*Particle Swarm Optimisation*' (PSO), '*Ant Colony Optimisation*' (ACO) and '*Bee Colony Optimisation*' (BCO) (Iliopoulou et al., 2019).

Where population-based techniques are especially strong for comparing large solution spaces, it is found that single-solution-based strategies are better for intensifying the search in local regions. In this category, Iliopoulou et al. (2019) mention three main options: '*Simulated annealing*' (SA), '*Tabu Search*' (TS) and '*Greedy Randomised Adaptive Search procedure*' (GRASP). Though there are many more possibilities. A commonality within these methods is that they all have mechanisms to prevent getting stuck in local optima.

Trying to combine best of two worlds, a few pieces of research have merged multiple techniques into a hybrid, such that one can cover the large solution space of a population-based method whilst using single-solution-based techniques to avoid local optima. Applying this newer field of study, however, comes at the cost of an increased model complexity (Iliopoulou et al., 2019). An important remark in the decision for a solution method is to acknowledge that there is no such thing as an absolute best strategy. Every specific problem needs a specific solution. In a search towards a fair comparison,

2.4.3. Line construction and improvement approach

An alternative way of searching for a strongly performing line configuration is by using a '*Line Construction and Improvement*' approach (LCI), which works from a slightly different perspective. After receiving the same input information regarding the operating environment, a '*Line Construction Procedure*' is started to find an initial line plan. This initial line plan is then step-wise improved and/or expanded until an optimum of threshold has been reached. A typical schematic overview of an LCI can be found in *Figure 2.7* (Kepaptsoglou & Karlaftis, 2009; López-Ramos, 2014).

Heuristics
Similarly to the previously explained Line Generation Procedure, the goal of the '*Line Construction*

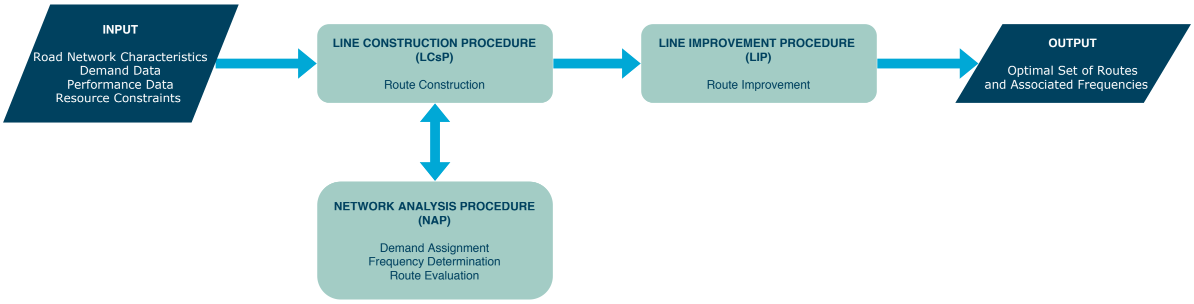

Figure 2.7: Typical Line Construction and Improvement Scheme (Kepaptsoglou & Karlaftis, 2009)

Procedure' (LCsP) is to provide the algorithm with initial lines. A contrasting element, however, can be found in the type of lines that have to be made. For the LGC, a complete set of feasible and non-changeable possibilities had to be defined, whereas the LCI only needs a starting point from where it can improve in the '*Line Improvement Procedure*' (LIP). In Schöbel (2012), it was discussed that the LCI is often application-driven, which makes that a variety of unique heuristics have been developed for specific problems. This brings that the LCsP and the LIP often go hand in hand, thus cannot be seen separately. However, the heuristics used are distinguishable into different categories.

An overview of these constructive heuristic categories is given by Quak (2003), who expands the work of Sonntag (1977). A first distinction is made between intuitive and numerical methods. The former can be described as a manual method, in which expert insights are tested by quality criteria, whereas the latter method bases its decisions on computations. Following the first stream, the numerical methods are further subdivided into their constructive strategies, for which three options are given: '*skeleton methods*' (based on unlinked node or arc rows larger than two elements), '*end-node assignments*' (where possible lines are made between these end-nodes, after which the best are selected) and '*network methods*' (in which the process starts without any form of structure). Furthermore, another subdivision can be made on the selection order, where two options are possible. Successive methods select a single line, which are being fixed after selection, whilst simultaneous methods select a collection of lines to be improved. Something that is also found by Guihaire & Hao (2008). The visualisation of these categories can be found in the upper-right corner of *Figure 2.5*.

Combining multiple heuristics

A brief review of the possible LCI applications was presented by (Schöbel, 2012), where it can be seen that the different constructive strategies and selection orders as described above are used in multiple combinations. Funnelling the list of examples down to a smaller number of approaches that are more frequently used gives that in general, four solution strategies are used.

The first (1) approach relates closest to the previously explained network method, as it is chosen to start from a line plan that contains every individual edge as a single line. These lines are then step-wise combined into longer feasible lines. A second mean (2) starts from a smaller set of lines that cover only a part of the network, which makes that it could be classified as a skeleton method. These infeasible lines are then to be expanded until a feasible and optimal solution is reached. Thirdly (3), one could also adjust most recently mentioned strategy and start by already feasible lines. In this situation, the focus is more towards the improvement of lines rather than the expansion. Finally, a fourth (4) approach comes closest to an end-node assignment strategy. Here, one starts with a complete set of (feasible) lines between each OD-pairs, from which two perspectives can be chosen. In the first, all routes are active after which the line plan is sequentially reduced by eliminating poorly performing lines or possibly editing them. In the second perspective, the heuristic starts with an empty line plan where the highest potential lines are sequentially added (Quak, 2003; Schöbel, 2012).

2.5. Solution Performance Measurement

Assessing the efficiency and effectivity of the output of transport networks can be a challenging task, as even within the same mode fundamental differences such as the business model, network size, company size, ownership structure and geographical context occur. This makes that a set of well-founded and integrated '*key performance indicators*' (KPI's) is essential for good judgement of the solution performance.

Covering relatively large distances but also being rather route infrastructure dependent, high-speed rail's characteristics are in between the classical transit and airline systems. As both transport modes are frequently evaluated differently, a review on assessments from both perspectives is being performed in the subsections below. This, to find out which KPI's would be most suitable for an HSR system.

2.5.1. Key performance indicators in the airline industry

Being a highly competitive market, the comparison between different airlines is considered important and therefore also to some extend regulated. Combining the frequently used KPI concepts of Holloway (2008), Belobaba et al. (2009), Doganis (2010), as was done by Lopes dos Santos (2019), five KPI categories can be made:

- Traffic based indicators
- Financial based indicators
- Load factor indicators
- Productivity based indicators
- Operations based indicators

Not all of the above-presented categories are as relevant to this specific research. Firstly, the last classification of '*operations based indicators*', is primarily focused on daily practices such as the average delay or the on-time performance, which are out of scope given their operational character. The same goes for the second-last classification of '*productivity based indicators*', that expresses how efficient resources such as labour or vehicles (i.e. airplanes) are used. These two have a more tactical character but are also not on the detail level of this research. The three top classifications are relevant though and are thus further elaborated below.

Table 2.4: Frequently used airline KPI's, as based on Holloway (2008), Belobaba et al. (2009) and Doganis (2010)

Category	Notation	Full Name	Name
Traffic based	ASK	Available Seat Kilometres	no. of seats offered x flown kilometres
	RPK	Revenue Seat Kilometres	no. of revenue passengers transported x flown kilometres
Financial based	CASK	Cost per ASK	operational costs / ASK
	RASK	Revenue per ASK	revenue collected / ASK
	Yield	Yield (or revenue) per RPK	revenue collected / RPK
	OP	Operating Profit	RPK × Yield – ASK × CASK.
Load Factor	LF	Load Factor	no. of passengers / no. of seats = RPK / ASK
	ALLF	Average Leg Load Factor	RPK / ASK for particular flight leg
	ANLF	Average Network Load Factor	RPK / ASK for entire network
	BELF	Break Even Load Factor	value for LF for which RASK equals CASK

Traffic- based key performance indicators

Traffic based indicators can be subdivided from two perspectives. The first one, '*Available Seat Kilometres*' (i.e. ASK), quantifies the supply offered by counting the number of seats made available per kilometre flown. In contrast to this, the second perspective measures the output that is used in the form of the '*Revenue Seat Kilometres*' (i.e. ASK), which gives an idea of the number of passengers that are transported and the total distance that they travelled. Each of the mentioned KPIs can be found in the overview of *Table 2.4*

Financial-based key performance indicators
Using financial-based indicators, it is possible to gain insights into the profitability of an airline. In *Table 2.4*, it can be seen that four main financial KPI's are defined. The first two - '*Cost per ASK*' (i.e. CASK) and '*Revenue per ASK*' (i.e. RASK) - give a sense of the average operational costs and revenues that are made by offering one seat for one kilometre. Following this, the '*Yield*' indicates the average prices that a customer pays per kilometre. Combining the financial and traffic based indicators, the '*operating profit*' can be determined by subtracting the expenses from the earnings.

Load factor-based key performance indicators
In a further step of comparing the supply and demand, load factor indicators can be used to reach a deeper insight into the fraction of offered seats that are actually used. The classical '*Load Factor*' (i.e. LF) is a value that describes the seat occupancy for a single flight. This can be extended to a certain leg or route that is operated by multiple flights, which is named as the '*Average Leg Load Factor*' (i.e. ALLF). Going even further, the '*Average Network Load Factor*' (i.e. ANLF) gives the same value but then for the whole network. The numbers derived in this category can not indicate how much of the offered capacity is used, but how much more effort has to be done to become profitable. This can be seen by the '*Break Even Load Factor*' (i.e. BELF), that is the load factor for which the operational expenses are equal to the money that is earned. The four mentioned KPI's can all be found in *Table 2.4*

2.5.2. Key performance indicators in the transit industry

Because of the application-driven character of the TNDFSP, a variety of similar modelling - and thus performance analyses - are found across the literature (Schöbel, 2012). In an attempt to measure the effectiveness of possible meta-heuristic solution techniques for this problem, Iliopoulou et al. (2019) made a comparative analysis. The results of this review show that the most frequently used indicators find their origin in the pioneering work of Mandl (1980), which are stated in *Table 2.5*

Table 2.5: Frequently used transit KPI's, as based on Mandl (1980) and Iliopoulou et al. (2019)

Notation	**Description**
d_0	Percentage of passenger demand satisfied without any transfers
d_1	Percentage of passenger demand satisfied with one transfer
d_2	Percentage of passenger demand satisfied with two transfers transfers
d_{un}	Percentage of passengers satisfied with more than two transfers or not
ATT	Average travel time (minutes per passenger)
TTT	Total travel time (minutes)

2.6. Research Positioning and Contribution

Following the background exploration, *chapter 1* (Introduction) defined two problems within the current high-speed rail practice and connected a practical knowledge gap to this, of which the last could be summarised as the potential improvement that can be made by an integrated HSR network design and the understanding on how such a network would look like. From the literature study in this chapter, it was found that the topic of high-speed rail, the quantitative design of transit networks in general (TNPP) and the more specific design of transit line configurations (TNDFSP) were each extensively researched areas. A study on exactly the interface of these three research fields might potentially be able to answer the unknown.

Assessing the scientific context for each of the three research fields, as displayed in *Table 2.6*, it was found that the interface of these research fields has not yet been studied. In other words: no previous scholar has addressed a TNDFSP study for an HSR network. Therefore, it is not yet known what requirements come with unique characters of this long-distance transport environment (such as deviating travel motives, infrastructural possibilities and a different time and size scale) and what type of model should be developed to solve this problem. Aiming to gain insights into the above, this research contributes to the filling of the previously defined practical knowledge gap by developing such a model.

Table 2.6: Scientific context of this research

	Year	Author	Research focus	Main interface to this research	Main difference to this research
High-Speed Rail *Research in the wider field of HSR, concerning impacts on surroundings and mode interactions*	2018	Prussi & Lonza	comparison of emission profiles for HSR and aviation	impact of actually achieved benefits in external costs by mode substitution	analyses specific lines rather then networks; considers a more detailed level of emissions
	2017	Sun et al.	review work covering competition/cooperation with aviation on specific lines for different continents in search of commonalities	consideration of a continental approach for HSR	ex-post analyses; emphasises mutlimodality / cooperation with air network
	2016	Donners	assessment of the long-distance European rail passenger market potential, considering demand and supply	network perspective; substitution with other long-distance modes; searches for key components and impact of future network; works towards proposed network structure	does not consider the design of lines configurations
	2014	Allard & Moura	quantitative analysis of intermodal HSR and air network	quantitative design approach of air/HSR network	strong operator's perspective; small newtork; intermodal focus; importance of infrastructure; link perspective rather than line
	2014	Dobruszkes et al.	Impact of current European HSR on air services	focus on mode competition	ex-post analysis; does not consider networks, only legs
	2014	Finger	Governance comparison of national European railways	Searches for the performance and impacts of certain governance strategies in rail	considers conventional rail on a national scale
	2013	Givoni & Dobruszkes	mode substitution and induced demand by the introduction of HSR	focus on the design aspects of HSR that influence the substitution and generation	ex-post study of separate services; great emphasis on generation effects
	2013	Lovett et al.	Design of HSR line configurations	degree of freedom in line design, analyses of design choices	has a more tactical view; considers one line in small network, no competition with other modes
	2012	Pagliara et al.	search for important service attributes and passenger behaviour in air/HSR competition	emphasis on passenger benefits and operator response	search for service attributes rather than use of them; considers only one corridor
	2011	Dobruszkes	competition between HSR and air from a supply orientated perspective	acknowledgement of importance of design aspects	ex-post study, focuses on specific OD-pairs in western-Europe
	2011	Garmendia et al.	Difference in impact of road vs. HSR infrastructure on urban structure and mobility of sparsely populated areas	Consideration of road and HSR travel as interacting elements	ex-post study; does not consider line configurations and focus on secondary effects
	2010	Adler et al.	cost-benefit analysis of infrastructure in air/HSR competition	uses European HSR as case study, strategic character	Focus on infrastructure, models response or airline industry, works from links rather than lines, considers ticket pricing as decision variable
	2006	Givoni	Analyses the development, impact and competitiveness of HSR services, to design choices can be strategically used	link between design aspects and performance	analyses separate lines rather then networks; ex-post observations rather than active design
	1996	Janić	measuring the quality of service of the trans-European (conventional) railway network	Continental network scale of a rail mode	uses conventional rail only; measuring rather than designing
	1993	Janić	competition between HSR and air travel; assesses quality of service fox existing networks	competing character of HSR/air	identifies service attributes, rather then using them for design
	This study		**New contribution:** impacts on substitution, network design and multi-stakeholder performance for controlling line configurations in given infrastructure		

textitTable 2.6 (continued): Scientific context of the research

		Year	Author	Research focus	Main interface to this research	Main difference to this research
TNDFSP	*Relevant TNDFSP works without HSR*	2019	Heyken Soares et al.	regular TNDFSP with focus on demand estimation	demand-based line generation; terminal stations to limit the pool of lines	demand is generated by residential zones
		2014	Kiliç & Gök	algorithm for demand-based route generation	demand-based line generation	single mode, fixed demand, small network (V=15)
		2011	Gallo et al.	elastic demand in multi-modal system and the inclusion of external costs	Structure of constraints; elastic demand in multi-modal system and the inclusion of external costs	urban setting, objective aimed at network coverage, rather then costs
		2007	Zhao & Zeng	Obstacles found and solution strategies used for a very large bus transit network	applies the theories to real-scale problems	does not consider an external/societal factor
		2005	Lee & Vuchic	Transit network design with an elastic mode and fixed total demand	iterative approach in demand assignment; formulation of stakeholder interests; vehicle capacity determination	Transit demand varies over the day
		2004	Fan & Machemehl	Comparison of hybrid heuristic algorithms	solution techniques, formulation of objective function; transit trip assignment (lexicographic)	urban setting which with emphasis on differences in access/egress for bus stop locations
		This study		**New contribution:** TNDFSP for HSR environment with long-distance transport characteristics in a real-sized network scale		
TNPP	*Relevant TNPP works in (HS)R field*	2016	Yue et al.	train stopping patterns and schedules for HSR corridors	Modelling of HSR behaviour within a TNPP; driving characteristics	focus on one corridor and primary operator perspective
		2014	Allard & Moura	optimisation HSR and air intermodal passenger network design	qualitative interaction HSR and air	intermodal design, small network, costs of intermodality, edge based rather then line based
		2013	Li et al.	incorporation of more complex green aspects combined with passenger interests in train scheduling	importance of external costs for considerations of transit design	scheduling problem, thus mostly concerned with energy minimisation of specific trains
		2013	Lovett et al.	Design of HSR line configurations	degree of freedom of line design, analyses of design choices	has a more tactical view; considers one line in small network, no competition with other modes
		2013	Jin et al.	Train network design from a tactical to operational perspective	characteristics (constraints) of train operations	focuses more on the trains rather than the network
		2012	Jong et al.	Stopping patterns for Taiwan's HSR corridor	importance of HSR passenger travel time minimisation; HST driving characteristics	more tactical focus, small corridor,
		This study		**New contribution:** *Expanding TNPPs for HSR to a strategic level for a given infrastructural network*		

3

Methodology

The main goal of this research is to contribute to the four objectives as formulated in the '*Introduction*' (*chapter 1*). Given the size, complexity and limited qualitative knowledge in the topic of HSR network design, it was chosen to perform a quantitative experiment. This experiment simulated the transit planning process for HSR line configurations in a long-distance transport environment. By performing different scenarios and interpreting the trade-offs in the quality of service (network coverage and directness), but also the economic profitability and societal impact, lessons were extracted on a variety of aspects. In *chapter 2*, it was found that this problem can be defined as a '*Transit Network Frequency and Design Setting Problem*' (TNDFSP), which is more frequently used for conventional public transport systems. However, to make this problem applicable to this study, a range of adaptions - following from the literature review - were made. This chapter covers the methodological elaboration of this problem, which is built upon a six-step approach. An overview of this is presented below.

- *section 3.1* - '*Approach*' introduces the requirements related to the study and what effects they have on the methods decisions.
- *section 3.2* - '*Problem Definition*' defines a customised version of the TNDFSP, such that this quantitatively describes the problem of optimising HSR line configurations in an undefined setting.
- *section 3.3* - '*Model Formulation*' formulates a novel heuristic that strategically searches the solution space for strong performing results in a reasonable time, given the fact that the inherent complexity of the TNDFSP (see *subsection 2.2.1*) makes that it cannot be solved using conventional techniques.
- *section 3.4* - '*Experimental Set-Up*' explains the different experiments that are to be performed and constructs the relevant scenarios.

3.1. Approach

This study attempts to use a customised version of the '*Transit Network Frequency and Design Setting Problem*' (TNDFSP) to learn more design on the design of line configurations in - and the potential contribution of - an HSR network. Given the time and computational limitations, several modelling choices had to be made. To limit the impact of these limitations, to ensure accurate results and to match the strategic character of the research, an assessment on the model's requirements was made in *subsection 3.1.1*. Following this, the actual methodological approach and chosen simplifications are stated in *subsection 3.1.2*.

3.1.1. Model requirements

Systematically formulating the model requirements ensures a consistent path towards a problem-adequate model. This systematic formulation is done by providing a framework in which the model aims to the best result regarding the research objectives from *subsection 1.3.3*, whilst also respecting the boundaries that follow from the research scope and other realism factors.

For this research, the two required components as explained above have been defined as '*model objectives*' and '*model constraints*', where the former relates to the goals and the latter to the boundaries. These two are then further subdivided into '*functional requirements*' (that help to capture the intended behaviour of the system) and '*non-functional requirements*' (that defines a quality attribute of the system).

Model objectives
As a primary goal, the model has to be able to answer the research questions that work towards the development of a functional model. This results in the following functional objectives (FO) and non-functional objectives (NFO).

FO1 - Network characteristics:
The model should give clear supply-side network characteristics as output, such that it is possible to understand how the network looks like and how it should be designed.

FO2 - Performance details:
The model should give clear performance details, for both the operator's costs perspective and the user's benefits perspective, such that it is possible to compare the performance of different scenarios.

FO3 - Traffic flows:
The model should give detailed traffic flow information, such that it is possible to understand the solution effectivity and the interaction with other modes.

NFO1 - Computation time:
The model should have a limited computation time, preferably maximally a few days, such that it is possible to perform a more extensive analysis and test multiple different scenarios.

NFO2 - Flexibility:
The models should be easily adaptable, such that it is possible to test multiple difference and contrasting scenarios.

Model constraints
The constraints are responsible for providing the model with boundaries and obligations, making sure that it reaches a minimum performance within realistic proportions for answering the problem related to the main research question. This results in the following functional constraints (FC) and non-functional constraints (NFC).

FC1 - HSR characteristics:
The model must be able to cover the typical and most relevant attributes HSR travel, meaning that network size & characteristics, the operator's services and the passenger's behaviour realism are all requisites.

FC2 - Reasonably optimal solution:
The model must be able to improve the route configuration until a point where it is possible to distinguish the characteristics of better performing scenarios and its associated properties, such that it is possible to extract the relevant lessons from this optimisation process.

NFC1 - Limited complexity:
The model must be of limited complexity, such that it is possible to construct and evaluate it within a three-month time frame.

3.1.2. Methodological approach and problem assumptions

Following the requirements, several modelling choices were made to match the strategic character of the research, simplify the problem and emphasis the research goal. From an overall perspective, the study considers a situation which is in a continuous state, such that the expenses for the construction of infrastructure or the acquisition of vehicles are not taken into account. The associated time-span of this continuous state equals one operational day of eighteen hours. In this state, all costs components are considered relative to a situation with no HSR whatsoever. Additionally, the network's infrastructure is uncapacitated to provide the problem with solution freedom. Below, an overview of further modelling assumptions is stated:

List of assumptions:

- The total demand is assumed to be fixed, meaning that generation or time effects are not taken into account.
- The demand per mode is variable (elastic) according to the level of service and assigned assuming a stochastic uncongested user equilibrium.
- Both the mode-specific demand and the total demand are assumed to be symmetric
- A path does not include more than two transfers
- Transfers can take place at any vertex
- Dwell times are assumed to be the same at each stop
- Car travel is possible between all OD pairs
- Travellers within the same node are not taken into account
- The fleet of HST vehicles is homogeneous for all of their characteristics
- Vehicles do not interact whatsoever; hence all vehicles travel with the same speed profile, independent from local traffic conditions.
- The available HSR infrastructure does not limit the vehicles by speed or capacity
- no operational strategies like deadheading or short-turning are taken into account
- The networks infrastructure is uncapacitated; thus no maximum frequency is maintained in edges or vertices
- Rail infrastructure is interoperable for the whole network

3.2. Problem Definition

In *chapter 2*, it was found that the standard problems which quantitatively describe the search towards optimal transit systems are called ‘*Transit Network Planning Problems*’ (TNPP). More specifically, problems controlling for the selection of lines and their according frequencies are called the ‘*Transit Network Design and Frequency Setting Problem*’ (TNDFSP) (Ibarra-Rojas et al., 2015; Guihaire & Hao, 2008), of which the contextual region is revisited in *Figure 3.1*.

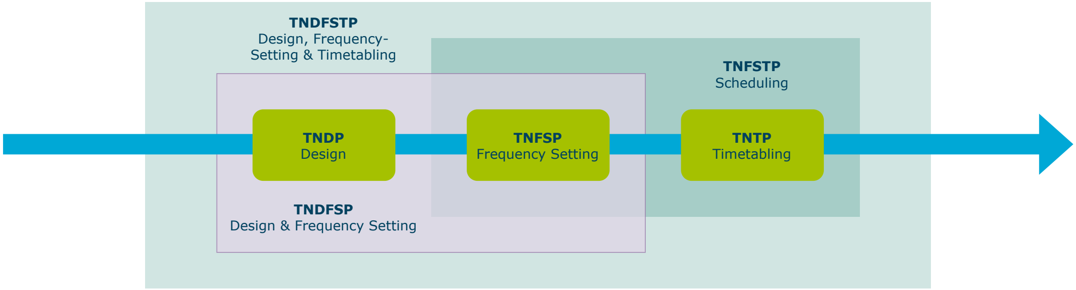

Figure 3.1: Schematic Overview of high-level multi-sub-problem TNPP’s (Guihaire & Hao, 2008) *(revisited Figure 2.3)*

In this section, a modified version of this TNDFSP will be defined, such that it can describe the design of any HSR system in a long-distance transport network. First, the problem’s general description will be introduced in *subsection 3.2.1*, and its associated parameters will be introduced in *subsection 3.2.2*. This is then followed by *subsection 3.2.3* which discusses the decision variables and *subsection 3.2.4* where the objectives of the stakeholders and their numerical representations are given. To ensure feasible results and limit the computational burden, several constraints are imposed on the model, which are stated in *subsection 3.2.5*.

3.2.1. General problem description

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, of which a brief overview can be found in *Table 3.2.2*.

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*' $V = \{v_1, v_2, ..., v_{|v|}\}$ and a finite set of connections between these cities that are represented as '*edges*' $E = \{e_1, e_2, ..., e_{|E|}\}$. Furthermore, different ways of transport are distinguished by '*modes*' $M = \{m_1, m_2, ..., m_{|q|}\}$. Following this given graph, a '*line*' can be defined as a service that is a sequence of directly connected vertices: $l = \{v_{first}, ..., v_{last}\}$. Combining multiple of these separate line together results in a '*set of lines*' $L = \{l_1, l_2, ..., l_{|L|}\}$. 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 so-called '*transfer path*' p^t. Together, these paths form the set of paths $P = \{p_1, p_2, ..., p_{|P|}\}$, where each pair of vertices has only one such path. An overview of sets and indices is presented in *Table 3.1*

Table 3.1: Overview of this model's indices and sets

Name	Alt. Name	Symbol	Index in set	Notation
Graph	network	G	*n/a*	*n/a*
Vertex	node	v_i	$i, j \in V$	$V = [v_1, v_2, ..., v_{\|i=V\|}]$
Edge	link	e_c	$c \in E$	$E = [e_1, e_2, ..., e_{\|c=E\|}]$
Line	route	l_k	$k, h \in L$	$L = [l_1, l_2, ..., l_{\|k=L\|}]$
Mode	*n/a*	m_q	$q \in M$	$M = [m_1, m_2, ..., m_{\|q=M\|}]$
Direct Path	*n/a*	p^d	$d \subset P$	$P = \{p_1, p_2, ..., p_{\|P\|}\}$
Transfer Path	*n/a*	p^t	$t \subset P$	$P = \{p_1, p_2, ..., p_{\|P\|}\}$

3.2.2. Problem parameters

As previously explained in *subsection 3.2.1*, the graph G of this network consists of vertices v, edges e and lines l. Additionally, the transportation function within this network can be performed by different modes of transport k. Within this graph, either direct paths pd or indirect paths pt using lines can be used to move vertices. The characteristics of these six entities provide the problem with its structural operating environment, of which a more detailed elaboration is done below.

Vertex notations

The vertices v 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 have geographical locations, which are represented by their latitudes ϕ_v and longitudes λ_v and that describe their angle relative to the equator- and pole planes.

Besides representing cities, the vertices do also portray the railway stations and airport systems (set of reachable airports) associated with them. This means that, in addition to generating traffic, they also have a function in the boarding, alighting and transferring of passengers. With this, it comes that each of the vertices has parameter values on the access times $t^{acs}_{v,m}$ and egress times $t^{egs}_{v,m}$ (depending on conditions like the average remoteness of airports or the density-population function of the city) and the transfer time $t^{trf}_{v,m}$

Edge notations

The individual vertices v are linked by the edges e. These edges represent the presence of either the physical (e.g. rail) or non-physical (e.g. air) connections, which are denoted by the term $e^{exs.}_{i,j,m}$ that describes the actual existence of an edge between nodes v_i and v_j for mode m. This is done in a

Table 3.2: Overview of this model's vertex parameters

Notation	**Unit**	**Description**
V	[-]	number of vertices v
ϕ_v	[∘]	latitude of vertex v
λ_v	[∘]	longitude of vertex v
$t_{v,m}^{acs}$	$[min]$	access time of vertex v for mode m
$t_{v,m}^{egs}$	$[min]$	egress time of vertex v for mode m
$t_{v,m}^{trf}$	$[min]$	transfer time of vertex v for mode m

binary form, where $true = 1$ and $false = M$. Following the different geographical location of vertices v and mode m characteristics, each of the edges comes with its unique set of properties, resulting in variations of '*edge riding time*' indicated by $t_{e,m}^{rid}$. The determination of this edge riding time follows from two main components: the true edge distance $ds_{i,j}^{true}$ and the mode m that travels it. The true edge distance primarily follows from the direct distance which is corrected by a mode specific detour factor fac_m^{dt} which originates from mode's m ability to travel more or less direct routes. The resulting equation is stated in *Equation 3.1*. The required direct edge distance $ds_{i,j}^{dir}$ is calculated using the Haversine function, as presented in *Equation 3.2*.

$$ds_{i,j}^{true} = ds_{i,j}^{dir} \cdot fac_m^{dt} \tag{3.1}$$

and

$$ds_{i,j}^{dir} = R^{Earth} \cdot 2\arcsin\sqrt{\sin^2\left(\frac{\phi_i - \phi_j}{2}\right) + \cos\phi_i \cos\phi_j \sin^2\left(\frac{\lambda_i - \lambda_j}{2}\right)} \tag{3.2}$$

where:

R^{Earth} = radius R of the earth in $= 6.371 \cdot 10^6 m$

Ultimately, the riding time $t_{e,m}^{rid}$ also depends on the mode's cruising speed s_m^{crs} and driving characteristics. A more elaborate decomposition on this driving time and the additional trip components is provided in *subsection 3.2.2*. An overview of mentioned edge-related parameters can be found in *Table 3.3*.

Table 3.3: Overview of this model's edge parameters

Notation	**Unit**	**Description**
E	[-]	number of edges e
$e_m^{exs}(v_i, v_j)$	[-]	existence of edge e between vertices v_i and v_j $(true = 1, false = M)$
$ds^{dir}(v_i, v_j)$	$[m]$	direct (greater circle) distance between vertices v_i and v_j
ln_e^{str}	$[m]$	stretching length of edge e for mode m
fac_m^{dt}	[-]	detour factor of transport mode m
s_m^{crs}	$[m/s]$	operating speed at edge e for mode m
$t_{e,m}^{rid}$	$[s]$	total riding time at edge e for mode m

Line notations

Chaining a series of consecutive vertices v that are linked by edges e of the same mode, makes a line l_k. Lines can be used by passengers to travel between the vertices v that are part of this line. The total stretching length of this line l_k is defined as $ln^{str}_{l_k}$ and can be determined by summing the stretching length of the individual edges ln^{str}_{e} that are included in the line, of which the comprising set is denoted as Ω^{l_k}. An important side note in this is that travelling over a certain line l_k does not mean that all of the edges are visited by the passenger. Whether this is true, is indicated by $\beta^{l_k}_{ijab}$. The value for this is 1 when if the passenger demand flow $dm^{l_k}_{i,j}$ uses edge (a,b) and 0 in other cases.

Table 3.4: Overview of this model's line parameters

Notation	Unit	Description
$ln^{str}_{l_k}$	$[m]$	stretching length of line l_k
Ω_{l_k}	[-]	set of edges (a, b) assigned to line l_k
$\beta^{l_k}_{ijab}$	[-]	1 if the flow $d^{l_k}_{i,j}$ uses edge (a,b), else 0

Mode notations

This research is primarily focused on the design of HSR line configurations and the interplay between users, the operator and society. To ensure a complete view, it is necessary to model HSR, but also the presence of competing modes. The problem knows three means of travel: (1) air, (2) high-speed rail and (3) private car. These modes differ on vehicle characteristics and procedural operations, which results in different trip characteristics when travelling between vertices. These differences are further analysed below.

Travel time functions:

The most important factor in comparing different modes for a trip is the time that is required. This total travel time $t^{tot}_{i,j,m}$ can consist of five main components. The (1) '*access time*', (2) '*waiting time*', (3) '*in-vehicle time*' , (4) '*transfer time*' and (5) '*egress time*'. An overall formulation of this is given in Equation 3.3. Depending on whether a direct path or indirect path between two nodes is available, the travel times between these vertices are denoted to be $t^{p^d}_{i,j}$ for direct paths and $t^{p^t}_{i,j}$ for in-direct (transfer) paths.

$$t^{tot}_{i,j,m} = t^{acs}_{v_i,m} + t^{wai}_{v_i,m} + t^{inv}_{v_i,v_j,m} + t^{trf}_{pt_s} + t^{egr}_{v_j,m} \tag{3.3}$$

The exact definition of travel time components are all depended on the applicable vertices and modes. For most of these factors, differences in parameter values can be observed due to procedural differences. Examples are longer waiting times at airports due to higher security levels or negligibly access and egress times when using cars, as these usually allow for door-to-door travel. However, more significant procedural differences are found in the construction of the in-vehicle time.

In-vehicle time (airplane):

Equation 3.4 describes a typical flight leg along an edge. The first term, t^{tko}, represent the time that is needed for the airplane to taxi, take-off and reach its cruising speed. Similar to that, the last term (t^{lnd}) accounts for the time that is needed to decelerate, land and reach the gate. Finally, the most variable part of the in-vehicle time equation is described by the middle term. Here, the greater circle distance is multiplied by a mode-specific detour factor, after distances covered in the take-off or landing processes have been subtracted. The remaining distance is covered by the average cruising speed s^{crs}_{m}, leaving a cruising time as result.

$$t^{inv,air}_{e_c(i,j)} = t^{tko} + \left(\frac{ds^{dir}_{i,j} \cdot fac^{dt}_{air} - ds^{acc}_{air} - ds^{dec}_{air}}{s^{crs}_{air}} \right) + t^{lnd} \tag{3.4}$$

where:

t^{tko} = time needed for the airplane to taxi, take-off and reach its cruising speed
ds^{acc}_{air} = distance covered in complete take-off procedure
t^{lnd} = time needed for the airplane to reach landing speed, land and taxi
ds^{dec}_{air} = distance covered in complete landing procedure

In-vehicle time (high-speed rail):
The edge in-vehicle time function of high-speed rail, as given in *Equation 3.5*, is constructed similarly but is also characterised by a few differences. The two outside dwelling time terms (t^{dwl}) describe the time needed to unload and load passengers at the station. Moving to the inside, t^{acc} and (t^{dec}) indicate the time needed to accelerate respectively decelerate. Finally, the middle term calculates the cruising time between the stations, which is done similarly to the flying time function above.

$$t_{e_{i,j}}^{inv,hsr} = \frac{t^{dwl}}{2} + t_{hsr}^{acc} + \left(\frac{ds^{dir}(v_i, v_j) \cdot fac_{hsr}^{dt} - ds_{hsr}^{acc} - ds_{hsr}^{dec}}{s_{hsr}^{crs}}\right) + t_{hsr}^{dec} + \frac{t^{dwl}}{2} \tag{3.5}$$

where:

t_{hsr}^{acc} = time needed for the high-speed train to accelerate
ds_{hsr}^{acc} = distance covered in the acceleration procedure
t_{hsr}^{dec} = time needed for the train to decelerate
ds_{hsr}^{dec} = distance covered in the deceleration procedure
t^{dwl} = time needed for the dwelling procedure

The in-vehicle times are important for user travel time calculations, but also for the HSR operator's line feasibility confirmation as will be further discussed in *subsection 3.2.5* and available seat kilometres. Summing the edge specific in-vehicle times for a line l_k and the knowledge of turn-around processes, it is possible to calculate the line-specific round trip time $t_{l_k}^{rt}$.

$$t_{l_k}^{hsr,rt} = 2 \cdot \sum_{e \in \Omega_{l_k}} \left(t_{e_{i,j}}^{inv,hsr}\right) + 2 \cdot t^{hsr,tat} \tag{3.6}$$

where:

$t^{hsr,tat}$ = turn-around time of high-speed train
Ω_{l_k} = set of edges assigned to line l_k

In-vehicle time (car):
Car In-Vehicle Time: Finally, the in-vehicle travel time function of the third mode (car) is given in *Equation 3.7*. Given their relatively short acceleration and deceleration times, in combination with their lower cruising sped, their times are only based on the cruising speed over the travelled distance.

$$t_{e_c(i,j)}^{inv,car} = \frac{ds_{i,j}^{dir} \cdot fac_{car}^{dt}}{s_{car}^{crs}} \tag{3.7}$$

Table 3.5: Overview of this model's mode parameters

Notation	Unit	Description
sc_m		vehicle seating capacity of mode m
fac_m^{load}		design load factor of mode m
s_m^{crs}		average cruising speed of mode m
$t_{i,j}^{l_k}$		total travel time between vertices i and j on line l_k
$t_{i,j}^{tr}$		total travel time between vertices i and j along transfer path pt_s
$t_{l_k}^{hsr,rt}$		round trip time of line l_m
$t^{hsr,tat}$		turn-around time of high-speed train
f_{l_k}		frequency at route l_k

Demand notations

As also mentioned in *subsection 3.1.2* on assumptions, the demand in the model is based on two main simplifications: (1) a fixed total demand with a variable mode-specific demand that is (2) symmetric between OD-pairs. The total (fixed) demand between the vertices v_i and v_j is given by the parameter $dm_{i,j}^{tot}$. Accordingly, the mode-specific demand (based on services offered) is given by $dm_{i,j}^{m}$.

$$f_{l_k} = \frac{q_{l_k}^{max}}{sc_m * fac_m^{load}} \tag{3.8}$$

Based on the proposed line configurations and the according network performance, the passenger demand $dm_{i,j}^{m}$ is assigned to specific direct paths $(p_{i,j}^{d})$ and indirect paths $(p_{i,j}^{t})$ along the network, of which the process is further elaborated in *subsection 3.3.4*. Laying all these paths on top of each other, an edge specific demand $dm_{e_{a,b}}$ can be determined. More important, it is also possible to determine the demand on edge $e_{a,b}$ for line $l_k(i,j)$, which is the value represented by $dm_{e_{a,b}}^{l_k}$. With this line and edge specific demand available, it becomes possible to determine the maximum flow of passengers $q_{l_k}^{max}$ for line l_k. This value can then be combined with the previously explained (*subsection 3.2.2*) seating capacity and design load factor to find the number of vehicles needed to facilitate the demand on line l_k, as done in *Equation 3.8*.

Table 3.6: Overview of this model's demand parameters

Notation	Unit	Description
$dm_{i,j}^{total}$		Total travel demand between vertices i and j
$dm_{i,j}^{m}$		travel demand between vertices i and j for mode m
$dm_{e_c(a,b)}^{l_k}$		travel demand between vertices i and j on line l_k ;
$dm_{i,j}^{p^d}$		travel demand between vertices i and j along direct path pd_r
$dm_{i,j}^{p^t}$		travel demand between vertices i and j along transfer path pt_s
$q_{l_k}^{max}$		maximum flow occurring on the line l_k

3.2.3. Problem decision variables

In the literature study of *subsection 2.3.2*, 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 will also be used in this research, where the set of lines is described as $L = \{l_{k=1}, l_{k=2}, ..., l_{k=L}\}$ and the according frequencies as $F = \{f_{l_{k=1}}, f_{l_{k=2}}, ..., f_{l_{k=L}}\}$. Together, they form a '*line concept*' $C(L,F)$ where a set of lines L are denoted with a set of associated frequencies F. An overview of the model's decision variables can be found in *Table 3.7*.

Table 3.7: Overview of this model's decision variables

Notation	Unit	Description
$L = \{l_{k=1}, l_{k=2}, ..., l_{k=L}\}$	[-]	set of lines
$F = \{f_{l_{k=1}}, f_{l_{k=2}}, ..., f_{l_{k=L}}\}$	[veh/day]	frequency on line l

3.2.4. Problem objectives

The problem as formulated for this research is a cost-oriented model, as explained by Schöbel (2012). In essence, these models have the goal to minimise the operational costs when being subject to service and capacity requirements. The precise formulation of this goal highly depended on the exact problem and will be defined in the subsections below.

Objective function statement

The optimisation question of this research is a multi-objective decision-making problem, meaning that it considers multiple stakeholder's perspectives. To account for these perspectives, the objective function consists of three main costs components: the user's (C_{user}), operator's ($C_{operator}$) and society's ($C_{society}$) costs. Varying the relative weight of these components allows for the comparison of different policy scenarios and stakeholder importance. The weight of each factor is indicated with a factor ψ, of which the aggregated value reaches 100. Together, this results in the statement of *Equation 3.9*.

$$Minimise \;\; Z = (\psi^{user} \cdot C^{user}) + (\psi^{operator} \cdot C^{operator}) + (\psi^{society} \cdot C^{society}) \tag{3.9}$$

Costs components: User

The costs that are experienced by users follow from the time spent on travelling and the associated monetary value that is given to this time (Value of Time, indicated as VoT). As explained in *subsection 3.2.2*, a trip can consist of five main elements: the (1) '*access time*', (2) '*waiting time*', (3) '*in-vehicle time*', (4) '*transfer time*' and (5) '*egress time*'. Considering a network where the demand has been assigned to specific modes and paths, the user costs can be determined by the use of the following formulae.

Access time costs:

The (1) access time $t_{v,m}^{acs}$ is the average time needed to cover the geographical distance between the actual origin of a passenger's trip and the place where the desired mode can be boarded. The time needed for this process differs per vertex and mode, given the differences in vertex properties (i.e. population size and level of mobility) and typical mode-specific boarding locations (i.e. closeness to city centre). Multiplying the average access time needed with the number of passengers using a certain vertex as an access point for their mode gives *Equation 3.10*.

$$c^{access} = VoT^{acs}\left(\sum_{v}\sum_{m}\left(q_{v,m}^{acs} + t_{v,m}^{acs}\right)\right) \tag{3.10}$$

Waiting time costs:

The (2) waiting time $t_{v,m}^{wai}$ is the average time that a passenger needs to wait at the boarding location before departure. Depending on the mode that is used, this time factor can, for example, include passport and security checks or obliged early check-in. The process and location dependencies make that the average waiting time differs per mode and vertex, as can also be seen in *Equation 3.11*.

$$c^{waiting} = VoT^{wai}\left(\sum_{v}\sum_{m}\left(q_{v,m}^{wai} + t_{v,m}^{wai}\right)\right) \tag{3.11}$$

In-vehicle time costs:

The (3) in-vehicle time $t_{ij,m}^{inv}$ is the actual time that a passenger is travelling between vertices i and j with mode m, thus excluding possible transfer times. A more precise and mode-specific formulation of these in-vehicle times is given in *subsection 3.2.2*. The general in-vehicle time costs equation is stated in *Equation 3.12*. Here, the total in-vehicle costs are determined per mode per edge by summing the flows occurring at the edge of interest $e_c(a,b)$ as induced by all direct and transfer paths using that edge. Multiplying this with the time it takes to travel between nodes a and b results in the total hours spent on this edge.

$$c^{in-vehicle} = VoT^{inv}\left(\sum_{m}\sum_{e}\left(\left(\sum_{p_d}\left(q_{p_d,e}^{e,m}\right) + \sum_{p_t}\left(q_{p_t,e}^{e,m}\right)\right)\cdot t_{e,m}^{inv}\right)\right) \tag{3.12}$$

Transfer time costs:

The (4) transfer time t_{hsr}^{trf} is the average time that it takes to transfer between two lines l_k, in case of a passenger following an indirect path between its origin and destination vertex. In most TNDP's, this time depends on the frequency of the lines since passengers and vehicles of different lines are assumed to arrive randomly from each other. Given the long-distance character of this research; however, it is assumed that timetables are adjusted to each other and passengers prepare their trip, which makes that this value can be averaged. The cost function of *Equation 3.13* combines the average transfer time with the flow of passengers following this indirect path and the associated number of transfers.

$$c^{transfer} = VoT^{trf}\left(\sum_{m}\sum_{p_t}\left(\sum_{i,j} q_{m,p_t}\cdot\left(n_{p_t}^{trf}\cdot t_{hsr}^{trf}\right)\right)\right) \tag{3.13}$$

Egress time costs:
The (5) egress time $t_{v,m}^{egr}$ is the average time needed to cover the geographical distance between the place where the transport mode is deboarded and the actual destination of a passenger's trip. This makes that this term, which is stated in *Equation 3.14*, is the opposite of the access time. The main difference in the formulation phase is that now the destination is considered.

$$c^{egress} = VoT^{egr}\left(\sum_{v}\sum_{m}\left(q_{v,m}^{egr} + t_{v,m}^{egr}\right)\right) \tag{3.14}$$

Costs components: operator
The operator in this problem is responsible for financing the system, which brings that this stakeholder has an interest in minimising these costs for the service provided. According to (Zschoche et al., 2012), the operating expenditures are the ongoing costs to provide the services required for the operation of a (high-speed) railway undertaking, such as the train staff, energy use, overhead costs, track access charges and station management. The same authors find that staff costs and rolling stock maintenance expenditures represent the highest share of railway costs for the United Kingdom's network. Following this, the problem of this research includes (1) '*operational expenses*' and (2) '*maintenance expenses*' of the high-speed rail system. These two costs components are further defined in *Equation 3.15* and *Equation 3.16*, according to the marginal cost-km function related to the type of operator costs.

$$c^{operational} = \sum_{l_k\in L}\left(2\cdot ln_{l_k}^{str}\cdot f_{l_k}\cdot sc_{hsr}\right)\cdot c^{oper.,marg.} \tag{3.15}$$

and;

$$c^{maintenance} = \sum_{l_k\in L}\left(2\cdot ln_{l_k}^{str}\cdot f_{l_k}\cdot sc_{hsr}\right)\cdot c^{main.,marg.} \tag{3.16}$$

where:

$c^{oper.,marg.}$ = marginal operator operational expenses in $[€/seat - km]$
$c^{main.,marg.}$ = marginal operator maintenance expenses in $[€/seat - km]$
sc_{hsr} = vehicle seating capacity of high-speed rail

Costs components: society
The societal costs of passenger transport follow from indirect effects that are not privately paid by the actual user, but rather by society. Internalising these costs can be done by integrating an external costs factor into the objective function. This cost component, as stated in *Equation 3.17*, combines the flow of passengers on a mode-specific edge with the associated external costs per kilometre of this mode and the length of this edge.

$$c^{societal} = \sum_{m} \sum_{e} \left(\left(\sum_{p_d} \left(q_{p_d,e}^{e,m} \right) + \sum_{p_t} \left(q_{p_t,e}^{e,m} \right) \right) \cdot ln_e^{str} \cdot c_m^{ext.,marg.} \right) \tag{3.17}$$

where:

$c_m^{ext.,marg.}$ = marginal aggregated external costs for mode m in $[€/passenger - km]$

Aggregated objective function formulation

Expanding the basic objective statement of *Equation 3.9* with the operator's, user's and societal cost components - as formulated in the paragraphs above - results in the objective function of this problem, which is stated in *Equation 3.18* below.

$$\begin{aligned}
Min \;\; Z = \psi_{user} \quad & \cdot \left[VoT^{acs} \left(\sum_{v} \sum_{m} \left(q_{v,m}^{acs} + t_{v,m}^{acs} \right) \right) \right] & + \\
\psi_{user} \quad & \cdot \left[VoT^{wai} \left(\sum_{v} \sum_{m} \left(q_{v,m}^{wai} + t_{v,m}^{wai} \right) \right) \right] & + \\
\psi_{user} \quad & \cdot \left[VoT^{inv} \left(\sum_{m} \sum_{e} \left(\left(\sum_{p_d} \left(q_{p_d,e}^{e,m} \right) + \sum_{p_t} \left(q_{p_t,e}^{e,m} \right) \right) \cdot t_{e,m}^{inv} \right) \right) \right] & + \\
\psi_{user} \quad & \cdot \left[VoT^{trf} \left(\sum_{m} \sum_{p_t} \left(\sum_{i,j} q_{m,p_t} \cdot \left(n_{p_t}^{trf} \cdot t_{hsr}^{trf} \right) \right) \right) \right] & + \\
\psi_{user} \quad & \cdot \left[VoT^{egr} \left(\sum_{v} \sum_{m} \left(q_{v,m}^{egr} + t_{v,m}^{egr} \right) \right) \right] & + \\
\psi_{operator} \quad & \cdot \left[\sum_{l_k \in L} \left(2 \cdot ln_{l_k}^{str} \cdot f_{l_k} \cdot sc_{hsr} \right) \cdot c^{oper.,marg.} \right] & + \\
\psi_{operator} \quad & \cdot \left[\sum_{l_k \in L} \left(2 \cdot ln_{l_k}^{str} \cdot f_{l_k} \cdot sc_{hsr} \right) \cdot c^{main.,marg.} \right] & + \\
\psi_{external} \quad & \cdot \left[\sum_{m} \sum_{e} \left(\left(\sum_{p_d} \left(q_{p_d,e}^{e,m} \right) + \sum_{p_t} \left(q_{p_t,e}^{e,m} \right) \right) \cdot ln_e^{str} \cdot c_m^{ext.,marg.} \right) \right] & +
\end{aligned} \tag{3.18}$$

3.2.5. Problem constraints

To ensure feasible results that also remain within computational limits, the model's solution possibilities are bounded by a series of constraints. The constraints apply to multiple aspects of the problem and serve different functions. For structure reasons, they are divided into three categories: (1) '*Line Design Constraints*', (2) '*Frequency and Timetable Constraints*' and (3) '*Passenger Path Constraints*'. Below, an assessment of each of the categories is made.

Line design constraints

The contribution of line design constraints for this problem is twofold. Firstly, (1) assigning certain limits to line design increases the realism of the proposed solution, as unfeasible lines are eliminated. However, equally important is that (2) the number of lines that have to be evaluated greatly impact the computational burden of the problem. By strategically reducing the number of feasible lines, the applied constraints can contribute to a quick solution finding. An overview of the line design constraints is provided in *Table 3.8*.

Table 3.8: Overview of this model's Line Design Constraints

Constraints	**Name**	**Description**	**Reference**
Line Design	Line length	minimum distance covered per line	*Equation 3.19*
	No. of stops	minimum number of stops per line	*Equation 3.20*
	Round Trip Time	maximum round trip time	*Equation 3.21*
	Line symmetry	line $l(i,j)$ from v_i to v_j equals $l_(j,i)$ from v_j to v_i	*Equation 3.22*
	Infrastructural line detour	maximum detour within infra. network	*Equation 3.23*
	Geographical line detour	maximum detour compared to greater circle distance	*Equation 3.24*

Minimum line length:
The line length constraint of *Equation 3.19* bounds the problem solution to lines that have at least a minimum stretching length of $ln_{l_k}^{str,min}$. This measure ensures a differentiation to conventional railway lines, as well that it contributes to the level of operational and practical efficiency from the operators perspective.

$$ln_{l_k}^{str,min} \leq ln_{l_k}^{str} \qquad \forall \qquad l_k \in L \tag{3.19}$$

Minimum number of stops:
Additional to the previous requirement concerning the minimum line length, the constraint of *Equation 3.20* contributes to the efficiency of the solution by excluding lines with fewer than $n^{s_l,min}$ stops.

$$n^{s_l,min} \leq n^{s_l} \qquad \forall \qquad l_k \in L \tag{3.20}$$

Round trip time:
Practicalities - such as staff working hours, cleaning moments or daily maintenance - can limit a vehicle's daily operational hours. This factor is included in the model by the use of the '*Round Trip Time*' constraint as described in *Equation 3.21*, where the round trip time is determined by the double summation of the edge in-vehicle and terminal station t^{buf} buffer times.

$$t_{l_k}^{hsr,rt} \leq t_{l_k}^{hsr,rt,max} \qquad \forall \qquad l_k \in L \tag{3.21}$$

Line symmetry:
To ensure continuity, it is desirable to have symmetrical lines, meaning that they run the same but opposite sequence of stops in both directions. The mathematical formulation of this '*line symmetry*' constrain is described in *Equation 3.22*.

$$l_k(i,j) = (\, l_k(j,i)\,)^{-1} \qquad \forall \qquad i,j \in V \tag{3.22}$$

Infrastructural line detour:
To reduce the number of lines, those with too strong infrastructural detours can be excluded by *Equation 3.23*, which compares the stretching length of line $ln_{l_{k(i,j)}}^{str}$ to the shortest possible path $p_{i,j}^{d,min}$ through the graph by a factor $fac^{dt,infra}$

$$ln_{l_{k(i,j)}}^{str} \leq fac^{dt,infra} \cdot p_{i,j}^{d,min} \tag{3.23}$$

Geographical line detour:
Again, to reduce the number of lines in the pool of lines, those that are deviating too much from the

greater circle distance due to natural barriers like water- or mountain bodies can be excluded by the use of *Equation 3.24*. Here, the line length $ln^{str}_{l_{k(i,j)}}$ is compared to the greater circle distance $ds^{gc}_{i,j}$ with a factor $fac^{dt,geo}$.

$$ln^{str}_{l_{k(i,j)}} \leq fac^{dt,geo} \cdot ds^{gc}_{i,j} \tag{3.24}$$

Frequency and timetable constraints

Numerous TNDFSP researches consider a set of feasible line frequencies and vehicle headways, such that it is possible to construct user-friendly timetables in succeeding design phases (Gallo et al., 2011). However, given the longer time-horizon (thus more strategic research) and the less repetitive character of long-distance travel; however, the problem of this research does not consider this. Nonetheless, three requirements - deduced from the main above described standard - are still applied to ensure a feasible result. An overview of frequency and timetable constraints is stated in *Table 3.9*

Table 3.9: Overview of this model's Frequency and Timetable Constraints

Constraints	Name	Description	Reference
Frequency & Timetable	Min. frequency	minimum frequency prevents negativity ghost lines	*Equation 3.25*
	Int. frequencies	only integer frequencies are allowed	*Equation 3.26*
	Freq. symmetry	continuity in number of trains per direction	*Equation 3.27*

Minimum frequency:

A minimum frequency constraint, as given in *Equation 3.25*, ensures non-negativity for the lines that are selected. For every single line, one could also consider a maximum frequency. However, doing this implies that the problem becomes combinations as spilling passengers reduces the level of service and thus influences the mode-specific demand.

$$f_{min} \leq f_{l_k} \qquad \forall \qquad l_k \in L \tag{3.25}$$

Integer frequencies:

For realism and practical planning reasons, it is desirable to work with integer frequencies. This has been formulated in *Equation 3.26*

$$f_{l_k} = \mathbb{Z} \qquad \forall \qquad l_k \in L \tag{3.26}$$

Frequency symmetry:

The problem of this research does not incorporate operational strategies, such as deadheading or short turning. This brings that, to ensure continuity, frequencies on symmetrical lines have to be identical. This '*frequency symmetry*' constraint is stated in *Equation 3.27*.

$$f_{l_k(i,j)} = \left(f_{l_k(j,i)} \right)^{-1} \qquad \forall \qquad i,j \in V \tag{3.27}$$

Passenger path constraints

From the method validation - as will later be performed in *chapter 5* - it was found that the model was not able to find feasible or realistic solutions when running the model without restrictions on the passenger's ability to travel through the network. This, because some less desirable paths turn out to result in relatively low passenger benefits whilst requiring high operator expenses, thus leaving the finalised network in an undeveloped stage. This led to the inclusion of three constraints, which are displayed in *Table 3.10* and further elaborated on below.

Table 3.10: Overview of this model's Passenger Path Constraints

Constraints	Name	Description	Reference
Passenger Path Constraints	Max. no. of transfers	limits the number of transfers	*Equation 3.28*
	Strategic pricing (infrastructural)	excludes infrastructural detouring passengers	*Equation 3.29*
	Strategic pricing (geographical)	excludes geographical detouring passengers	*Equation 3.30*

Maximum number of transfers:
Firstly, *Equation 3.28* limits the maximum number of transfers per path. This constraint is mainly for computational reasons - as the search for transfer paths is very extensive - but it is also an essential tool for the design and performance of the network, as will be found in *section 5.2* on the method's validation and *section 6.3* on passenger path control experiments.

$$n^{trf}_{p^t} \leq n^{trf,max}_{p^t} \qquad \forall \qquad p^t \in P \tag{3.28}$$

Strategic pricing for unprofitable passengers:
Again, *section 5.2* proves the necessity of excluding unprofitable passengers from the system, as this leaves the solution with a network that is built up from multiple unconnected sub-networks, so-called '*network islands*'. The first strategic pricing constraint is described by *Equation 3.29*, which excludes passengers that follow a path $p(i,j)$ (direct or indirect) through the network that deviates with a factor $fac^{SPL,infra}$ in distance and time from the shortest path time $t^{inv,min}_{p^d(i,j)}$.

$$p(i,j) = \begin{cases} feasible, & \text{if } t^{inv\&trf}_{p(i,j)} \leq fac^{SPL,infra} \cdot t^{inv,min}_{p^d(i,j)} \\ infeasible, & \text{otherwise} \end{cases} \tag{3.29}$$

Similarly, the second strategic pricing constraint, as displayed in *Equation 3.30*, quantitatively describes the exclusion of passengers that follow a path which detours from their greater circle due to natural barriers. An important note from the experiment of *section 6.3* on passenger path control strategies was that no indication for the effectiveness of this constraint could be found.

$$p(i,j) = \begin{cases} feasible, & \text{if } ln^{str}_{p(i,j)} \leq fac^{SPL,geo} \cdot ds^{gc}_{i,j} \\ infeasible, & \text{otherwise} \end{cases} \tag{3.30}$$

3.3. Model Formulation

In *subsection 2.2.1* on the complexity TNDFSPs, it was found that conventional solution strategies are non-sufficient for real-scale problems, which makes that the solution strategy is reliant on (meta) heuristics. This section is concerned with the development of a solution methodology which is able to find a result for the defined problem of *section 3.2*, whilst also respecting the requirements of the methodological approach of *subsection 3.1* and using the lessons of the literature review that was performed in *chapter 2*.

An initialisation of the model's formulation is given in *subsection 3.3.1*. This consists of a detailed underpinning for a solution strategy, after which a high-level approach is formulated for this specific study. Following this, the three main components of the proposed heuristic are discussed in *subsection 3.3.2* (LGP; '*Line Generation Procedure*'), *subsection 3.3.3* (LCP; '*Line Configuration Procedure*') and *subsection 3.3.4* (NAP; '*Network Analysis Procedure*'). Finally, the outputs that are to be produced by the model are presented in *subsection 3.3.5*.

3.3.1. Model initialisation

The problem as presented in *section 3.2* can be categorised as a '*Transit Network Design and Frequency Setting Problem*' (TNDFSP). As explained in *subsection 2.2.1* on '*Problem Complexity*', it was shown by preceding researches that these problems typically come with six characteristic difficulties. Additionally, considering that the problem of this research works on a real-life scale (more specific the European HSR network), it can be expected that the presented network will reside a substantial number of vertices and feasible lines in between. Combining this with the secondary decision variable on frequencies and the previously mentioned NP-hardness of the problem, it follows that this problem quickly reaches a very extensive solution space that is hard to explore. This is in line with the previous finding that these problems are rarely solvable using conventional techniques. The paragraphs below work towards the formulation of an approach, which considers both the study's goals as well as the typical TNDFSP characteristics.

Considerations and model development

Summarising the model's objectives and constraints of *subsection 3.1.1* into four main requirements that are relevant for the solution approach, it is found that the model's solution approach has to be (1) light-weight and (2) flexible, such that is possible to perform an extensive analysis for different objective scenarios and parameters. Additionally to this, the model is required to (3) regularly report clear output during and after the optimisation process, as this allows for an actual understanding of the development towards good performing solutions. Finally, to ensure accurate and reliable findings, it is also important that the model comes to (4) reasonably optimal and representative solutions. Given the focus of this research to an understanding of design choices rather than the delivery of an exact building plan, it not necessarily needed to find the most perfect answer.

Taking the typical TNDFSP difficulties into account and analysing a variety of transit planning works, Kepaptsoglou & Karlaftis (2009) found two fundamental solution strategies (as discussed in *section 2.4*). These strategies require either a starting network of which the lines can be altered ('*Line Configuration & Improvement*'; LCI) or a set of lines from which a selection can be made ('*Line Generation & Configuration*'; LGC). Given the currently limited available knowledge on how such networks or lines should look like, it is chosen to use the latter option (LGC) and provide the system with a diverse palette of lines. The greater advantage of using this strategy is the ability to start with a relatively large number of candidate routes. This allows for more variations and thus improved results, but is also beneficial as the current knowledge on line configurations for HSR is rather limited.

High-level solution approach

The proposed '*line Generation and Configuration Method*' (LGC) approach was defined by Kepaptsoglou & Karlaftis (2009) and previously discussed in *section 2.4*. In *Figure 3.2*, a high-level overview of this solution approach is presented. The figure consists of five main components. As '*Input*', it receives the initial problem definition as discussed in *section 3.2* and the operationalised parameters of *chapter 4*. Together, these make an environment to work in. Executing a range of procedures, it works towards the '*Output*'. This output consists of a resulting line configuration (thus set of lines and frequencies) with their associated performance details.

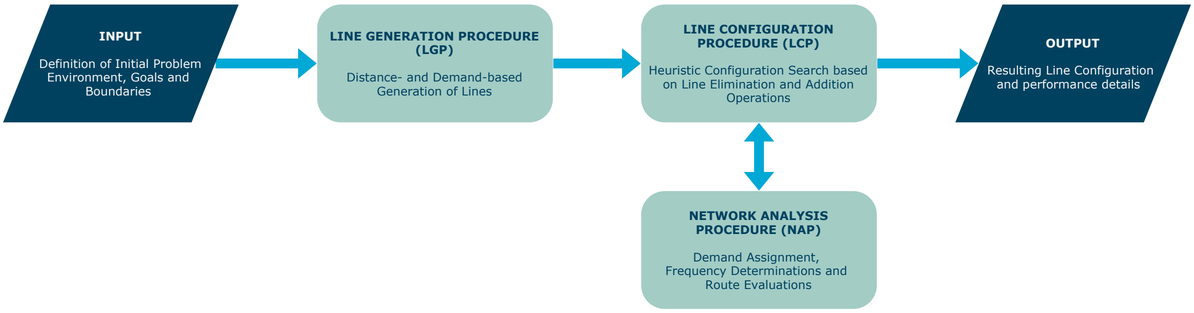

Figure 3.2: Proposed high-level solution approach

To reach this state, three main procedures are used. Firstly, the '*Line Generation Procedure*' (LGP) builds a pool of feasible and strategically designed lines. These lines are then transferred to the '*Line Configuration Procedure*' (LCP). This procedure guides the search for a strong performing solution by strategically selecting multiple sets of lines. The proposed configurations are simulated and assessed on their performance in '*Network Analysis Procedure*' (NAP). Following this, the LCP decides which next move is most suitable, meaning that the latter two are in continuous consultation with each other.

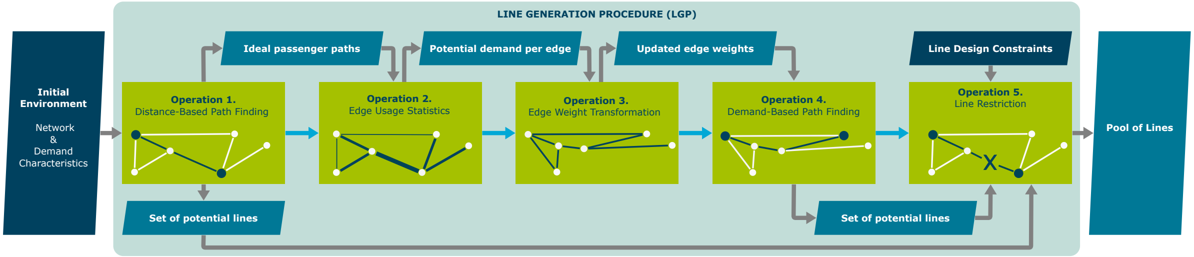

Figure 3.3: Flowchart of the customised Line Generation Procedure (LGP) - (detail of *Figure 3.2*)

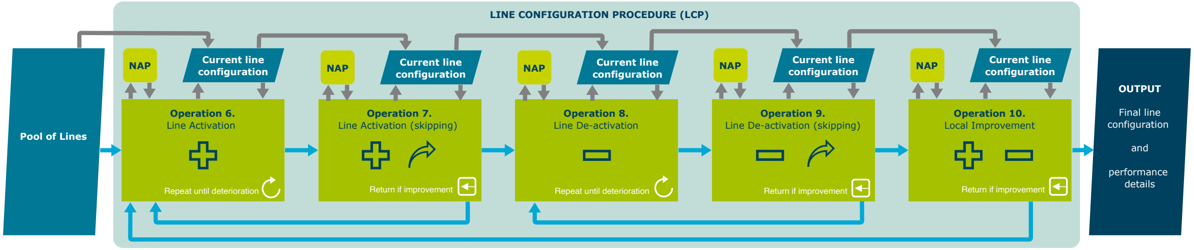

Figure 3.4: Flowchart of the customised Line Configuration Procedure (LCP) - (detail of *Figure 3.2*)

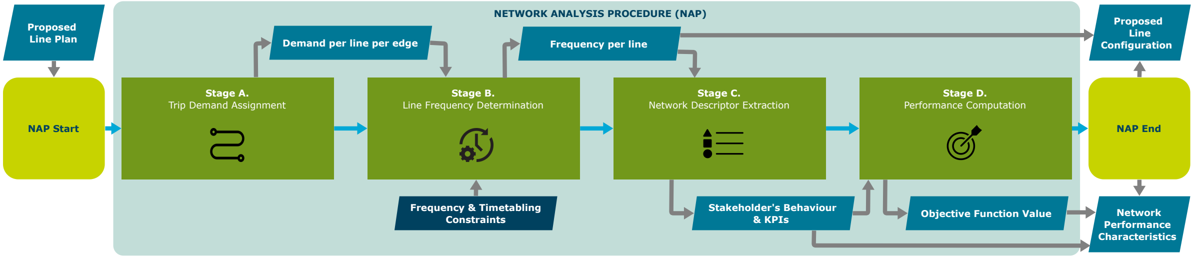

Figure 3.5: Flowchart of the customised Network Analysis Procedure (NAP) - (detail of *Figure 3.2*)

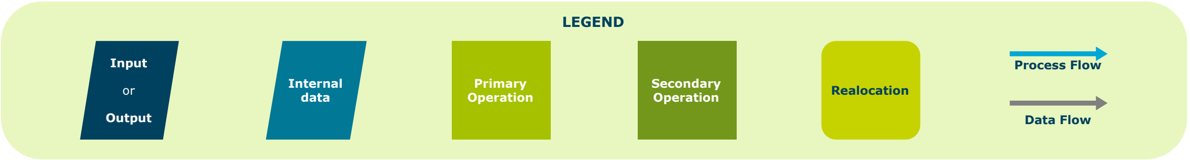

Figure 3.6: Legend for the flowchart components

Framework of the detailed solution approach

The three main procedures of the typical '*Line Generation and Configuration*' method leave a lot of room for a customised approach, allowing the solution model to conform the problem's challenges and solution requirements. Expanding the high-level solution approach of *Figure 3.2* into a more detailed overview of processes, the customised approach of this specific model is presented in *Figure 3.3* for the Line Generation Procedure, *Figure 3.4* for the Line Configuration Procedure and *Figure 3.5* for the Network Analysis Procedure. In these frameworks, the three main procedures are again recognisable by the turquoise blocks. The procedures are split-up in multiple operations (green), which are then connected by process flow arrows (blue) and information exchange flow arrows (gray), as displayed in the legend of *Figure 3.6*.

The proposed model for this research starts at the upper-left corner of *Figure 3.2*, where the initial environment is presented to the Line Generation Procedure (LGP). This LGP combines travel time along the edges and the preferred passenger paths between vertices to come up with a strategically chosen set of candidate lines. Together, these candidate lines form the '*Pool of Lines*' (indicated in bright-blue), which feed the subsequent Line Configuration Procedure.

Following the LGP, the Line Configuration Procedure (LCP) is initiated with a completely deactivated pool of lines. Using a line activation operation (6.) to sequentially increase the number of lines, a line deactivation operation (8.) to eliminate lines and a local improvement operation (10.) to swap lines, the LCP works its way to the desired state of a multi-line network. To prevent getting stuck in local optima, operations 7. and 9. allow for temporary deteriorations before moving on to the next strategy.
.

The operations of the LCP show constant interactions with Network Analysis Procedure (NAP), which originates from the LCP's required knowledge on the performance of different decision alternatives. To find these performances, the LCP constantly consults the NAP, which is responsible for this task. The NAP follows a procedure in which passenger paths through the HSR network are determined with a transfer minimisation assumption, after which the passengers are assigned to different modes using random regret minimisation theories. With this knowledge, the required frequencies, graph descriptors and system performance are determined.

Example graph for further illustrations

The heuristic, as proposed in this chapter frequently performs operations that build upon previously acquired information. To illustrate and explain these actions more clearly, a hypothetical example graph $G^e x$. is introduced. A visualisation of this graph is given in *Figure 3.7*. Here it can be seen that it consists of the vertices $V = \{A, B, C, D, E, F\}$, that it is partially connected by undirected edges and that the weight of these edges is indicated by a number representing the riding time $t_{e,m}^{riding}$.s The example graph does not distinguish for different modes but does include a travel demand between vertices. *Figure 3.8* shows the demand matrix $D^{ex.}$ that is associated to $G^e x$..

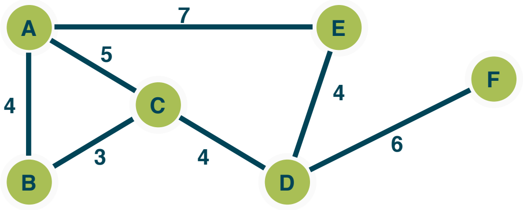

Figure 3.7: Examplementary graph $G^{ex.}(V, E)$

$$D^{ex.} = \begin{pmatrix} 0 & 4 & 7 & 3 & 6 & 1 \\ 4 & 0 & 7 & 2 & 1 & 1 \\ 7 & 7 & 0 & 6 & 4 & 2 \\ 3 & 2 & 6 & 0 & 5 & 3 \\ 6 & 1 & 4 & 5 & 0 & 2 \\ 1 & 1 & 2 & 3 & 2 & 0 \end{pmatrix}$$

Figure 3.8: Examplementary demand matrix $D^{ex.}$

3.3.2. Line Generation Procedure

The Line Generation Procedure (LGP) is responsible for providing the algorithm with a set of lines from which it can select a set. According to Kiliç & Gök (2014), the efficiency of a TNDFSP-like problem mainly depends on the quality of the initial line solution set and the ability to search the solution space, although the former is typically more important. *Balance between quality and*

problem size:
Given that a line activation and deactivation heuristic is used in this research, it should be accounted for that the solution space is not as extensively and diversely examined as by some other meta-heuristics. To compensate for this, it is even more important to provide the system with high-quality lines. Additionally, considering the goals for the solution approach as formulated in *subsection 3.3.1*, it is also important that the set of lines resulting from the LGP is not unnecessarily large. Safeguarding this contributes to a smaller computational burden, as it requires less direct effort for the LGP as well as indirect effort for the LCP and NAP. however, within this process, a balance should be found in the detraction of the solution quality that will follow from this decision.

Previous attempts in improving the quality of line generation procedures:
Many of the older works (e.g. Sonntag (1977) and Mandl (1980), started their TNPP's by generating a pool of lines that consisted of the shortest paths between all OD-pairs, based on either distance or time. With this method, two problems arise: (1) an exponentially growing number of lines for a linear increase in vertices and (2) a set of lines that only considers the minimisation of distances rather than intelligent use of demand knowledge. To minimise the drawbacks of these fundamental methods, two main modifications are proposed. The first relates reducing the number of lines by smartly using symmetry, imposing constraints and pre-selecting more probable lines, whereas the second relates to the utilisation of expected traffic flows. For this second modification, the '*shortest path usage map*' theory as formulated by Kiliç & Gök (2014) and further developed by Heyken Soares et al. (2019) is used.

Combining the fundamental methods with the two modifications as explained above, results in the proposal of the LGP framework as was previously depicted in *Figure 3.3* and is revisited in *Figure 3.9*. Here, it can be seen that the LGP consists of five separate operations. The first operation finds shortest paths based on riding times $t_{e,m}^{riding}$ with a two-fold goal: to identify idealised passenger paths (output above) and construct the first candidate lines (output below). Continuing into the next two operations, the edge usage statistics strategy of Kiliç & Gök (2014) is applied to describe favourable edges and the principles of Heyken Soares et al. (2019) are used to translate these into new edge weights, that consider both the time and expected demand. Following this, demand-based paths are constructed in the fourth operation. Finally, all proposed lines are tested for feasibility on line design constraints as formulated in *subsection 3.2.5*, which are included via '*Input II.*'.

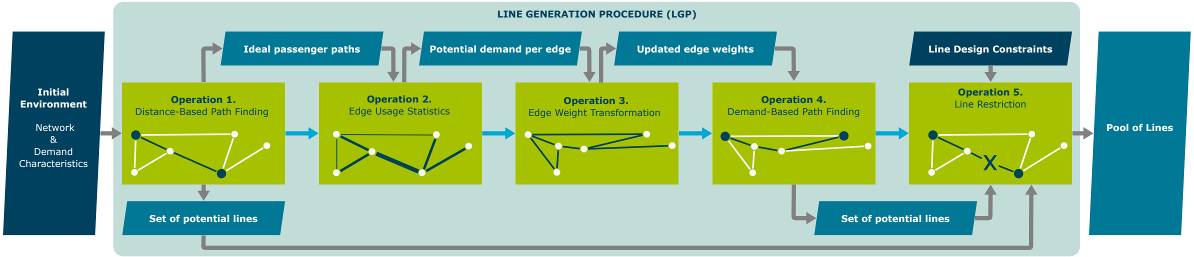

Figure 3.9: Flowchart of Line Generation Procedure (LGP) - (revisit of *Figure 3.3*)

Operation 1: Distance-Based Path Finding
To find the ideal passenger flows - from the passenger's perspective - a shortest path search is performed, for which it is chosen to apply Dijkstra's algorithm (Dijkstra, 1959). Using the available infrastructure and the associated riding time edge weights, a shortest path is determined for each OD-pair. This step results in a shortest path matrix SP, of which an illustration for the example network is given in *Figure 3.10*. Here, a path between origin v_i and destination v_j is denoted as a sequence of edges $\{e(v_i, v_{...}), ..., e(v_{...}, v_j)\}$. For space-saving reasons, the e has been left out.

$$SP^{ex.} = \begin{bmatrix} \text{n/a} & \{(A,B)\} & \{(A,C)\} & \{(A,C),(C,D)\} & \{(A,E)\} & \{(A,C),(C,D),(D,F)\} \\ \{(B,A)\} & \text{n/a} & \{(B,C)\} & \{(B,C),(C,D)\} & \{(B,A),(A,E)\} & \{(B,C),(C,D),(D,F)\} \\ \{(C,A)\} & \{(C,B)\} & \text{n/a} & \{(C,D)\} & \{(C,A),(A,E)\} & \{(C,D),(D,F)\} \\ \{(D,C),(C,A)\} & \{(D,C),(C,B)\} & \{(D,C)\} & \text{n/a} & \{(D,E)\} & \{(D,F)\} \\ \{(E,A)\} & \{(E,A),(A,B)\} & \{(E,D),(D,C)\} & \{(E,D)\} & \text{n/a} & \{(E,D),(E,F)\} \\ \{(F,D),(D,C),(C,A)\} & \{(F,D),(D,C),(C,B)\} & \{(F,D),(D,C)\} & \{(F,D)\} & \{(F,D)(D,E)\} & \text{n/a} \end{bmatrix}$$

Figure 3.10: Example shortest path matrix $SP^{ex.}$

Operation 2: Edge Usage Statistics

The edge usage $u(i,j)$ is a value that indicates the relative crowdedness on a link when considering the flow of passengers and edge length. To find this, the regular edge weights (riding times $t_{e,m}^{riding}$) are combined with the demand matrix D and the shortest path matrix SP. The edge usage value $u(i,j)$ can be determined by the use of *Equation 3.31*, where the passenger flows using a specific edge are divided by its own edge weight (riding time). For illustration, the usage matrix graph for the example network is given in *Figure 3.12*.

$$u'(i,j) = \frac{1}{t_{e,m}^{riding}} \cdot \sum_{\forall x,y} \mathbf{1}_{e(i,j)} \left(SP_{i,j}\right) \cdot dm_{x,y}^{m}$$
$$where: \tag{3.31}$$
$$\mathbf{1}_{e(i,j)} \left(SP_{i,j}\right) = \begin{cases} 1 \; if \; e(i,j) \in SP_{x,y} \\ 0 \; if \; e(i,j) \notin SP_{x,y} \end{cases}$$

To be able to use these numbers in further stages, the values of the usage matrix can be normalised by the use of *Equation 3.32*. After this modification, all numbers range between 0 and 1. The result for the example graph can be found in *Figure 3.13*.

$$u(i,j) = \frac{u'(i,j)}{\sum_{\forall x,y}(u'(i,j))} \tag{3.32}$$

$$DM_{ex}^{e,est.} = \begin{pmatrix} & 5 & 11 & & 7 & \\ 5 & & 10 & & & \\ 11 & 10 & & 19 & & \\ & & 19 & & 11 & 9 \\ 7 & & & 11 & & \\ & & & 9 & & \end{pmatrix}$$

Figure 3.11: Estimated aggregated demand per edge (example)

$$U'_{ex} = \begin{pmatrix} & 5/4 & 11/3 & & 7/7 & \\ 5/4 & & 10/3 & & & \\ 11/3 & 10/3 & & 19/2 & & \\ & & 19/2 & & 11/4 & 9/6 \\ 7/7 & & & 11/4 & & \\ & & & 9/6 & & \end{pmatrix}$$

Figure 3.12: Estimated usage per edge/distance (example)

$$U_{ex.}^{nor.} = \begin{pmatrix} & 0.26 & 0.77 & & 0.21 & \\ 0.26 & & 070 & & & \\ 0.77 & 0.70 & & 1.00 & & \\ & & 1.00 & & 0.58 & 0.32 \\ 0.21 & & & 0.58 & & \\ & & & 0.32 & & \end{pmatrix}$$

Figure 3.13: Estimated and normalised usage per edge/distance (example)

Operation 3: Edge Weight Transformation

From this stage on, a diversion from the technique of Kiliç & Gök (2014) is made. This, to follow the direction of Heyken Soares et al. (2019) with a slightly different accent. In their work, Heyken Soares et al. (2019) perform a simple transformation on the edge usage statistics by inverting the values and using them as weights for the edges in the graph. This action results in a map where highly used edges have shortest "distances", such that they are chosen by a shortest path algorithm. So far, this strategy will be followed.

Searching for a relatively large number of lines between a relatively small number of (terminal) vertices, Heyken Soares et al. (2019) gradually decreases the importance of the edge usage compared to riding time for multiple cycles. However, given that for this research one demand-based line per OD-pair results in an already substantial number of lines, it is chosen to combine the two weight-types in a constant manner. To do this, the formula of *Equation 3.33* and the relative importance factor fac^{usage} are introduced.

$$w^{comb}(i,j) = \left(u^{nor.,inv}(i,j) \cdot fac^{usage}\right) + \left(t^{rid,norm.}(i,j) \cdot (1 - fac^{usage})\right) \tag{3.33}$$

To perform the statement of *Equation 3.33*, a few modifications are necessary. In order to counter the opposite relations of edge usage (positive) and riding times (negative), it is decided to inverse the former one to $u^{nor.,inv}(i,j)$, as illustrated for the example graph in *Figure 3.14*. Following this, the travel times are normalised to create an equal comparison, which are indicated by $t^{rid,norm.}(i,j)$. The result of this move for the example graph can be seen in *Figure 3.15*. In *Equation 3.33*, one new factor is introduced: fac^{usage}. This factor determines the relative importance between the edge usage and the original riding times, a value that can vary between 0 and 1. An arbitrary value of $fac^{usage} = 0.75$ is used for this example, of which the outcomes for the example graph can be seen in *Figure 3.16*. This value of fac^{usage} differs along different stages of the research and will be indicated likewise.

$$U^{nor.in.}_{ex.} = \begin{pmatrix} & 0.74 & 0.23 & & 0.79 & \\ 0.74 & & 0.30 & & & \\ 0.23 & 0.30 & & 0.00 & & \\ & & 0.00 & & 0.42 & 0.68 \\ 0.79 & & & 0.42 & & \\ & & & 0.68 & & \end{pmatrix}$$

Figure 3.14: Inverted usage per edge/distance (example)

$$T^{rid,nor.}_{ex.} = \begin{pmatrix} & 0.57 & 0.71 & & 1.00 & \\ 0.57 & & 0.43 & & & \\ 0.71 & 0.43 & & 0.57 & & \\ & & 0.57 & & 0.57 & 0.86 \\ 1.00 & & & 0.57 & & \\ & & & 0.86 & & \end{pmatrix}$$

Figure 3.15: Normalised riding times per edge (example)

$$W^{comb.}_{ex.} = \begin{pmatrix} & 0.70 & 0.35 & & 0.84 & \\ 0.70 & & 0.33 & & & \\ 0.35 & 0.33 & & 0.14 & & \\ & & 0.14 & & 0.46 & 0.73 \\ 0.84 & & & 0.46 & & \\ & & & 0.73 & & \end{pmatrix}$$

Figure 3.16: Combined edge weights for fac^{usage} = 0.75 (example)

Operation 4: Demand-Based Path Finding

Aiming for a relatively small but also higher quality pool of lines, the previously found adjusted edge weights can be used to construct lines that consider both travel times and edge demand preferences. In this fourth operation, the lines are again found by the use of the Dijkstra's shortest path algorithm as introduced in Operation 1. Dijkstra (1959). This step results in a demand-based path matrix DP, of which an illustration for the example network is given in *Figure 3.17*. For the example graph, it is seen that two new routes are found: from '*A*' to '*B*' and from '*B*' to '*E*'.

$$DP^{ex.} = \begin{bmatrix} \textit{n/a} & \{(A,C),(C,B)\} & ” & ” & ” & ” \\ \{(B,C),(C,A)\} & \textit{n/a} & ” & ” & \{(B,C),(C,D),(D,E)\} & ” \\ ” & ” & \textit{n/a} & ” & ” & ” \\ ” & ” & ” & \textit{n/a} & ” & ” \\ ” & \{(E,D),(D,C),(C,B)\} & ” & ” & \textit{n/a} & ” \\ ” & ” & ” & ” & ” & \textit{n/a} \end{bmatrix}$$

Figure 3.17: Example Demand-Based Path matrix $DP^{ex.}$

Operation 5: Line Restriction

Together, Operation 1. and Operation 4. provide the '*Line Restriction*' operation (5.) with a range of possible lines for the solution. Given the iterative character of the LCP, it is desirable to remove lines that are infeasible at an early stage, as this reduces the computational burden. In this phase, lines are removed based on two principles: (1) identicality and (2) line design constraints. Later on, in the '*Method validation*' of this research (see section 5.1 on '*Heuristic performance*'), it will be found that the remaining number of lines is still too large for a real scale problem to be solved. To overcome this, two more restrictive steps are taken: (3) the assignment of key cities where lines have to begin or terminate and (4) the tactical selection of lines. More on these steps can be found in subsection 5.1.3 on '*Computation time control*'.

Removing lines based on identicality:
The edge usage statistics as determined in Operation 2 and applied in operations 3. and 4. only partially determine the demand-based path between two vertices, which makes that it is possible to find a demand-based path which is identical to a distance-based path. Something that was also seen in *Figure 3.17*, where only two new lines were found. To prevent double work, identical lines are reduced to one.

Imposing the line design constraints:
The final line configuration $C(L, f_l)$ is subject to three types of constraints, as explained in subsection 3.2.5. The first of these three - line design constraints - can already be implemented in this phase of the model, as infeasible lines would only blur further processes. In *Table 3.11*, an overview of effectuated constraints is stated.

Table 3.11: Overview of this model's Line Design Constraints *(revisit of Table 3.8)*

Constraints	Name	Description	Reference
Line Design	Line length	minimum distance covered per line	*Equation 3.19*
	No. of stops	minimum number of stops per line	*Equation 3.20*
	Round Trip Time	maximum round trip time	*Equation 3.21*
	Line symmetry	line $l(i, j)$ from v_i to v_j equals $l_(j, i)$ from v_j to v_i	*Equation 3.22*
	Infrastructural line detour	maximum detour within infra. network	*Equation 3.23*
	Geographical line detour	maximum detour compared to greater circle distance	*Equation 3.24*

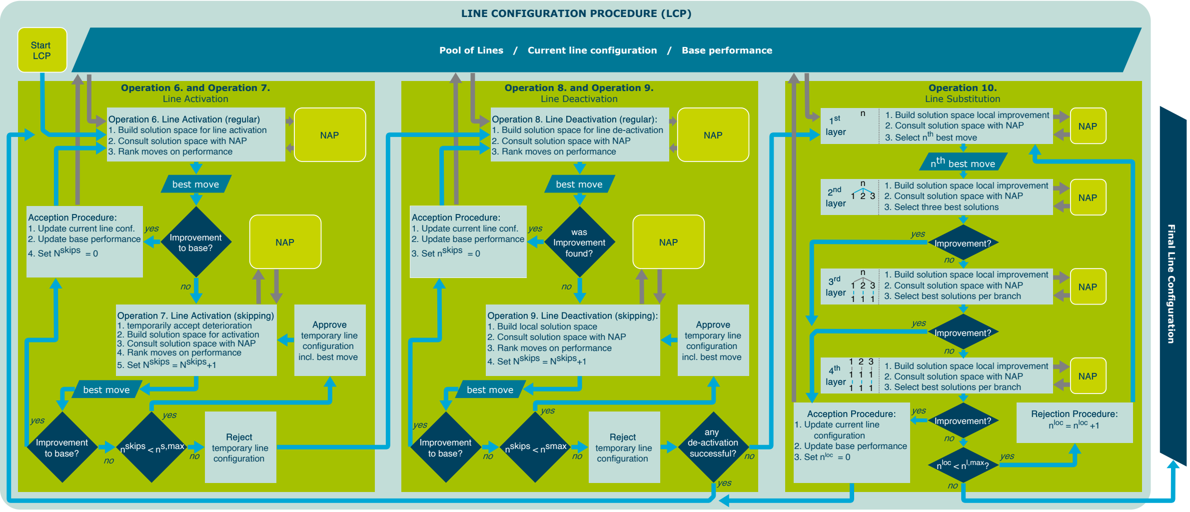

Figure 3.18: Line Configuration Procedure (LCP) - detailed version of *Figure 3.4*

3.3.3. Line Configuration Procedure

To coordinate the search towards a strong performing line configuration, a heuristic local search algorithm with a greedy hill-climbing character is proposed. This algorithm uses the pool of lines resulting from the LGP as input and works towards an idealised line configuration by systematically scanning the solution neighbourhood of a current state and activating or deactivating individual lines. The Line Configuration Procedure (LCP) consists of five subsequent operations that are in constant contact with the NAP to evaluate the performance of proposed solutions. In *Figure 3.18*, a detailed overview of the LCP's operations is given, which was previously stated in *Figure 3.4* in a simplified manner. Here, the events happening in the five operations and their internal decisions are stated. In the paragraphs below, the operations are further analysed.

Operation 6 and Operation 7: Line Activation

Beginning on the left-hand side of *Figure 3.18* and starting from an empty set of lines, the very first operation of the LCP ('*Operation 6.*') is responsible for the step-wise activation of lines that have a high contribution to the network. Essentially, this operation searches for the local optimum that is closest to the starting solution by a local neighbourhood search. The neighbourhood $N^{LA}(LC^{r})$ of a line configuration plan at iteration r is defined as the set of possibilities that can be reached by the activation of any active individual line from the current position. An example of a typical neighbourhood is presented in *Figure 3.19*.

$$LC^{it} = \begin{vmatrix} l_1 \\ l_2 \\ l_3 \\ l_4 \\ \vdots \\ l_{K-1} \\ l_K \end{vmatrix} = \begin{vmatrix} 1 \\ 0 \\ 1 \\ 0 \\ \vdots \\ 0 \\ 1 \end{vmatrix} \quad \rightarrow \quad N^{LAO}(LC^{it}) = \begin{vmatrix} 1 \\ \mathbf{1} \\ 1 \\ 0 \\ \vdots \\ 0 \\ 1 \end{vmatrix} \begin{vmatrix} 1 \\ 0 \\ 1 \\ \mathbf{1} \\ \vdots \\ 0 \\ 1 \end{vmatrix} \dots \begin{vmatrix} 1 \\ 0 \\ 1 \\ 0 \\ \vdots \\ \mathbf{1} \\ 0 \end{vmatrix}$$

Figure 3.19: Example of a Line Activation Operation (LAO) neighbourhood

For every iteration, the complete neighbourhood is presented to the NAP. In response to this, the NAP communicates the resulting objective values back to the LCP. With its greedy character, '*Operation 6.*' selects the best performing solution and sets this as its new state. Hereafter, the next iteration is started, which is repeated until no further improvement is found. Performing this operations for the entire pool of lines means that the number of iterations is bounded by the triangular number T_k, with k being the size of the '*Pool of Lines*'. From this it follows that the computational burden of this operation mainly follows from the extensiveness of the NAP, the size of the network and the number of lines that are given by the LGP, as every marginal increase in the number of lines K_{tot} comes with a maximum of K_{tot} extra NAP consults.

To reduce the risk of ending at a local optimum, '*Operation 7.*' repeats the same process of line activation, but with the ability to accept a maximum number of s temporary deteriorating iterations. For this study, an arbitrary value of $s = 10$ was applied. Finding a delayed improvement, the line configuration is updated and '*Operation 6.*' is restarted. If no further improvement is found, a continuation towards '*Operation 8.*' and later on the right-hand side is made.

Operation 8 and Operation 9: Line deactivation

These operations of line deactivation are very similar to the previous operations, although they work from the opposite perspective. '*Operation 8.*' starts with the most recent line configuration and is responsible for the step-wise deactivation of lines that prove to be redundant due to more recently added lines. Similar to the line activation operations, this phase searches for the local optimum that is closest to the current solution by the use of a steepest descent neighbourhood search method. A typical neighbourhood of this is given in *Figure 3.19*.

$$LC^r = \begin{vmatrix} l_1 \\ l_2 \\ l_3 \\ l_4 \\ \vdots \\ l_{K-1} \\ l_K \end{vmatrix} = \begin{vmatrix} 1 \\ 0 \\ 1 \\ 0 \\ \vdots \\ 0 \\ 1 \end{vmatrix} \rightarrow N^{LDO}(LC^r) = \begin{vmatrix} \mathbf{0} \\ 0 \\ 1 \\ 0 \\ \vdots \\ 0 \\ 1 \end{vmatrix} \begin{vmatrix} 1 \\ 0 \\ \mathbf{0} \\ 0 \\ \vdots \\ 0 \\ 1 \end{vmatrix} \dots \begin{vmatrix} 1 \\ 0 \\ 1 \\ 0 \\ \vdots \\ 0 \\ \mathbf{0} \end{vmatrix}$$

Figure 3.20: Example of a Line Deactivation Operation (LDO) neighbourhood

Just like the previous operations, this Line Deactivation Operation is in continuous contact with the NAP for evaluating possible solutions, which can be seen by the data flows to the NAP in *Figure 3.18*. Again, with its greedy character, it selects the best possible move in each iteration until no further improvement is found.

The ninth phase ('*Operation 9.*') repeats the line deactivation strategy of '*Operation 8.*' and is again allowed to accept a maximum $s = 10$ temporary deteriorations, such that it decreases the chance of ending in local optima. If improvement is found, the LCP is sent towards a repetition of '*Operation 8.*'. However, if no improvement is found in this stage, two possible paths can be followed. The first path moves all the way back to '*Operation 6.*' in the case that at least one line has been deactivated in either '*Operation 8.*' or '*Operation 9.*'. A great advantage of this step is that it provides the chance of recapturing lines that have a lower function in an early-stage network but a strong function a further developed state. If however no alterations have been made to the line configuration that was delivered by the activation procedures, a continuation is made to '*Operation 10.*'.

Operation 10: Line Substitution

Where the first four LCP operations (6, 7, 8 and 9) are mainly constructed to quickly work towards a solution, '*Operation 10.*' changes the emphasis towards a more local and thorough search. The function of this is two-fold, as this helps to (1) get out of a local optima and (2) slightly improve a the close-to-final line configurations. The principle of this operation is based on the complex substitution of lines, which allows for a wider variety of moves but also brings a greater computational burden.

The substitution possibilities are obtained by three main measures. Firstly (1), the local neighbourhood is expanded to both the activation and deactivation of lines, for which an example is presented in *Figure 3.21*. Following this (2), multiple iterations are are assessed after each other, such that a combination of steps can be performed. To ensure new solutions, (3) temporary deteriorations are accepted. Doing this for all neighbourhoods in all iterations would result in an impracticably large decision branch. Therefore, only the steps as depicted in '*Operation 10.*' of *Figure 3.18* are performed.

$$LC_r = \begin{vmatrix} l_1 \\ l_2 \\ l_3 \\ l_4 \\ \vdots \\ l_{K-1} \\ l_K \end{vmatrix} = \begin{vmatrix} 1 \\ 0 \\ 1 \\ 0 \\ \vdots \\ 0 \\ 1 \end{vmatrix} \rightarrow N^{LSO}(LC_r) = \begin{vmatrix} \mathbf{0} \\ 0 \\ 1 \\ 0 \\ \vdots \\ 0 \\ 1 \end{vmatrix} \begin{vmatrix} 1 \\ \mathbf{1} \\ 1 \\ 0 \\ \vdots \\ 0 \\ 1 \end{vmatrix} \begin{vmatrix} 1 \\ 0 \\ \mathbf{0} \\ 0 \\ \vdots \\ 0 \\ 1 \end{vmatrix} \begin{vmatrix} 1 \\ 0 \\ 1 \\ \mathbf{1} \\ \vdots \\ 0 \\ 1 \end{vmatrix} \dots \begin{vmatrix} 1 \\ 0 \\ 1 \\ 0 \\ \vdots \\ \mathbf{1} \\ 1 \end{vmatrix} \begin{vmatrix} 1 \\ 0 \\ 1 \\ 0 \\ \vdots \\ 0 \\ \mathbf{0} \end{vmatrix}$$

Figure 3.21: Example of a Line Substitution Operation (LSO) neighbourhood

Starting above in the first sub-iteration, the n^{th} best move of the local neighbourhood is selected. ($n^{max} = 18$ for this study). In the following sub-iteration, three branches are constructed by selecting the 1^{st}, 2^{nd} and 3^{rd} performing moves from the previous point. To also assess effects that occur later, these branches are then deepened by performing a greedy search for three more levels. As a result, three possible decision paths starting at the n^{th} move are established. If improvement was found in one of these paths, the LCP returns back to '*Operation 6.*'. If this is not the case, the sequence of sub-iterations is repeated for n^{max} times ($n^{max} = 18$ for this study) until an improvement is found. If this does not happen, the LCP is terminated.

3.3.4. Network Analysis Procedure

The ultimate goal of the Network Analysis Procedure (NAP) is to determine the performance of a proposed set of lines, such that the Line Configuration Procedure (LCP) gets feedback as to whether it is moving in the right direction. To compute this, the NAP needs to execute four tasks: (1) demand assignment, (2) line selection, (3) frequency determination and (4) line evaluation. As a whole, the NAP has a considerable influence on the realism of the model, as this procedure simulates the behaviour of users and operators. Of these tasks and due to its complex character, especially the assignment of passengers to lines (tasks 1 and 2) is amongst the critical issues for designing a transit network (Kepaptsoglou & Karlaftis, 2009).

The four main tasks of a typical NAP are translated for this research and stated in the proposed NAP outline of *Figure 3.22*. Receiving a line selection from one of the LCP operations (7, 9 and 10), the NAP starts at the yellow box on the left-hand side. In stage A, the vuser's behaviour is simulated by simultaneously assigning passengers to modes and associated paths within this mode. Following this, Stage B simulates the operator's response by determining the line frequencies required to supply for this demand per line. Now that it is known how the network is used, Stage C computes the graph descriptors, which give an indication of the feasibility and allow for interpretation. Finally, Stage D uses the indicators to calculate the system performance. The output of Stages C and D is communicated to the relevant LCP operation. The exact approaches and construction of the stages is further discussed in In the subsections below.

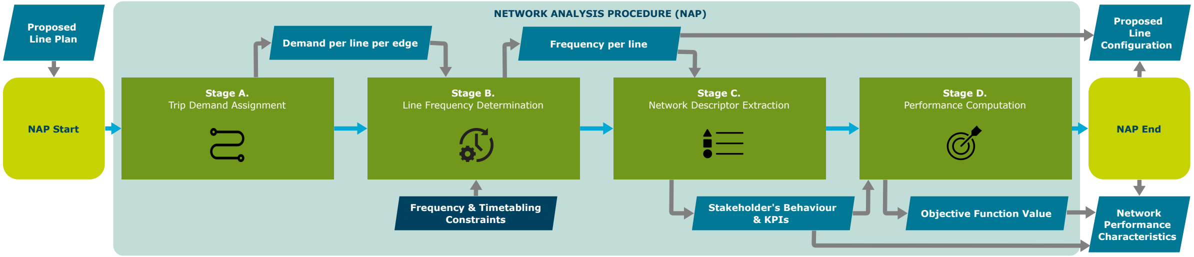

Figure 3.22: Network Analysis Procedure (NAP) - (revisit of *Figure 3.5*)

Stage A: Trip Demand Assignment

As previously mentioned, the '*Trip Demand Assignment*' stage is responsible for simulating the user's behaviour, which is one of the more critical issues for designing a transit network considering its influence on the realism of the model. In this phase, it is decided which mode passengers choose for their trip and how the exact path within this mode looks like. To determine this, the two steps have to be executed in reverse order: first a search for the best routes within a mode is performed, after which possibilities of different modes are compared with each other.

In *subsection 2.3.3*, it was examined that traffic assignment is a wider field of research comprising a variety of problem environments and solution strategies. Accordingly, it was also found that only a smaller selection of these situations is applicable to this type of research (TNDFSP). In general, the pathfinding approaches within a mode could be divided into: (1) '*multipath assignments*' based on user acceptability (e.g. frequency share rules), (2) '*lexicographic strategies*' based on transfer minimisation and (3) other '*flow-concentration techniques*' that also consider the operator's perspective.

Approach considerations:

A crucial difference between regular transit and long-distance transport is the importance the frequency as a service attribute. Where transit travel is characterised by more randomised access arrivals, less information transparency, fewer trip preparation and shorter trips in general, the opposite is found for long-distance travel. This difference means that it is more likely that passengers are able to plan their ideal path on beforehand, From which it follows that the multipath assignment is less suitable. Additionally, the operator's perspective is already indirectly considered in the model by the inclusion in the objective function, making also the third category unfitting. Finally, the lexicographic transfer minimisation theory remains as the last and most suitable option. A statement that originates from the reasoning that transfers inherently come with a decrease of comfort, an increase of travel time and a higher probability detour-paths, making it an easily avoidable hindrance.

With the above knowledge, it is chosen to apply a lexicographic transfer minimisation strategy for this model. Originally proposed by Han & Wilson (1982) (in combination with minimisation of travel and waiting time) and more recently expanded by Fan & Machemehl (2004) (with a greater focus on access and egress times as well as multi-modal transport), this method is applied in multiple ways. For this research, a combination of both is used. An overview of the proposed operation is presented in *Figure 3.23*.

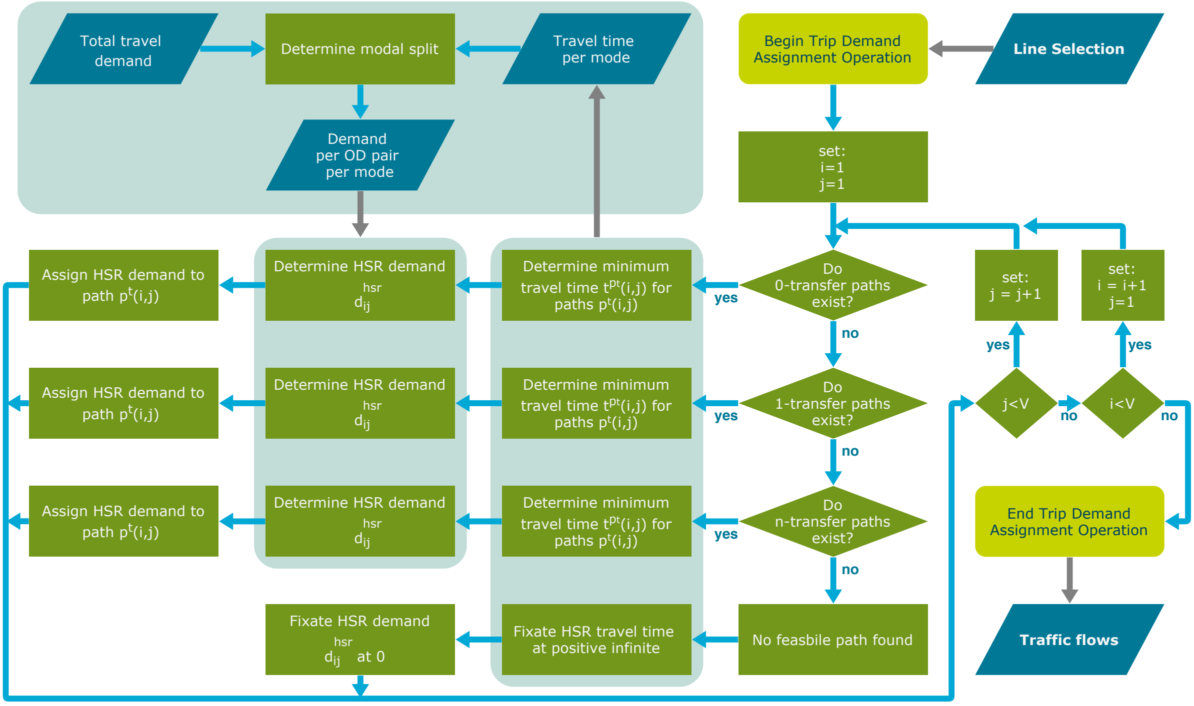

Figure 3.23: Flowchart Stage A: Trip Demand Assignment operation

HSR path determination:

The HSR Path Determination process is described in *Figure 3.23*. Starting at the yellow box in the upper-right corner, the operation receives a line selection from one of the LCP operations, after which the origin and destination vertices are fixed at $i = 1$ and $j = 2$. Performing a quick check to prevent paths between identical origins and destinations, the model starts running down the flowchart. Here it be seen that the operation searches in a step-wise procedure for paths with a minimum number of transfers, up to a maximum of t^{max}.

Having found this, the flow turns left and determines the minimum travel time path (comprising t^{riding}, t^{dwell} and $t^{transfer}$) out of all path options. This time is then presented to the '*Mode Choice Determination*' module on top of the flowchart, which is further explained in the paragraph below. The output of the Mode Choice Determination module is a demand for HSR traffic along a certain path. This demand is then assigned to this the associated line segments. An exception is made for vertices that are not connected within the maximum (t^{max}) number of transfers. Their HSR trip is assumed infeasible, for which the total demand has to depend on the alternative modes.

Having determined the passenger flow on a line as induced by a specific OD-pair, the process moves back to the right side of the chart. Here a systematic process makes sure that all relevant OD-pairs are presented to the Demand Assignment Operation. Having completed the whole OD-matrix, the traffic flows are presented to Stage B (Line Frequency Determination) of the NAP.

Mode choice determination:

As previously mentioned, the Mode Choice Determination Module is an important step within the Trip Demand Assignment Operation. Halfway the operation, when it is known how much time an HSR trip between two vertices takes, it is possible to compare the offered HSR service with the services of other modes. This process is described in the upper left corner of *Figure 3.23* and results in a number of passengers opting for each mode.

To describe the travel behaviour regarding mode choice for long-distance transport, it is proposed to use the modal split method of Donners (2016). This approach is based on the '*Random Regret Minimisation*' theory of Chorus et al. (2008), which is a theory that allows for the modelling of negative emotion avoidance rather than payoff maximisation and that acknowledges that the decision-making of travellers may not be fully compensatory in the context of multi-attribute alternatives. The main formulation for this model is presented in *Equation 3.34*. Here, R_m is the regret value for mode m, γ_{TT} is the sensitivity for the attribute TT and χ_{mTT} is the mode-specific attribute value.

$$R_m = \sum_{n \neq m} \sum_{TT} ln\left(1 + e^{\gamma_{TT} * (\chi_{nTT} - \chi_{mTT})}\right) - ln(2) \quad ; \quad \forall \quad m \in M \tag{3.34}$$

Assuming that the error is extreme value type 1 independent and identically distributed, brings that the probability $P(m)$ of choosing mode m is given by *Equation 3.35*,

$$P(m) = \frac{e^{-R_m}}{\sum_{TT} e^{-R_n}} \quad ; \quad \forall \quad m \in M \tag{3.35}$$

Stage B: Line Frequency Determination

In this stage, the second decision variable of line frequencies is assigned to the proposed set of lines, such that a complete line configuration $C(L, f_l)$ can be established. The '*Line Frequency Determination*' is based on the traffic flows that result from the previous stage, when trips were assigned to different modes, paths and lines. The required frequency f_{l_k} for line l_k is determined using the formula of *Equation 3.36*. Here, the maximum flow over the line is divided by the vehicle capacity c_m and the design load factor $fac_m^{des.load}$.

$$f_{l_k} = \frac{Q_{L_k}^{max}}{sc_m * fac_m^{des.load}} \tag{3.36}$$

Earlier on, in *subsection 3.2.5*, it was noted that the the line frequency is subject to a minimum frequency constraint f^{min} (as was formulated in *Equation 3.25*). This, to ensure non-negative solutions and prevent "ghost lines", which do exist but are not used. Additionally, it would make sense to imply a maximum line (or even edge or vertex) frequency at this point. However, this implies that passengers and frequencies have to re-assigned in an iterative way, which imposes a rather large computational effort. Given the fact that tactical infrastructure use is out of scope for this thesis and that in reality one can also adjust vehicle capacity, it is decided to simplify and thus neglect this factor. Finally, to guarantee a solution that is continuous in time, the model is restricted to solutions in which the frequency of line $l(i,j)$ equals that of $l(j,i)$. An overview of constraints effectuated in this stage can be found in *Table 3.12*.

Table 3.12: Overview of this model's Frequency and Timetable Constraints - *(revisit of Table 3.9)*

Constraints	Name	Description	Reference
Frequency & Timetable	Min. frequency	minimum frequency prevents negativity ghost lines	*Equation 3.25*
	Int. frequencies	only integer frequencies are allowed	*Equation 3.26*
	Freq. symmetry	continuity in number of trains per direction	*Equation 3.27*

Stage C: Graph Descriptor Extraction

The goal of Stage C (the '*Graph Descriptor Extraction*') is to extract the properties and characteristics of the line configuration $LC(L, f_l)$, such that it becomes possible to test for constraint feasibility (Operations 7 & 9), determine the system performance (Stage D) and interpret results afterwards. The data extracted in this stage is stored at the performance.

Stage D: System Performance Computation

In Stage D, the '*System Performance Computational Operation*' or SPCO, the efficiency of the proposed line configuration $LC(L, f_l$ is determined. To do this, the outcomes of the previous stage are inserted in the objective function, as is briefly revisited in *Equation 3.9 - revisited* below.

$$Minimise \quad Z = (\psi_{user} \cdot C_{user}) + (\psi_{operator} \cdot C_{operator}) + (\psi_{external} \cdot C_{external}) \tag{3.9 - revisited}$$

3.3.5. Output of the model

The model's output is used for the interpretation, performance assessment and comparison of different scenarios, which is done by the use of Key Performance Indicators (KPIs). In *section 2.5*, an analysis on widely used Key Performance Indicators for both airline and transit systems was performed. Given the in-between character of this research, it is chosen to use KPIs from both research fields. Resulting from this is a list of four KPI-categories, which are explained in the subsections below. A comprehensive overview is provided in *Table 3.13*.

Objective values and cost functions

The objective values and cost functions give insights into the effectivity of a tested scenario. Considering all costs and weights, value Z gives an overall leading performance score. Splitting this up separate costs for the operator, user and external factors providers better understanding on who experiences relative benefits.

HSR network characteristics

The second category describes how the proposed solution looks like, such that it can be understood why it performs a certain way. First, the n_l indicates the number of active lines. Following this, a range of KPIs explaining the typical distance properties, stop properties and frequency properties are proposed. Finally, the last four KPIs explain the way the network is exploited. I other words: which vertices and edges are amongst the more ore less important edges.

HSR operator's perspectives

Minimising costs, the operator will intrinsically aim for a highly efficient network. However, being subject to other stakeholders and interests, a certain divergence is inevitable. The three KPIs of this category together (ASK, RPK and ANLF), provide knowledge on how the efficient the actually provided service is.

User's perspective

This final KPI category gives answers to how the passengers use the network. The first two (d^n and d^{un}) are specifically focused on the HSR traveller. They explain how often passengers have to transfer and whether they can actually reach their destination within a reasonable number of transfers. Following this, the distance and travel time indicators explain how many people use specific modes, for what trip length this is and how long it takes them.

Table 3.13: Overview of this model's output parameters

	Notation	Unit	Description
Objective Values & Cost Functions	Z	$[€]$	total objective function value
	$C^{operator}$	$[€]$	total operator costs
	C^{user}	$[€]$	total user costs
	$C^{external}$	$[€]$	total external costs
HSR Network Properties	n^{l}	$[-]$	number of lines in the graph
	$D^{l,min}$	$[km]$	minimum line distance
	$D^{l,max}$	$[km]$	maximum line distance
	$D^{l,avg}$	$[km]$	average line distance
	$n^{s_l,min}$	$[-]$	minimum number of stops per line
	$n^{s_l,max}$	$[-]$	maximum number of stops per line
	$n^{s_l,avg}$	$[-]$	average number of stops per line
	$D^{s_l,avg}$	$[km]$	average network stop distance
	$f^{l,min}$	$[veh./d]$	minimum line frequency
	$f^{l,max}$	$[veh./d]$	maximum line frequency
	$f^{l,avg}$	$[veh./d]$	average line frequency
	$V^{l,min,10\%}$	$[-]$	set of lowest connected vertices (no.of directly accessible vertices)
	$V^{l,max,10\%}$	$[-]$	set of highest connected vertices (no.of directly accessible vertices)
	$E^{l,min,10\%}$	$[-]$	set of lowest passenger flow edges
	$E^{l,max,10\%}$	$[-]$	set of highest passenger flow edges
HSR Operator's Perspective	ASK	$[€]$	Available seat kilometres
	RPK	$[€]$	Revenue seat kilometres
	$ANLF$	$[€]$	Average network load factor
User's Perspective	$d^{0}, d^{1}, d^{\cdots}, d^{n}$	$[-]$	percentage of HSR passengers with n transfers
	TTD_{m}	$[h]$	Total Travel Distance (as the crow flies) per mode m
	TTT^{tot}	$[h]$	Total Travel Time for whole graph
	TTT^{m}	$[h]$	Total Travel Time per mode m
	ATT^{tot}	$[h]$	Average Travel Time for whole graph
	ATT^{m}	$[h]$	Average Travel Time per mode m
	$MS{\cdot}trip, m$	$[h]$	Modal Split in number of trips per mode m
	$MS^{d}ist, m$	$[h]$	Modal Split per distance per mode m

3.4. Experimental Set-Up

With the defined problem (*section 3.2*) and the formulated heuristic model to solve this (*section 3.2*), it becomes possible to perform multiple experiments that can together provide the insights that are necessary to answer the research question. The formulated experiments are each coupled to the research goals, which makes a total number of four experiments. The first of these ('*Experiment I*)' is concerned with the simulation of the initial performance, such that later moves can be compared. In '*Experiment II*' and '*Experiment III*', analyses are performed to find the importance of several design and policy choices. Finally, '*Experiment 4.*' constructs two synthesised scenarios which are improved based on the previously learned lessons and compares the outputs. This provides insights into the potential contribution of improved design for line configurations, as well as understanding on how these networks look like.

- **Experiment 1:** Estimation of the initial network's characteristics and performance
- **Experiment 2:** Analysis on pricing and governance strategies
- **Experiment 3:** Analysis on high-speed rail design variables
- **Experiment 4:** Assessment of synthesised scenarios and comparison with inital standard

To be able to perform these experiments, the problem is operationalised towards the context of the European continent and the currently available technologies, such that the simulations take place in a realistic context whilst also allowing an assessment on the potential impact of a centralised European high-speed rail. This operationalisation is performed in *chapter 4* and results in a ready-to-use model.

Experiment 1: Estimation of initial network characteristics and performance
To estimate the performance of an initial network in the current conditions, a first simulation is performed using this standard parameterisation of *chapter 4* whilst replicating the EU's believe in a free market and under-representation of external costs, a scenario which will be defined as the '*1. Liberalisation*' scenario in the following paragraph.

Experiment 2: Analysis on pricing and governance strategies
The first variable analysis investigates the impacts of different pricing and governance strategies by altering the weights of the objective functions as well as some characteristic parameters. This is done by the definition of six scenarios, which are stated in the overview of *Figure 3.24*. This overview shows a two-sided division between a '*free Market*' and '*Central Organisation*' governance strategy. In line with their names, this distinction is made to simulate the differences between the policy choice to leave the network development to private parties - as currently favoured by the EU -, and developing the network from a centralised perspective. These differences are modelled by a 20% reduction on operator costs in the '*free market*' and a 50% reduction on transfer time in the '*centralised organisation*'.

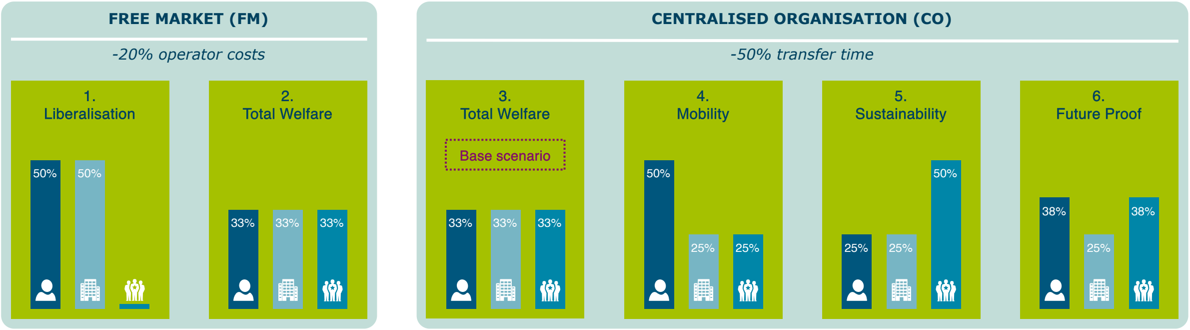

Figure 3.24: Overview of modelled pricing and governance scenarios

Following this first division, the six scenarios are further characterised by their pricing policies. These are indicated using the names of the green box and are characterised by the weights assigned to the objective function of *Equation 3.9*, which considers the user, operator and society. On the left-hand side, the '*1. Liberalisation*' scenario represents a market that that is only concerned with the balance of interests between users and operators. Moving to the right, the '*Total Welfare*' scenarios internalises the true external costs, and the further scenarios represent the active subsidisation of different interests for policy goals. Theoretically, ten unique scenarios could have been defined using these variables. These are, however, not all simulated given the unlikeliness of an actively subsided free market or a centralised organisation that does not consider societal costs.

Experiment 3: Analysis on high-speed rail design variables

To contribute to ‘*Research Goal II.*’ and find the importance of design variables, a selection of ten parameters was selected for a third analysis. An overview of the proposed simulations is stated in *Figure 3.25*, where it can be seen that the parameters are divided into three categories. The first (1) category concerns the properties of vehicles that are used on the network, the second (2) concerns the characteristics of and limitations on the paths that are made by passengers travelling through the network; and the third (3) concerns the lines that make the ‘*Pool of Lines*’, from which a selection is to be made by the heuristic. All the parameters within these categories are tested by running the base scenario whilst adjusting the parameter of interest within a certain range. This range is based on the values that are found in the parameterisation of the European case study of *section 4* and that are regarded to be within feasible limits.

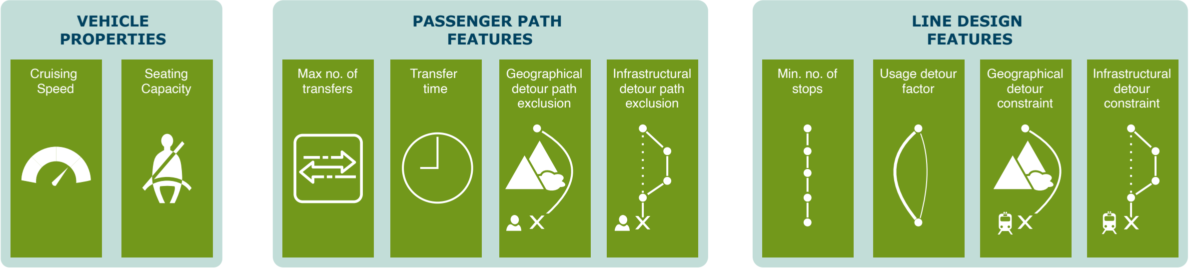

Figure 3.25: Overview of modelled HSR design variable scenarios

Experiment 4: Assessment of synthesised scenarios

The last experiment uses the lessons from the previous experiments to determine the potential impact of improved HSR line configurations and their associated characteristics, with which it becomes possible to answer the research question. This experiment is performed by defining two improved scenarios: the (1) ‘*economical*’ scenario, that works towards an efficient cost-benefit ratio; and the (2) ‘*extensive*’, which works to a network that prioritises its contribution to policy goals.

4

Case Study of the European Network

In search of the potential significance of a European high-speed rail network, the problem was parameterised to realistically describe the characteristics of this European continent and the currently available technologies. The subsections below discuss the parameterisation of each of the main network components, which were already introduced in *section 3.2* on the '*Problem Formulation*'.

The parameterisation starts in *section 4.1*, where the relevant cities and airports are stated and where their characteristics are deviating. This is followed by *section 4.2* on the edge specification, that will define the connections between the edges and the impact they have on travel times. Thereafter, *section 4.3* introduces the three modes that can be used to travel through the graph, after which *section 4.4* presents the three stakeholders in the model. To ensure realism and a swift computational time, constraints were introduced the '*problem definition*', which will be more specifically activated in *section 4.5*. To round up, *section 4.6* describes a novel methodology for the demand estimation, which will then also be activated for this problem.

4.1. Vertex Specifications

The problem as described in *section 3.2* knows two types of vertices: Cities and airports. Both vertices have a separate function and distinctive characteristics, which are addressed in the paragraphs below.

City vertices

In search of viable international train services, Donners (2016) defined a selection of the most significant metropolitan areas for a high-level European Network. Firstly filtering on larger urban areas that are connected by rail infrastructure, a long-list of possible cities emerged. Ranking these on several criteria - the population, regional GDP and research activities - the selection was reduced to a smaller sub-set of 110 cities. Further eliminating or merging cities that are in very close proximity (25-30 km), including capitals for underrepresented countries and adding 14 non-Schengen cities ultimately resulted in a list of 125 key cities.

The selection as made by Donners (2016) is almost directly used as input for this model. The only adjustment regards the exclusion of Ireland's capital city Dublin. The research in this thesis does not take water connections into account, which makes that this city is isolated from the rest of the network. The remaining 124 metropolitan areas are projected on the map of *Figure 4.1* by blue dots.

City population and area

The vertices in the model do not only represent the city they are named to, but also the entire metropolitan area that is associated with them. For the characteristics of these areas, the '*NUTS 2016 classifications*' as defined by Eurostat (2020b) are used. The NUTS classification is a system that hierarchical divides the economic territory of the EU and the UK, which allows for comparison of regional statistics, the collection of socio-economic data and the framing of EU policies. The classification consists of three layers: NUTS1 (104 major socio-economic regions), NUTS 2 (281 basic regions) and NUTS3 (1384 small regions).

For this parameterisation, the population and land area of the relevant NUTS3 regions were used. The relevance of these regions was determined by the definitions as determined by Eurostat, as the NUTS3 regions are already assigned to specific metropolitan areas. The result of this was an overview of populations and land area. On the top, Istanbul (15.1M inh.), London (13.4M inh.) and Moscow

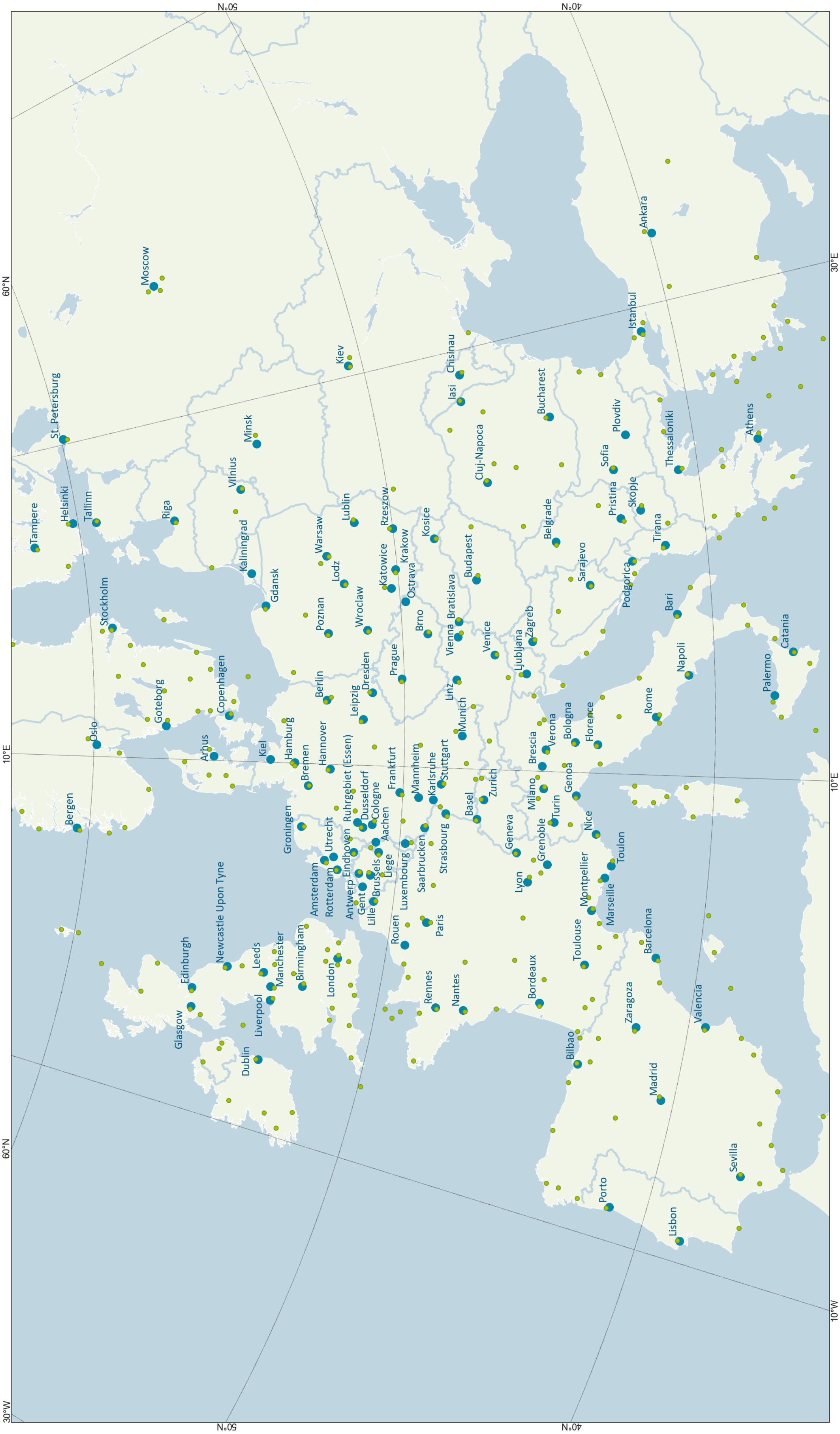

Figure 4.1: Map of the cities (blue) and airports (green) that are considered in this study

(12.4M inh.) were found. This line was closed by Kaliningrad (0.48M inh.), Groningen (0.44M inh.) and Podgorica (0.20M inh.).

Airport vertices

The continent of Europe counts many larger and smaller airports. The function of these airports in this specific model is two-fold: (1) their connections represent a network that offers a travel alternative for passengers travelling between cities and (2) their current passenger flows provide input for the total demand estimations. To make a selection of the relevant airports, Eurostat's freely accessible database on the European flight statistics was consulted (Eurostat, 2020a).

Using a voluntary annual questionnaire, Eurostat gains insights into passenger and cargo flows between European airports. The questionnaire is answered by 35 countries: The EU27-2020, Iceland, Montenegro, North Macedonia, Norway, Serbia, Switzerland, Turkey and the United Kingdom. In this survey, all countries reported the traffic from and to their main airports. Excluding extra-European traffic flows from the data set, a total of 385 airports were identified. In *Figure 4.1*, these airports are projected on the European map by green dots.

Geographical location of the vertices

The geographical location of the 509 vertices is indicated by the latitude ϕ and longitude λ. These values are found using Nominatim's application programming interface (API) for finding locations on Earth by name and address (Nominatim, 2020). The API was provided with two types of text strings. For the location of the 124 metropolitan areas, this was: '*[country], [city name] city-centre*'. For the location of the 385 airports, this was: '*[ICAO-code] airport*'.

The result came out positive for all requests. The values were verified by manually checking a sample of ten cities and ten airports. It was found that all twenty locations we're as expected, though some small precision errors were observable. For cities, this follows from the multi-interpretable definition of city-centre, which is sometimes slightly different than expected. Here a maximum deviation of 1 kilometre is expected. For airports, it is seen that the location is frequently established on one of the runways. This is true when considering the location for airplanes, but not for access or egress times of passengers. Here, the error is expected to be no larger than 2 kilometres. Four of the results are given in *Figure 4.2*, *4.3*, *4.4* and *4.5*.

Figure 4.2: Geographical location of Barcelona City Centre

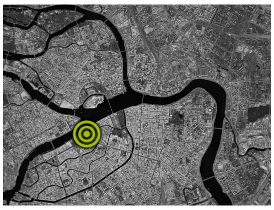

Figure 4.3: Geographical location of Saint Petersburg City Centre

Figure 4.4: Geographical location of EGCC (Manchester) airport

Figure 4.5: Geographical location of LYBE (Belgrade) airport

Access and egress times

The model knows two types of access and egress trips. Those within a city (home ↔ city-centre) and those between a city and an airport. Both are addressed in different ways, as will be explained in the paragraphs below.

For the access and egress times within a city, the actual size of the metropolitan area is considered to be the normative factor of variability. In other words, the average traveller of Podgorica reaches its city centre a lot faster than one in London would. These differences are modelled by assuming the metropolitan area to have a circular shape, as was done in *Figure 4.6*. For an equally distributed area, the average distance of a point in a circle to the centre is 2/3 of its radius. However, considering the higher density towards the city centre the higher average speed on longer distances, it is estimated that the average distance to the centre equals 1/4 of the radius.

Using an average city speed s_{city}^{avg} of 30 km/h and detour factor fac_{city}^{dt} of 1.10 (Donners, 2016), it becomes possible to calculate the average access/egress time for a specific city with the formula of *Equation 4.1*.

$$t_{v_i}^{acc/egr,avg} = \frac{ds_{v_i}^{acc/egr} * fac_{city}^{dt}}{s_{city}^{avg}} \tag{4.1}$$

where:

$t_{v_i}^{acc/egr,avg}$ = the average access/egress time within city V_i in h
$ds_{v_i}^{acc/egr}$ = the average access/egress distance within city V_i in km
fac_{city}^{dt} = the average detour factor within a city (= 1.10)
s_{city}^{avg} = the average speed within a city (= 30 km / h)

The method, as described above, loses accuracy when travelling larger and more heterogeneous paths, which is exactly what happens when evaluating the access/egress routes between cities and airports. Encountering different types of barriers such as mountains, water bodies, urbanised areas, road conditions and borders, it becomes more difficult accurately capture these effects in a mathematical function. Because of this, it is chosen to it is chosen to use the API (Application Programming Interface) of OpenRouteServices (Heidelberg Institute for Geoinformation Technology, 2020).

The OpenRouteService API is used to find the fastest possible route by car between the two locations, as defined by their coordinates. Considering the relatively short flights modelled in this research, access and egress duration between cities and airports are bounded to 2.5 hours. An example of this is given in *Figure 4.8*, where the access/egress routes between Berlin and its associated airports is given.

Figure 4.6: Visualisation of inner city access/egress modelling

From	To	Time
EDDT (Tegel)	Berlin CC	0:19
EDDB (Schönefeld)	Berlin CC	0:37
EDDP (Leipzig)	Berlin CC	1:44
EDDC (Dresden)	Berlin CC	2:01
EPSC (Goleniow)	Berlin CC	2:01
ETNL (Rostock)	Berlin CC	2:12

Figure 4.7: Example: access/egress times for Berlin city-centre and surrounding airports

Figure 4.8: Example: Access/egress car paths for Berlin

4.2. Edge Specifications

The vertices (both cities and airports) are connected by edges, which can be used by travellers as a mean to move between the nodes. The model distinguishes three edge types: air, rail and road. In the paragraphs below, each of these are addressed.

Air connections

The 385 airports (as defined in the paragraph on airport vertices in *section 4.1*) are connected by a wide range of air routes. To find out which routes exist and with what frequency, Eurostat's (Eurostat, 2020a) database on the European flight statistics was once again consulted. The questionnaire, as used by Eurostat, does not only ask for the main airports but also the number of flights operated between these airports.

For this research, the flight data for the year 2019 is used. However, this data is not fully complete, as the results from Serbia and Sweden are not available yet. To resolve this, their 2018 data is used as a reference. It is not expected that these limitations greatly influence the result, given that airline networks do not change overnight. Furthermore, the data as provided by Slovakia is excluded since their reporting is only at aggregated country level. The error caused by this is also considered relatively small, as most routes will be reported by the airports receiving passengers from Slovakia.

The resulting network of edges between airports is visualised by the purple lines in *Figure 4.9*. Evaluating these purple connections might suggest an almost complete network. However, when taking a closer look at the blue-highlighted networks of '*Faro Airport (LPFR)*' and '*Sofia Airport (LBSF)*', it can be seen that each airport is only connected to a certain selection of other airports.

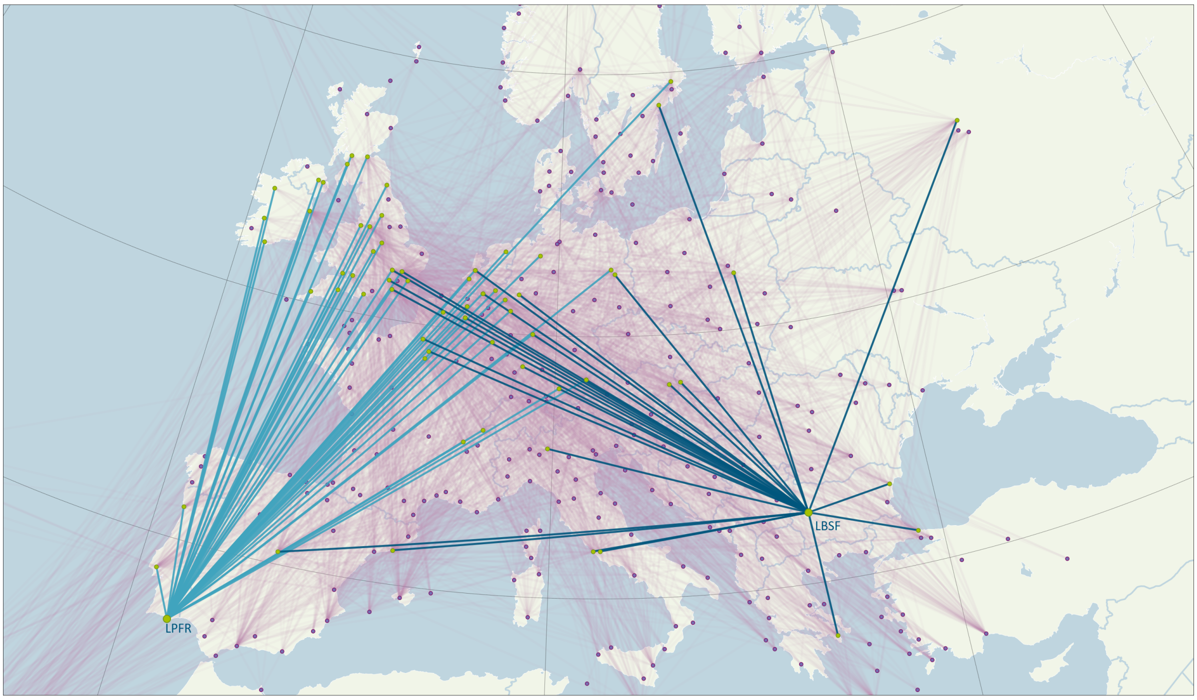

Figure 4.9: Network of air connections between main European airports highlighted in blue: Faro Airport (LPFR) and Sofia Airport (LBSF)

Road connections

As was also discussed in the paragraph on access and egress times between cities and airports in *section 4.1*, it becomes harder to realistically capture barriers such as water bodies or boundaries on larger distances in mathematical expressions. Because of this, it is once again chosen to use the API of OpenRouteService (Heidelberg Institute for Geoinformation Technology, 2020).

The OpenRouteService API is used to find the fastest possible route by car between the two locations, as defined by their coordinates. The vertices are connected by the complete European road network as available in July 2020, according to the maps of OpenRouteServices Heidelberg Institute for Geoinformation Technology (2020). This network - including both lower and higher capacity roads, highways, ferries and toll roads - allows to travel between all of the city pairs, also using nodes that are not part of 124 core city selection. Something that could also be seen in *Figure 4.8*.

Performing this routine for the whole network results in two OD-matrices, one for distances and one for durations. As an example, 6 OD-pairs with multiple political and natural barriers are presented in *Table 4.1*. To verify the accuracy of these results, they are compared with two other well-known route planners: '*Google Maps*' Google inc. (2020) and '*Rome2Rio*' Rome2Rio Pty. Ltd. (2020). These results are expressed in *Table 4.2*. The overview shows that the three find relatively similar results in which small deviations, both positive and negative, are found. These deviations show no obvious trend for a specific city, nor do they indicate a skewed pattern. With these numbers, it is expected that the error is to remain within a close to random 10% range.

	Bel.	**Gro.**	**Ham.**	**Man.**
Belgrade	*n/a*	15:37	14:02	22:47
Groningen	15:37	*n/a*	2:56	11:16
Hamburg	14:02	2:56	*n/a*	12:41
Manchester	22:47	11:16	12:41	*n/a*

Table 4.1: Example in-vehicle durations by car [h] (extracted from: Heidelberg Institute for Geoinformation Technology (2020))

	Belgrade		**Groningen**		**Hamburg**		**Manchester**	
	GM	R2R	GM	R2R	GM	R2R	GM	R2R
Bel.	*n/a*		+0,3	-1.4	+4.5	+1.9	-2.0	+3.1
Gro.	+0,3	-1.4	*n/a*		-3.3	-5.1	-8.3	-0.9
Ham.	+4.5	+1.9	-3.3	-5.1	*n/a*		-2.7	+3.6
Man.	-2.0	+3.1	-8.3	-0.9	-2.7	+3.6	*n/a*	

Table 4.2: Comparison of the in-vehicle travel time duration by car in percentage point (extracted from: Google inc. (2020) and Rome2Rio Pty. Ltd. (2020))

Railway connections

In the study of Donners (2016), the 124 key cities were connected using an infrastructural railway network that is based on the Trans-European Rail Network as proposed by the European commission (2013). For this research, the same network is used, although slight adjustments are made. This network, as depicted in *Figure 4.10*, connects the cities in blue by the purple links.

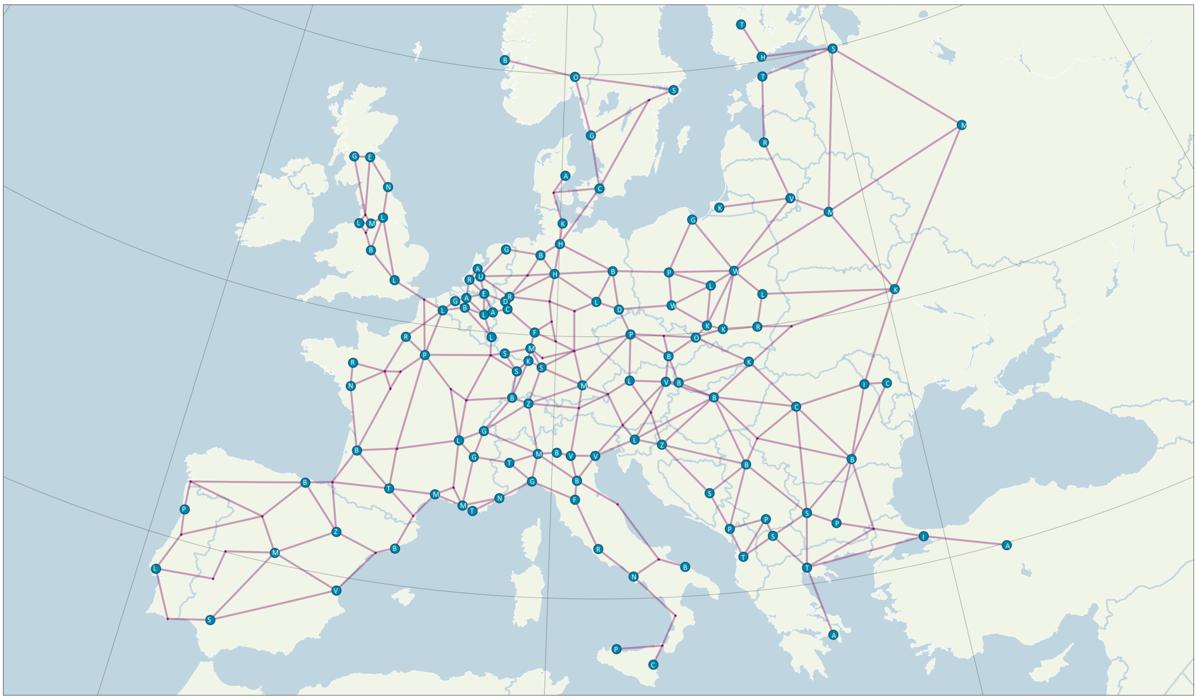

Figure 4.10: Network of railway infrastructure between selected core cities

The first adjustment regards the type of infrastructure, as it is assumed in this research that all links are fit for high-speed rail. This a relatively strong assumption, but is chosen to do so, as it leaves the model free in fining new lines that might justify the construction of infrastructure in a later phase, rather than be bounded by the current views, expectations and design decisions. Furthermore, having a closer look at *Figure 4.10* shows that not all lines are truly direct. In the work of Donners (2016), it is explained that additional network nodes (see purple dots) are included to increase the realism of the representation. In this study, These dots are used to evaluate to possible direct connections between key cities, but not for the distance of the links. This distance is based on the road distance between vertices, as was discussed the previous paragraph concerning road connections, which are corrected by the standard vehicle detours of car (1.20) and high-speed rail (1.09).

4.3. Mode Specifications

In the research of Donners (2016), the available transport services consisted of five unique travel mode options: Airplane, high-speed train, conventional train, car and bus. Each with their own characteristics. In *section 4.6*, it will be explained that this model uses air traffic demand as a source for total demand. Using this as input, it means that no accurate data on short-distance transport will be available. Because of this, it chosen to exclude the bus option, as it is mostly competitive on paths up to 200 km. From the remaining four modes, conventional rail is eliminated as it was not possible to gather precise travel times, because it is mainly competitive with shorter distances and because it is likely to nest with high-speed rail.

The argumentation above means that the model uses airplane, high-speed train and car as remaining travel options. In the following paragraphs, each mode will be discussed separately.

Airplane characteristics

The airplane travels between the airports using the feasible air connections as defined in *section 4.2*. The duration of a flight (from gate to gate) between two of these airports consists of multiple phases: taxiing, take-off, cruising, landing and taxiing again. This path is visualised in by the bright blue line in *Figure 4.11*.

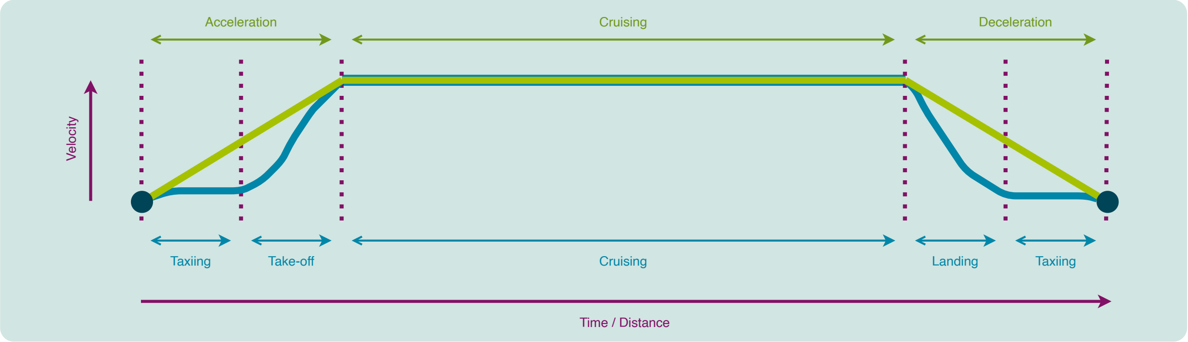

Figure 4.11: Visualised vehicle trip phases for air travel (Authors elaboration, partially based on high-speed train modelling of Connor (2014), see *Figure 4.12*)

This flight path is simplified for modelling by dividing into three linear parts: acceleration, cruising and deceleration. The duration of this simplified flight can be described using the equation as was stated in *Equation 3.4* and which has been revisited in *Equation 3.4 - revisited*. Using the mode-specific parameters of *Table 4.5*, results in a matrix of flight times between the set of airports.

$$t_{e_c(i,j)}^{inv,air} = t^{acc} + \left(\frac{ds^{dir}(v_i, v_j) \cdot fc_{air}^{dt} - ds_{air}^{acc} - ds_{air}^{dec}}{s_{air}^{crs}} \right) + t^{acc} \qquad \text{(3.4 - revisited)}$$

Four characteristic outcomes of *Equation 3.4 - revisited* have been illustrated in *Table 4.3*, where a range of different flights to Amsterdam Airport Schiphol are given. In the table next to this, *Table 4.4*, the flight durations as reported by Skyscanner Ltd (2020) are stated. The parameters of the flight *Equation 3.4* were fitted to the flight durations that were observed, such that they conform to each other. The associated parameter values for flight paths are stated in the second column of *Table 4.5*.

		EHAM (NL-Amsterdam)
EGKK	**(UK-London)**	1:18:41
LEIB	**(ES-Ibiza)**	2:40:00
UUEE	**(RU-Moscow)**	3:24:18
GCFV	**(ES-Fuerteventura)**	4:29:23

Table 4.3: Example values for in-vehicle travel time duration (in hours) by plane according to *Equation 3.4 - revisited*

		EHAM (NL-Amsterdam)
EGKK	**(UK-London)**	1:15 - 1:30
LEIB	**(ES-Ibiza)**	2:35 - 2:45
UUEE	**(RU-Moscow)**	3:15 - 3:30
GCFV	**(ES-Fuerteventura)**	4:30 - 4:35

Table 4.4: Comparison of the in-vehicle travel time duration by car in percentage point (extracted from: Skyscanner Ltd (2020))

In *Table 4.5*, an overview of the standard mode characteristic parameters is given. Regarding the trip time components, only the waiting time is defined as a constant parameter. This value of 110 minutes is based on the dings of Park & Ahn (2010), who found that that passengers for short-haul flights on average arrive between 100 to 120 minutes before the scheduled departure.

Table 4.5: Travel time and vehicle characteristics of air travel (author's elaboration, partially based on: Ashford & Benchemam (1987), Belobaba et al. (2009) and Park & Ahn (2010))

Airplane	**Trip Time Components**		**In-vehicle time**		**Vehicle Properties**	
	factor	**value**	**factor**	**value**	**factor**	**value**
✈	t^{access}	*var.*	$t^{acceleration}$	30 min	$cap^{seating}$	*n/a*
	$t^{waiting}$	110 min.	$ds^{acceleration}$	50 km	fc^{detour}	1.00
	$t^{in-vehicle}$	*var.*	$s^{cruising}$	850 km/h		
	$t^{transfer}$	*n/a*	$t^{deceleration}$	30 min		
	t^{egress}	*var.*	$ds^{deceleration}$	50 km		
			t^{dwl}	*n/a*		

Car characteristics

The duration of car trips is based on the travel times of the road connections that were found in *section 4.2*. However, these road time are calculated for direct trips. In reality, it cannot be expected that drivers of long-distance trip make these journeys without pausing every few hours. To include this time, an additional time factor of 10% is added to the total time. The total overview of parameters that are relevant for car travel is stated in *Figure 4.6*.

Table 4.6: Travel time and vehicle characteristics of car travel (author's elaboration, partially based on: Donners (2016))

Car	**Trip Time Components**		**In-vehicle time**		**Vehicle Properties**	
	factor	**value**	**factor**	**value**	**factor**	**value**
🚗	t^{access}	0 min	$t^{acceleration}$	0 min	$cap^{seating}$	*n/a*
	$t^{waiting}$	0 min	$ds^{acceleration}$	0 min	fc^{detour}	1.20
	$t^{in-vehicle}$	*var.*	$s^{cruising}$	*var.*	fc^{rest}	1.1
	$t^{transfer}$	*n/a*	$t^{deceleration}$	0 min		
	t^{egress}	0 min	$ds^{deceleration}$	0 min		
			t^{dwl}	*n/a*		

High-speed train characteristics
given the current state of HSR, which is relatively limited compared to other the modes, it is more complicated to use revealed data as a reference for travel times along the network. For this reason, it is chosen to use the assessment of Campos & de Rus (2009) on world-wide HSR systems. The assessment results in a number of stylised facts.

Most relevant for this research are the vehicle seating capacity and the maximum driving speed. Campos & de Rus (2009) finds when specifically analysing Spanish, French, German and Italian systems, that the vehicle seating capacities range between 329 and 627 seats per vehicle. Because this capacity is not one of the decision variables, it is chosen to use a relatively low value of 350 seats, such that does not become a blurring factor.

Following this, it is seen that the maximum vehicle speed ranges between 230 and 330 km/h, with an average of 296 km/h. Considering that it is not always possible to drive at the maximum speed, it is chosen to use a value of 275 km/h as cruising speed. However, just like the airplane, the train comes with more trip phases than just cruising; namely dwelling, accelerating and decelerating. These phases have been visualised in *Figure 4.12*.

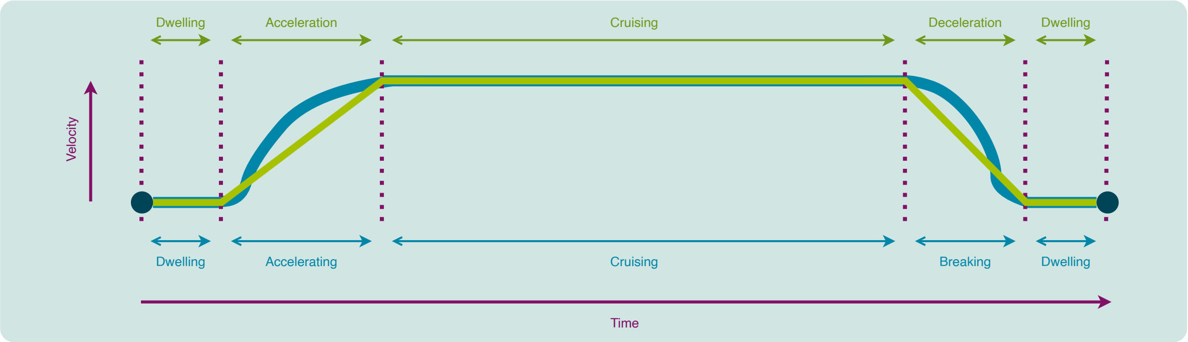

Figure 4.12: Visualised vehicle trip phases for high-speed rail travel (partially based on: Connor (2014))

The curved accelerating and deceleration patterns are simplified by straight lines, that carry the same properties on the distance covered and time consumed, as based on modelling high-speed trains by (Connor, 2014). Using the same parameters for acceleration ($0.3m/s^2$) and deceleration ($0.5m/s^2$), the values as stated in the second column of *Table 4.7* are found. For the dwelling time, a value of 5:00 minutes was assumed.

Table 4.7: Travel time and vehicle characteristics of high-speed train travel (author's elaboration, partially based on: Campos & de Rus (2009), Connor (2014) and Donners (2016))

High-Speed Train	Trip Time Components		In-vehicle time		Vehicle Properties	
	factor	**value**	**factor**	**value**	**factor**	**value**
	t^{access}	*var.*	$t^{acceleration}$	4:15 min	$cap^{seating}$	350
	$t^{waiting}$	15 min	$ds^{acceleration}$	9.75 km	fc^{detour}	1.09
	$t^{in-vehicle}$	*var.*	$s^{cruising}$	275 km/h		
	$t^{transfer}$	30 or 60 min*	$t^{deceleration}$	2:30 min		
	t^{egress}	*var.*	$ds^{deceleration}$	5.85 km		
			t^{dwl}	5:00 min		

* *subject to governance structure: 30 min for 'centralised organisation' and 60 min for 'free market' (see section 3.4)*

4.4. Stakeholder Specifications

The interests of the stakeholders as represented in the general objective function (of *Equation 3.18*, are all based on the costs they experience. In the subsection below, parameter values are assigned to all of the costs functions that are relevant to the parties involved.

User's characteristics

The user's sub-objective is to minimise its costs when travelling through the network. To translate the travel time to a monetary value, the value of time is introduced. This value, which represents the costs that somebody is willing to make for a travel time saving, varies over different trip and passenger types.

In Kouwenhoven et al. (2014), an assessment of the value of time for The Netherlands is made. This assessment considers different modes (car, conventional train, BTM and air), as well as different travel purposes (business, commuting, recreational and other). Given the long-distance transportation character of this research, it was chosen to use findings in the field of air transport. Here, it is seen that the value of time ranges between 85.75 for business trips to 47.00 for other trips, with an average of 51.75 for all trips. Continuing with the average value of 51.75, a few considerations have to be taken into account before this value can be used.

First of all, the report dates from 2010, meaning that yearly average inflation would have increased this to a slightly higher value. On the other hand, the research is performed in a relatively wealthy part of Europe (The Netherlands), which could suggest a lower value for the whole continent. As a rough indicator - considering that arguments for both directions are possible - it is assumed that the standard value of time approximates 50 euros/hour.

A single number for the value of time alone is not able to accurately capture the differences between the separate stages of a trip, as discussed by Ramjerdi (2010). In this work, the value time is divided into the five different stages and assigned a certain weight, especially focused on long-distance transport (100+ km). Using these weights for the previously determined value of time gives the value of time per trip segment as presented in *Table 4.8*.

Table 4.8: Value of time for long distance travellers per trip component (based on Kouwenhoven et al. (2014) and Ramjerdi (2010))

	Access	**Egress**	**In-vehicle**	**Transfer**	**Egress**
Weight [-]	1.36	1.50	1.00	1.50	1.36
VoT [€/h]	67.5	75	50	75	67.5

Operator's characteristics

The operator is responsible for the cost that are associated with operating and maintaining the network as is it is offered, which makes that it has a goal to minimise these costs components. To gain insights in the costs of running an HSR network, the assessment on world-wide HSR systems of Campos & de Rus (2009) was once again consulted. The work mentions three main costs components: rolling stock acquisition, operational costs and maintenance costs. Given the continuous-phase character of this research, it is decided to exclude the acquisition costs.

Table 4.9: Operator cost factors: Marginal operational and maintenance costs (based on: Campos & de Rus (2009))

	Operational costs [€/seat-km]	**Maintenance costs [€/seat-km]**
Value	0.130*	0.0122*

* *subject to governance structure: 100% for 'centralised organisation' and -20% for 'free market' (see section 3.4)*

Again, specifically focused on the current HSR systems in France (Thalys/TGV), Germany (ICE), Italy (ETR) and Spain (AVE), an assessment on the costs per seat-kilometre was made. It was found that the operational costs range between 0.078 and 0.177 euro per seat kilometre, with an average of 0.130. From the maintenance perspective, extreme values of 0.0050 and 0.0230 were found, with an average of 0.0122. For this researches, it was chosen to use the average values, as depicted in the second and third column of *Table 4.9*.

Society's characteristics

Transport by definition comes with its impact on the surroundings. These impacts are monetised by the name of external costs. Internalising these into the objective function of the problem, allows the model to search for solutions that contribute to a minimisation of this factor.

In a report (CE Delft, 2019) on the internalisation of transport externalities and sustainable infrastructure charging commissioned by the European Commission, an assessment of the external costs induced by different forms of long-distance transport was made. The main results of this are presented in *Table 4.10*. The external costs are divided into seven sub-components, all with their separate impact on society.

Table 4.10: Societal cost factors: Average external costs 2016 for EU28 passenger transport by cost category and transport mode (CE Delft, 2019)

	Air Plane (short-haul) [€-cent/passenger-km]	**High-Speed Train** [€-cent/passenger-km]	**Car** [€-cent/passenger-km]
Accidents	0.04	0.1	4.5
Air Pollution	0.30	0.0	0.7
Climate	2.39	0.0	1.2
Noise	0.46	0.3	0.6
Congestion	*n/a*	*n/a*	4.2
Well-to-Tank	1.06	0.3	0.4
Habitat Damage	0.03	0.6	0.5
Total	4.28	1.3	12.1

The components that are used in this table comprehend a variety of factors, as defined by CE Delft (2019). '*Accidents*' mainly involve the costs associated with the number of casualties, such as medical and administrative costs, but also production loss. '*Air pollution*' covers health effects, but also crop losses and loss of biodiversity. Similarly, but slightly different formulated, are the costs for '*climate change*'. These are considered to be the avoidance costs that are based on the targets of the Paris agreement. Following this, '*noise*' is mostly related to annoyance, '*congestion*' to delay & productivity losses, '*well-to-tank*' considers the negative effects of energy production and finally '*habitat*' damage focuses on fragmentation of ecosystems.

In *Table 4.10*, it can be seen that each of the modes score differently on the varying factors. These differences are mainly based on the characteristic properties of the modes, such as their reliance on physical infrastructure or the type of energy that is used.

4.5. Constraint Specifications

In *subsection 3.2.5*, on the definition of of problem constraints, two types of constraints were defined: '*Line Design Constraints*' and '*Frequency and Timetable Constraints*'. Some of these constraints have a more general character, which means that they prevent the model from searching for solutions that physically impossible. Other constraints have more practical function. In this section, these constraints and their parameterisation are further defined. An overview of these constraints and their values is given in *Table 4.11*.

For this problem, the line design constraints are the more '*practical*' constraints. For the line length constraint, a minimum distance of 200 km is chosen. The argumentation for this is two-fold: Firstly (1), it prevents nesting with conventional trains, which mainly operate below these distances and which do not represent the goal of this thesis. Secondly (2), it is possible to model the demand accurately at lower distances with the chosen method (see *section 4.6*). These demand estimations are based on revealed air travel data, which is barely existing below 200 km.

Similar to the line length constraint, it is chosen to apply a minimum of three stops per line (thus two terminal stations and one intermediate stop). This prevents the model from building a patchwork of separate lines that mainly compete with conventional train networks, rather than thinking from a network perspective. Finally, the round trip time is set to be 18 hours, in order to assure a vehicle symmetry that allows all vehicles to return to their home station within one day. Together with the turn-around-time as discussed in *subsection 4.4*, this means that a train can travel a maximum time-distance of 8.45 hours from its origin.

Table 4.11: Overview of parameterised constraints (author's estimations / design choices)

Constraints	Name	Value	Description	Reference
Line Design	Line length	200 km	minimum distance covered per line	*Equation 3.19*
	No. of stops	3 stops	minimum number of stops per line	*Equation 3.20*
	Round trip time	18 hours	maximum round trip time	*Equation 3.21*
	Line symmetry	*n/a*	line $l_{i,j}$ from i to j equals $l_{j,i}$ from j to i	*Equation 3.22*
	Infrastructural line detour	1.5	maximum detour within infra. network	*Equation 3.23*
	Geographical line detour	1.5	maximum detour compared to greater circle distance	*Equation 3.24*
Frequency & Timetable	Min. frequency	1 veh/day	prevents negativity and ghost lines	*Equation 3.25*
	Int. frequencies	*n/a*	only integer frequencies are allowed	*Equation 3.26*
	Freq. symmetry	*n/a*	continuity in number of trains per direction	*Equation 3.27*
Passenger Path Constraints	Max. no. of transfers	2 transfers	limits the number of transfers	*Equation 3.28*
	Strategic pricing (infra.)	1.10	excludes infra. detouring passengers	*Equation 3.29*
	Strategic pricing (geo.)	1.10	excludes geo. detouring passengers	*Equation 3.30*

4.6. Demand Estimations

The model of this thesis builds upon a transport demand between the cities of the network, in this case, the 124 core cities as defined in *section 4.1*. Due to the complexity of modelling such long-distance demand based on socio-demographic factors, it is chosen to expand revealed travel data from the airline industry, again using the Using a voluntary annual questionnaire of passenger and cargo flows between European airports (Eurostat, 2020a). However, using this revealed data comes with three main challenges.

Challenging aspects in translating air travel demand from airport to cities

Firstly (1), it projects travel flows between airports rather than cities, which is contradictory to a typical long-distance trip that originates and ends in a city rather than an airport. This means that the air travel flows have to be assigned to cities that are associated with the airport.

With this, the second (2) difficulty arises, as airport-city pairs are frequently part of a more complex system covering multiple entities. An example of this is the London Metropolitan Area, which is mainly served by five airports (City, Gatwick, Heathrow, Luton and Stansted). On the other hand, there are also airports which serve multiple cities, such as EuroAirport Basel-Mulhouse-Freiburg (LFSB) or cities that do not have a dedicated airport, such as Utrecht (Netherlands).

The third (3) challenging aspect concerns the fact that air travel flows only partially describe the overall travel demand between cities and that this fraction varies according to the relative performance of the airplane compared to competing modes. The most important explanation in this relates to distance, as it likely that people travelling between Lisbon and Moscow are more inclined to take the plane compared to travellers between Vienna and Bratislava.

Proposed methodology for transport demand estimations

To provide the model with an overall long-distance transport demand, that is based on revealed air transport demand and that respects the above-mentioned difficulties, the novel methodology as visualised in *Figure 4.13* is proposed. Here, the raw air traffic flows are transformed by fitting the expected travel behaviour between each city-city pair to the relevant airport-airport traffic flows. A detailed description of this methodology can be found in *appendix B*.

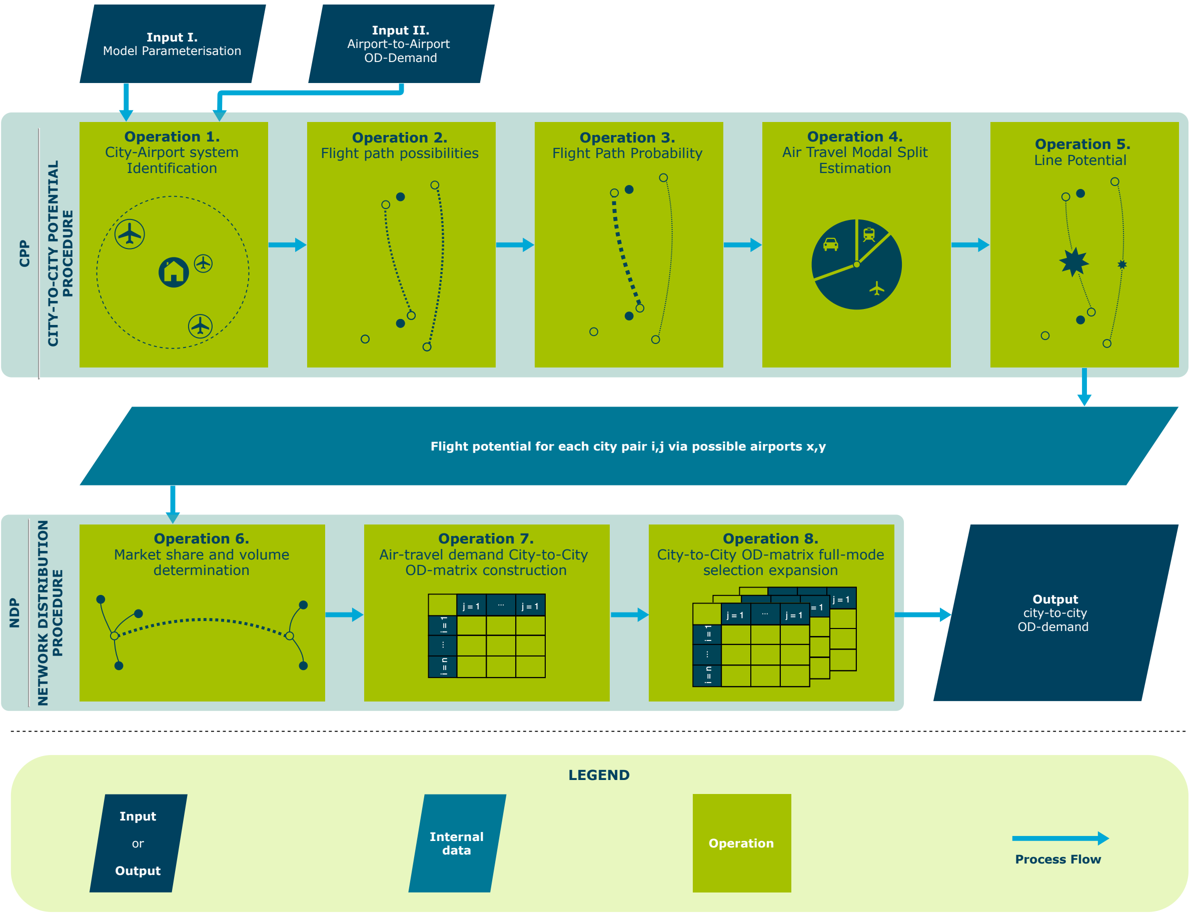

Figure 4.13: Demand estimation methodology (author's elaboration) - *(see appendix B for detailed description)*

The methodology starts at the upper left-hand corner in '*Operation 1.*', where the city-airport systems are determined assuming a 2.5-hour catchment area. This is then followed by '*Operation 2.*' where an inventory of possible flight paths between city-city pairs is made, considering both city-airport systems. Using a utility maximisation theory (based on access/egress times, border crossings and displaced vehicle time) estimations for the possibility of each flight to be taken are made for each city-city pair in ‘*Operation 3.*’. Subsequently, the average flight for such city-city pairs is compared with other modes (using the random regret theory as defined by Chorus et al. (2008) and applied to HSR by Donners (2016)) to determine its competitiveness and estimate a modal split. Following this, ‘*Operation 5.*’ assigns a so-called ‘*potential*’ to each flight leg, as can be expected from the travel times between the cities.

The methodology continues at ‘*Operation 6.*’, where the determined traffic flow potentials are combined, such that it becomes possible to explain the percentage of traffic on a certain flight leg which is induced by the demand of a given city-city pair. Scaling this value to the observed travel flows on a flight leg as stated by Eurostat (2020a), an exact number of passengers using that flight whilst travelling between two cities can be estimated in ‘*Operation 7.*’. This results in an OD-matrix of air passengers between certain cities. Finally, in ‘*Operation 8.*’, this air demand between city-city pairs was extrapolated to an overall traffic demand using the findings of Donners (2016) on the expected market share for air traffic per distance unit. Together, the operations resulted in an OD-matrix for long-distance travel demand between all of the 124 cities.

5

Validation

Before using the novel heuristic of *section 3.3* on the newly defined problem of *section 3.2*, an understanding of the method's uncertainty level of realism has to be assured. This chapter assesses the quality of the method from two perspectives. First, *section 5.1* performs a smaller test experiment to assess the accuracy and required computation times, after which this is translated to the real-scale event as parameterised in *chapter 4*. Following this, *section 5.2* performs a real-scale test experiment to see whether the model returns feasible results and what is to be adapted. Finally, *section 5.3* concludes by making an overview of all method adjustments.

5.1. Model Implementation and Performance

The implementation of the model and its solution strategy was written in '*Python 2.7.16*' using the environment of '*Spyder 3.3.6*', which was verified by continuous checks. All tests were performed using single personal computers with an Intel(R) processor, Core(TM) i5-8500, 3.00 GHz and 16 GB RAM memory.

The heuristic approach that was designed for this problem (as described in *section 3.3*), was supposed to significantly reduce the computation time needed whilst also providing accurate results. To gain insights into the model's performance on these two factors, it was tested on a relatively small network that allowed for a comparison with an exhaustive search that comprises all possible line configurations. This case will be described in *subsection 5.1.1*, after which the results for the small case and the implementations they bring, are discussed in *subsection 5.1.2*. Finally, *subsection 5.1.3* describes the adaptions that have been made to control the computation time for the large problem.

Table 5.1: Resulting '*Pool of Lines*' for the validation case

Line	Route	Stops	Length [km]	Duration [h]
1	Cologne - Dusseldorf - Ruhrgebiet - Hanover - Berlin	5	559,6	2,59
2	Cologne - Dusseldorf - Ruhrgebiet - Hanover	4	301,6	1,52
3	Munich - Leipzig - Berlin	3	562,8	2,33
4	Munich - Frankfurt - Cologne	3	529,0	2,20
5	Hamburg - Bremen - Ruhrgebiet - Dusseldorf - Cologne - Aachen	6	487,8	2,47
6	Hamburg - Berlin - Dresden	3	433,0	1,85
7	Kiel - Hamburg - Berlin	3	347,4	1,54
8	Munich - Frankfurt - Cologne - Aachen	4	594,4	2,58
9	Munich - Leipzig - Dresden	3	493,7	2,07
10	Munich - Stuttgart - Karlsruhe	3	272,7	1,27
11	Munich - Stuttgart - Mannheim	3	329,4	1,48
12	Ruhrgebiet - Dusseldorf - Cologne - Frankfurt - Mannheim - Karlsruhe	6	373,6	2,06
13	Ruhrgebiet - Bremen - Hamburg - Kiel -	4	447,5	2,05
14	Ruhrgebiet - Dusseldorf - Cologne - Frankfurt - Mannheim	5	309,7	1,68
15	Saarbrucken - Mannheim - Stuttgart - Munich	4	450,5	2,06
16	Saarbrucken - Mannheim - Frankfurt - Cologne - Dusseldorf - Ruhrgebiet	6	430,8	2,26
17	Stuttgart - Mannheim - Frankfurt - Hanover - Hamburg	5	656,9	2,95
18	Stuttgart - Mannheim - Frankfurt - Cologne - Dusseldorf - Ruhrgebiet	6	438,8	2,29

5.1.1. Description of the small test case

For this test, the sub-network of Germany was selected as the experiment boundary. Consisting of seventeen cities, 28 edges, 206 OD-pairs and a total daily internal transport demand of 149.000 passengers, it is regarded to be an adequate case. Given their size and geographical location, Berlin, Munich, Cologne and Hanover were assigned as terminal cities. The model was allowed to select - from the feasible lines - one route to the highest demand destination and one route that has the highest usage potential, for each of the terminal cities. Combining this with the connector lines for the non-connected cities results in a total of eighteen line options, which are displayed in *Table 5.1*. With these eighteen lines, the solution space of this problem has $2^{18} = 262.144$ unique possibilities.

5.1.2. Assessing the model's performance for the small test case

The heuristic search uses the procedures as developed in *section 3.3*. Starting with a fully deactivated line configuration, the heuristic uses hill climbing strategies to work its self towards a strong performing solution. In *Figure 5.1*, the steps as made by the heuristic model have been visualised. It can be seen that the main progress is booked in the first line activation phase, which is found in the upper left-hand corner. Adding ten lines, an improvement of the objective function of -1.827.061 is booked. This value will later turn out to approach the optimal value by 99.39%.

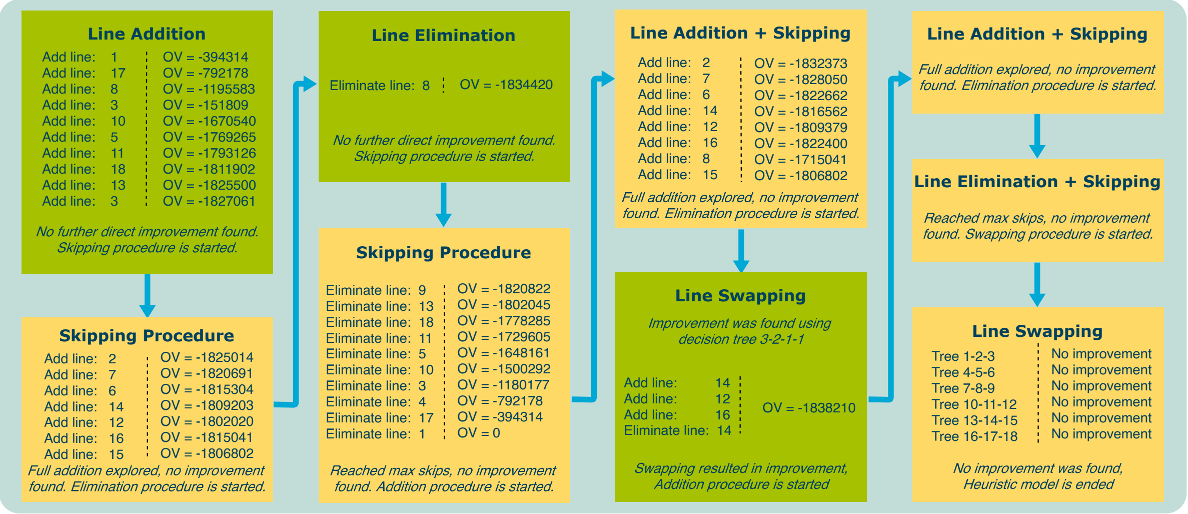

Figure 5.1: Resulting heuristic log process for the validation case

Analysis of the decisions made by the model

After adding line 3, it turns out that no direct improvement can be reached when adding one more line. In the next step, it starts to look forward by forecasting the effects of accepting a deterioration. It, however, finds that, after exploring the full line set, no improvement is found. This means that a step can be made towards the following phase, of line deactivation.

In the line deactivation, it is decided to cancel line 8. This increases the objective value to -1.834.420, or 99,79% of the final objective score for this model. In the consecutive skipping procedure, it turns out that no further improvements can be attained, which is also found for the subsequent line activation phase. Given that no improvements are found by adding or eliminating, it is decided to move to the substitution phase.

Performing the first substitution tree (1-2-3), which tries to find improvements by initially accepting the first, second and third performing step, it is seen that one path results in improvement. Adding lines 14, 12 and 16 does not give any direct advancements. However, when eliminating line 14 in a later phase, it is seen that a new improvement is found. Reaching an objective value of -1.838.210, the heuristic returns back to its previous strategies. It, however, does not find any further improvements in any other operation. The final line configuration as found for this case is given in *Table 5.2*

Table 5.2: Final line configuration for the validation case, as calculated by the heuristic model

Line no.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Active	1	0	1	1	1	0	0	0	1	1	1	1	1	0	0	1	1	1
Frequency	29	0	21	22	8	0	0	0	3	7	9	3	4	0	0	3	26	6

Comparison to an exhaustive search on quality and speed

As mentioned previously, the exhaustive search inquires every possible line configuration for the validation case, meaning that it has to consult the Network Analysis Procedure 262.144 times. The advantage of this is that an optimal solution can be guaranteed, though it comes at a very high computation time. In *Figure 5.2*, the results of the exhaustive search have been plotted against the results of the heuristic search. From this graph, two main findings can be identified.

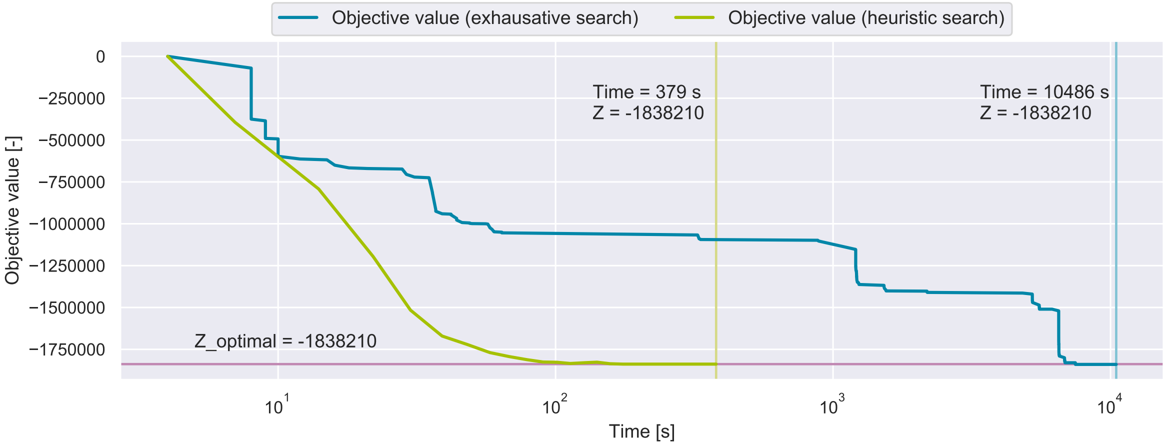

Figure 5.2: Performance comparison of heuristic and exhaustive search for validation case

First of all, it can be seen that the heuristic model has been able to reach the optimum objective value of -1.838.210. Comparing both results, it turns out that these objective values are reached with the exact same line configuration, meaning that the final solution is identical.

The second observation concerns the running times of both models. Running for 379 seconds, the heuristic model requires only 3,6% of the time needed by the exhaustive search. If one were to accept the score provided by the line activation only (99,39%), the required computation time would even decrease to 101 seconds, or 0,96% of the exhaustive computation time.

Implications of observed results for large-scale problem

The above findings provide insights into the functioning of the heuristic that was designed for this research. It shows a significant decrease in computation time whilst still being able to approach the optimal value. It should, however, be noted that an increased problem size changes to factors new to this.

Concerning the quality of the solution, it is expected that larger solution spaces bring more local optima and larger differences between the performance of different solutions. It is therefore foreseen that it will be more likely to end up in a local optimum, although it cannot be exactly defined how large this effect will be.

Regarding the computation time, it is expected that the differences between the exhaustive and heuristic search will increase with a larger problem size. From the separate iterations, it was seen that the computation time increases with the number of activated lines. This means that the computation time of the exhaustive search would be based on an average time required for a 50% activated set. For the heuristic search, however, a slightly different view is observed. Starting at an empty line configuration and rarely reaching a full configuration, it is seen that the average computation times per iteration are lower.

5.1.3. Computation time control for the large-scale problem

Performing the heuristic for the large scale problem that describes Europe with 124 vertices and associated edges, as presented in *chapter 4*, it was found that the computational burden became too large, with an estimated running of 70 years per simulation. The reason for this was defined to be two-fold: (1) a large pool of lines (≈7000 lines) and a (2) large number of OD-pairs (≈2□5000) to be considered. To reduce the size of the problem, these two factors were reduced by three measures that have been previously mentioned in *section 3.3* on the '*Heuristic model formulation*'. These measures were (1) the definition of key-cities, (2) the tactical deactivation of lines and (3) the lowering of the so-called demand resolution.

Selection of key-cities for lines to begin or terminate

The proposed Line Generation Procedure of *subsection 3.3.2* makes that a pool of lines could theoretically contain $2 \cdot (V^2/2)$ unique lines, if all demand-based lines were to be divergent from their shortest-path based alternative. Considering the exponential relation with the number of vertices, it was opted to reduce this number by assigning a selection of key-cities, which were defined as the only places where lines could either begin or terminate.

In search for a balance between a diverse palette of lines, but also a reduction of the computational burden, it was chosen to select 50 key-cities, which resulted in a theoretical reduction of 84% (from 15.376 to 2.500 lines). The choice of these 50 cities was made aiming for continuous coverage throughout the network and the largest passenger demands that were expected. This led to the selection of the 37 capital cities, that was supplemented by 13 cities regarded to be important for their geography or size. An overview of the key cities is stated in *Table 5.3*.

Table 5.3: Selected 50 key-cities for beginning or terminating lines

Tirana	Sofia	Helsinki	Rome	Chisinau	Bucharest	Madrid	Kiev	Munich	Frankfurt
Vienna	Zagreb	Paris	Pristina	Podgorica	Moscow	Stockholm	London	Barcelona	Manchester
Minsk	Prague	Berlin	Riga	Oslo	Belgrade	Zurich	Glasgow	Seville	Bordeaux
Brussels	Copenhagen	Athens	Luxembourg	Warsaw	Bratislava	Amsterdam	Porto	Ruhrgebiet	Istanbul
Sarajevo	Tallinn	Budapest	Skopje	Lisbon	Ljubljana	Ankara	Catania	Stuttgart	Lyon

Early and tactical elimination of lines for reduction pool of lines

To further reduce the problem's size, a tactical elimination of remaining lines was performed. Here, each key-city was separately assessed, as an inventory of all lines beginning or terminating here was made. Out of each city-specific inventory, a range of different lines were selected to be used for the actual '*Pool of Lines*', such that this sub-selection would still be a realistic representation of the original connections whilst ensuring enough different options.

The first (1) line type was based on '*closeness*', as it selected a number of shorter lines having a close-by terminal destination. Following this, the second (2) line type was based on the '*highest-demand*', which selected the lines travelling to the destination that attracted most passengers as seen from the origin city. These were lines usually characterised by a medium-long distance. Finally, the third (3) line category covered the '*highest-usage*' lines, which estimated the expected revenue passenger kilometre per line and selected those with the highest values, such that especially longer lines travelling high-demand itineraries were selected.

For this case study, it was found that selecting five lines on ‘*closeness*’, three lines on ‘*highest-demand*’ and three lines on ‘*highest usage*’, resulted in a pool of lines containing approximately 350 lines. This is slightly lower than the theoretical 550 lines, which can be explained by certain lines being selected twice from both the origin and destination station. However, the above line reduction methods of ‘*key-cities*’ and ‘*tactical lines selection*’ led to some non-key-cities not being connected by any through-line due to their geographic location, such as Groningen, Rennes or Tampere. It was chosen to also include one line based on ‘*closeness*’ and one line based on ‘*high-demand*’ for these cities. Together, this resulted in a pool of lines reaching approximately 400 lines.

Demand resolution: neglecting smaller demand flows
As was previously mentioned, the base parameterisation contained demand flows for 5.174 out of 7.688 possible OD-pairs in the European network. Calculating all of these brings a higher accuracy, but also comes at the costs of a nearly linear increase in computation time. To reduce the computational burden of this factor, it was chosen to only consider the greatest demand flows within the network. These were estimated using the total demand as determined in *section 4.6* combined with the expected share of HSR traffic per distance unit as estimated by Donners (2016), which is visualised by the bright-green line in *Figure 5.3*.

The expected HSR demand matrix enlarged the difference between certain traffic flows, as it is, for example, less likely for passengers between Lisbon and Madrid to take the train when comparing this to distances close to 500 km, such as Lisbon-Madrid. The estimations showed that 90% of all expected HSR traffic could be taken into account by only considering the approximately 1.000 largest OD-pairs, thus reducing the computational effort 80%. It was chosen to do this, which meant that OD-pairs having an expected HSR demand lower than $2 \cdot 20$ were excluded from the model.

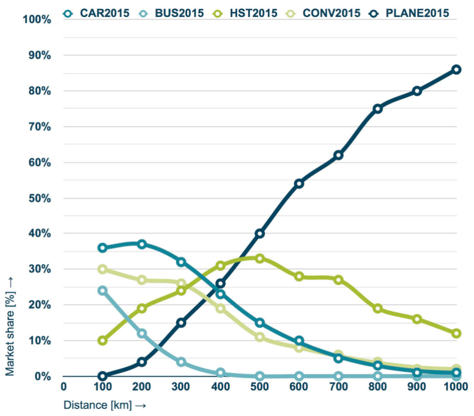

Figure 5.3: Modal split per distance for long distance travel, as determined by Donners (2016)

Resulting computational time after adaptions
Performing the three proposed measures to shorten the required computation time, it was observed that simulations were able to finish within three to five days, depending on the extensiveness of the final network.

5.2. Model Behaviour and Necessity of Passenger Path Control

To confirm the overall realism of the model’s outcomes, test runs were executed using the parameterisation of *chapter 4* for the large scale problem. Below, of the observed behaviours are discussed. First, *subsection 5.2.1* describes the implications of the model’s greedy behaviour, after which *subsection 5.2.2* identifies the problems that arise from undesirable passenger flows.

5.2.1. Implications of the model's greedy character

One of the first notabilities that becomes visible during the process of '*line activation*', is that the method is somewhat greedy. This comes forward by the fact that it starts by building relatively long lines, such as Glasgow-Ruhrgebiet, Zurich-Stockholm, Amsterdam-Madrid or Bratislava-Tallinn. This behaviour follows from the large number of passenger-kilometres that can be made using these lines and thus the strong reward it receives for the objective function value. This practice often continues for approximately 5-10 iterations, after which it will start to connect smaller routes to the main arteries.

It is seen that, in different configurations, the model frequently uses the same lines to start with. This suggests that these lines offer an effective start, by serving a few large demand flows that together justify a certain frequency of trains from the operator along that whole line, resulting in a positive and efficient cost-benefit ratio.

The behaviour as described increases the chance of ending up in local optima since the first long lines have an important influence on how the rest of the network is developed. It could very well be that the combination of other long lines with shorter connections might perform better, but that these are not seen.

For this research, it is regarded infeasible to adjust the heuristic in such a way that it could, later on, make large-scale changes to the network. However, it also assumed to be not highly problematic, given that this research is more focused on the general characteristics of a developed network, rather than the most optimal solution. Moreover, it would not necessarily be a strategy to build a network around the strongest performing links.

5.2.2. Undesirable passenger paths and how to control them

Simulating longer, another problem arises. It is seen that - in the base scenario - the model ends up with a network of something that can be described as separate island networks. This solution, for which the overall map is displayed in *Figure 5.4*, started with the greedy strategy of longer lines, as explained in *subsection 5.2.1*. In following iterations, smaller lines are joined to the longer existing lines. With this, they can connect new cities to a long line, allowing for a whole new set of passenger streams. Examples of this are the Oslo-Copenhagen line (which connects to the Zurich-Stockholm line), or the Edinburgh-Birmingham line (which connects to the Glasgow-Ruhrgebiet line).

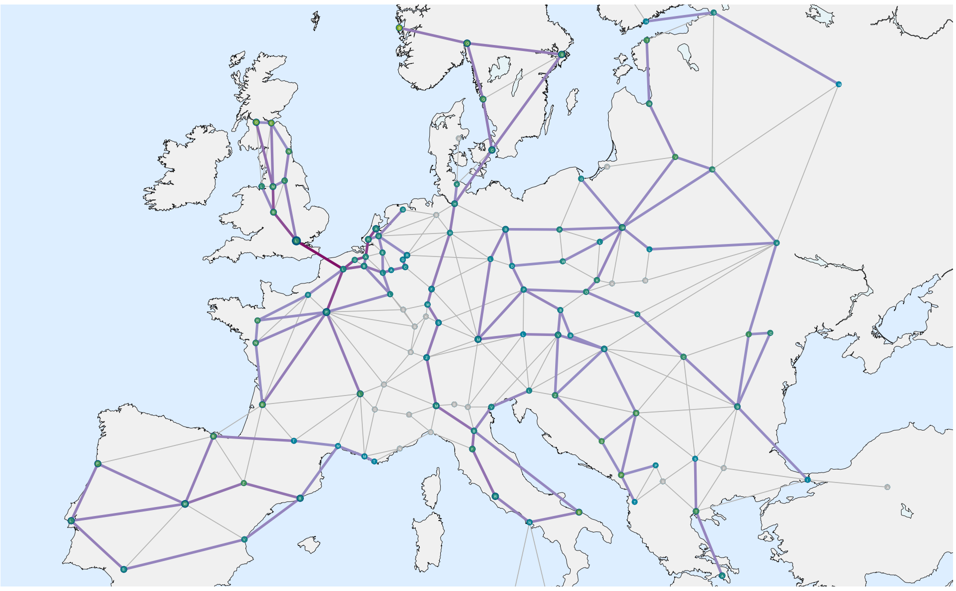

Figure 5.4: Developed network: separate island networks in the Total Welfare scenario (used infrastructure in purple)

Despite the logical sequence of events, it turns out that the model reaches a barrier somewhere, which prevents it from connecting the island networks to each other. Analysing further, it is seen that the model only allows for perpendicular line connections in the early stages of network development, when it works with longer lines. Contrasting to this, it is seen that these perpendicular line connections are not made when filling up the network with smaller lines in not yet densely connected areas. This suggests that the model experiences an effective disadvantage when connecting perpendicular streams of existing islands.

The best example of this theory can be found in the two lines that make a north-south connection: Stockholm-Zurich and Zurich-Rome. It can be seen that apart from some smaller connections, they are not connected to the other networks at all. From a logical perspective, it could be beneficial to integrate this line with the other networks on the east or west side. However, making this first connection is apparently not beneficial enough in order to be performed.

Identification of disadvantageous passenger path types:
To understand why the above happens, a more deepened focus on the balance between the operator costs and the user benefits has to be made. If one were, for example, to connect the Italian network island with the Central European network island by making a line between Munich, Ljubljana and Zagreb, a series of effects would occur. This new connection is visualised in *Figure 5.5* by the dark green lines.

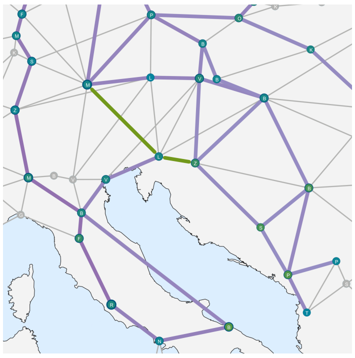

Figure 5.5: Existing network (purple) with newly added (green) line

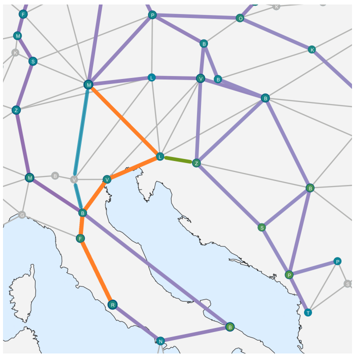

Figure 5.6: Infrastructural detour path induced by activating a new line

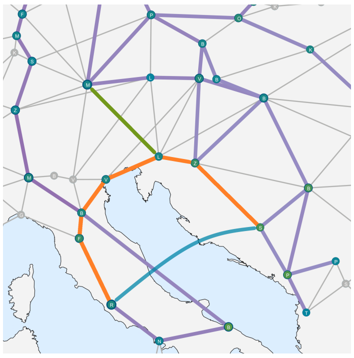

Figure 5.7: Geographical detour path induced by activating a new line

Where purple is current network, green is new line, orange is new passenger path and blue is ideal passenger path

Infrastructurally detouring passenger paths:
The first effect relates to the inefficient use of high-speed rail by passengers following non-optimal infrastructural paths. This issue is displayed in *Figure 5.6*, where the path for the newly introduced OD-flow between Rome and Munich is given. In an ideal scenario, these passengers would follow a path that travels via Bologna and Verona to Munich, as this is their shortest path through the network (blue line). However, they are now ’forced’ to travel via Ljubljana.

If the HSR is competitive enough, it might still attract a significant number of passengers. However, having to make this detour, the user benefits are smaller than they could potentially be, thus reducing the margin on the cost-benefit ratio. This effect is strengthened by an increased cost for the operator, as this stakeholder has to make more train-kilometres to transport these passengers from their origin to their destination.

Geographically detouring passenger paths:
The second negative effect induced by connecting the two networks comes from passengers travelling between geographically obstructed areas. An example of this is presented in *Figure 5.7*, where the path between Rome and Sarajevo is given. In this case, passengers travelling between

these two cities simply do not have a feasible alternative other than to encircle the Adriatic Sea.

Similar to the previous example, an HSR system that is competitive enough might still attract a considerable number of passengers on this route. Again, having to transport these passengers on such a long distance for such small benefits might not be attractive anymore when considering the operator costs.

Possible strategies to overcome the identified problem
Searching for literature, no previous documentation on the problems as described above was found. However, tweaking the parameters, three possible possibilities of reducing the impact of this problem were found: (1) '*Forceful subsidisation*', (2) '*Altering transfer possibilities*', (3) '*Strategic pricing*'

Forceful subsidisation:
The first option is relatively effective in what needs to do. Subsidising the system by increasing the weights for user and external interests, reduces the problems as experienced. Examples of this are given in *Figure 5.8* and *Figure 5.9*, where the networks for the '*Market Liberalisation*' and the '*Future Proof*' scenarios are given. It can be seen that problems are already less problematic in the latter scenario. Despite being an effective measure, it is not the most desirable. Subsidies are not necessarily meant to compensate for large-scale loss-making passengers, nor are they very cost-efficient.

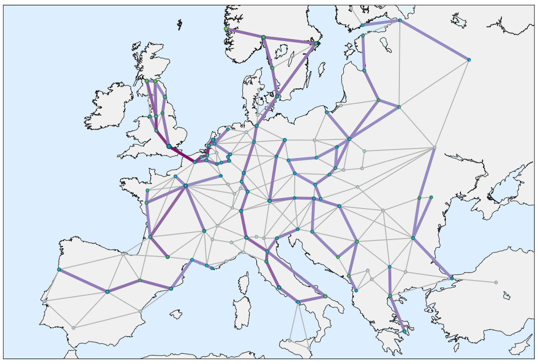

Figure 5.8: Developed network (Market Liberalisation)

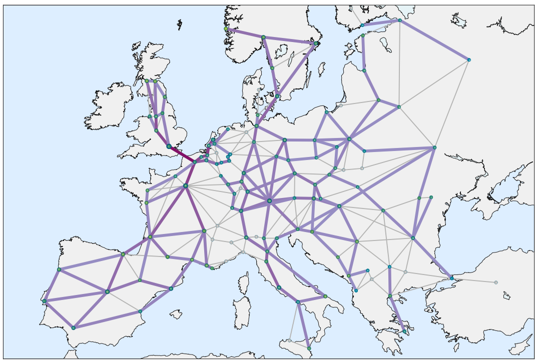

Figure 5.9: Developed network (Future Proof)

Altering transfer possibilities in time or numbers:
A second option for reducing problems regarding passenger path detours is to alter the transfer possibilities. Starting the transfer-time, it could be chosen to reduce this time. Given that detour passengers more often dependent on transfers, their benefits would be enlarged from a relative perspective, without affecting the operator costs. However, the current average transfer time is already set at 30 minutes for the '*Centralised Market*' scenarios. It is not regarded to make this time much shorter. On the other hand, it could be opted to make transfers less attractive by increasing the average transfer times or by setting a maximum of one or zero transfers. Though theoretically possible, it is considered a rather rude measure, as it also affects the more favourable passengers.

Strategic pricing for different passenger types:
A last option is to implement strategic pricing, in which unfavourable passengers are spilled from the system by charging them strongly increased ticket prices. This option is seen as the most elegant option, as it specifically focuses on passengers that undesirable, whilst the actual network is tailored to the passengers of interest. This option will be further expanded below.

Strategic pricing: multiple options for passenger exclusion
In the current model, it is not possible to influence the pricing of tickets for separate passenger streams. To be able to simulate strategic pricing anyway, it is chosen to simplify this matter by completely excluding the undesired OD flows, thus assuming that it is made impossible to travel

between certain ODs. This is done using two constraints, which are from now on integrated into the model.

Definition of infrastructural detour path constraint:
The first constraint limits the infrastructural path detours that can be made by passengers travelling between any V_i and V_j. This constraint, as defined in *Equation 3.35 - revisited*, describes a maximum deviation in travel time between the origins and destinations. Note that the travel time includes the transfer time, which makes that also long transfers on relatively short routes are excluded. If this constraint is not met, the demand on this OD-flow will not be considered.

$$P_{i,j}^{tt} < P_{i,j}^{ds,SP} * SPL^{infra} \qquad \forall \qquad i,j \in V \tag{3.35 - revisited}$$

where:

$P_{i,j}^{tt}$ = the travel time of the current best path P for passengers between V_i and V_j
$P_{i,j}^{tt,SP}$ = the travel time of the theoretically shortest path P for passengers between V_i and V_j
SPL^{infra} = the strategic pricing level for infrastructural detour paths

Definition of geographical detour path constraint:
The second constraint shows similarities to the first constraint. This constraint limits the geographical path detours that can be made by passengers travelling between any V_i and V_j, when comparing the length of their path to the greater circle distance between their origin and destination. This constraint, as defined in *Equation 3.35 - revisited*, has to be met, otherwise, the demand on this OD-flow will not be considered.

$$P_{i,j}^{ds,SP} < DS_{i,j}^{gc} * SPL^{geo} \qquad \forall \qquad i,j \in V \tag{3.35 - revisited}$$

where:

$P_{i,j}^{ds,SP}$ = the distance of the theoretically shortest path P for passengers between V_i and V_j
$DS_{i,j}^{gc}$ = The greater circle distance between V_i and V_j
SPL^{geo} = the strategic pricing level for geographical detour paths

Parameter level setting for strategic pricing constraints:
Introducing new parameters without any reference on their effects, it is important to secure an input that is both effective and realistic. To gain insights in the behaviour of this parameter, several smaller tests were executed. From this, it turned out values for both SPL factors in order size of $1.10 - 1.25$, seemed to show the desired effects. With this in mind, four large scale tests were performed, with combinations of the previously mentioned numbers for both factors. This resulted in networks as shown in *Figures 5.10, 5.11, 5.12* and 5.13.

Analysing the four networks by their lay-outs, it was first determined that the network of *Figure 5.13* ($SPL^{infra} = 1.25$ and $SPL^{geo} = 1.25$) seemed the least effective. The map still shows barrier between the west and east side of Europe, only being connected between Bordeaux and Zurich. Following this decision, the network of *Figure 5.12* ($SPL^{infra} = 1.25$ and $SPL^{geo} = 1.10$), was eliminated, given the difficulty that it still seems to have when it comes to the east and the west. It suggests that it is best to keep a low value for SPL^{infra}.

In the next phase, the upper two images of *Figure 5.10* ($SPL^{infra} = 1.10$ and $SPL^{geo} = 1.10$) and *Figure 5.11* ($SPL^{infra} = 1.10$ and $SPL^{geo} = 1.25$) were compared. At first glance, it seems like the network of *Figure 5.11* has more lines and shows a further development of the connectivity. However, it still experiences difficulties connecting and the west to the east in Paris-Ruhrgebiet-Amsterdam area. It is seen that large flows are not able to pass this region, whilst this does happen for the left-hand side scenario of *Figure 5.10*, where large flows between the United Kingdom, Germany and France are facilitated. The larger colour differences (thus relative higher edge loads) imply that this set-up is more efficient. Therefore, this option is chosen to continue with.

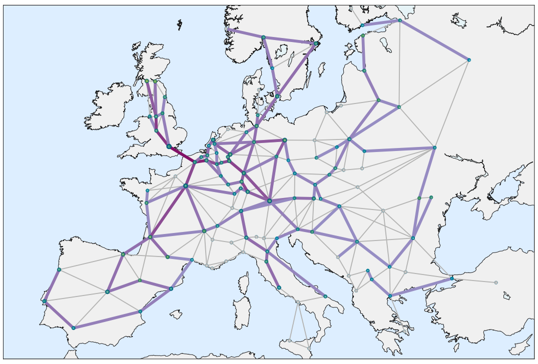

Figure 5.10: Developed network (Total Welfare) for $SPL^{infra} = 1.10$ and $SPL^{geo} = 1.10$

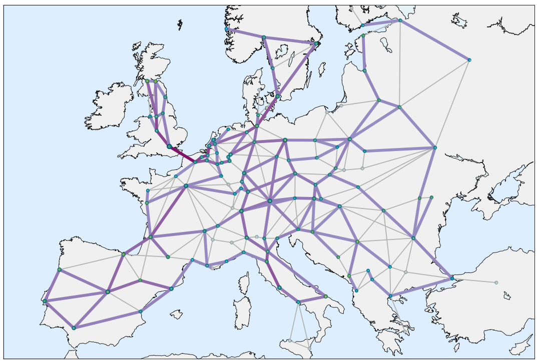

Figure 5.11: Developed network (Total Welfare) for $SPL^{infra} = 1.10$ and $SPL^{geo} = 1.25$

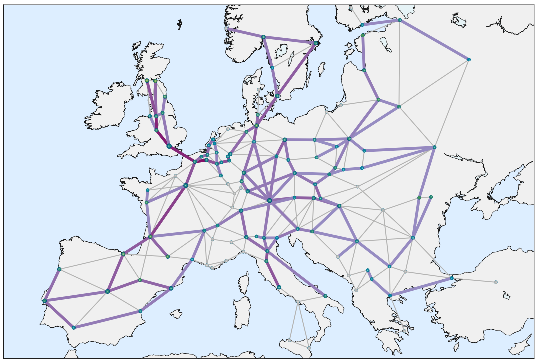

Figure 5.12: Developed network (Total Welfare) for $SPL^{infra} = 1.25$ and $SPL^{geo} = 1.10$

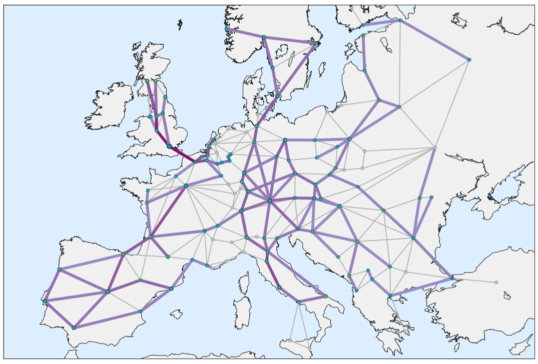

Figure 5.13: Developed network (Total Welfare) for $SPL^{infra} = 1.25$ and $SPL^{geo} = 1.25$

The decision as made on the SPL factors is made on limit data and knowledge. To increase insights on this, both strategic pricing levels will be further analysed in the analysis of *section 6.3* and *appendix D.2*.

5.3. Resulting Method Adjustments

The validation of this chapter demonstrated a number of shortcomings, both in problem description as well as in the strategy to solve the problem. A range of possible solutions was proposed, each connecting onto a different part of this research. To create an overview in the adaptions that were made, *Table 5.4* briefly describes all the observed problems and their adjustments.

Table 5.4: Overview of proposed adjustments to the model, based on the method validation

	Problem	**Proposed solution**	**Detailed info**	**Current method adjustment**	**Global impact analysis**	**Deeper impact analysis**
Compu. time	too many lines	terminal cities	*sec.5.1.3*	*sec.3.3.2*	*n/a*	*n/a*
	too many lines	tactical line reduction	*sec.5.1.3*	*sec.3.3.2*	*n/a*	*n/a*
	too many OD-pairs	demand resolution	*sec.5.1.3*	*sec.3.3.2*	*n/a*	*n/a*
Unprofitable passengers	balance user & operator benefits	forceful subsidisation	*sec.5.2.2*	*sec.3.2.4*	*sec.6.2*	*app.C*
	transferring passengers	altering transfer times	*sec.5.2.2*	*non*	*sec.6.3*	*app.D.2*
	transferring passengers	max. number of transfers	*sec.5.2.2*	*non*	*sec.6.3*	*app.D.2*
	geographical detours	strategic pricing	*sec.5.2.2*	*sec.3.2.5*	*sec.6.3*	*app.D.2*
	infrastructural detours	strategic pricing	*sec.5.2.2*	*sec.3.2.5*	*sec.6.3*	*app.D.2*

6

Results

Having a fully developed model allowed to search for answers to the research question and its sub-questions. This chapter states the results of the experiments as defined in the experimental set-up of *section 3.4*. First, *section 6.1* presents the outcome of (‘*Experiment I)*’, which is concerned with the simulation of the initial performance, such that later scenarios can be compared. This is then followed by *section 6.2* that discusses the analysis on the impact of pricing and governance strategies, as was defined in ‘*Experiment II*’. Continuing, *section 6.3* on ‘*Experiment III*’, assesses the relative importance of different HSR design variables in vehicle characteristics, passenger paths restrictions and line design features. Finally, *section 6.4* (‘*Experiment IV.*’) constructs two synthesised scenarios based on learned lessons, which allows determining the potential contribution and design characteristics of improved design for line configurations, when compared to the initial situation.

6.1. Benchmarking the Initial Performance

The first experiment (‘*Experiment 1*’; defined in *section 3.4*) concerned the estimation of the network’s performance and characteristics for the initial conditions, such that it could be used as a benchmark for further comparisons. These initial conditions were characterised by the standard case study parameterisation of *chapter 4*, the EU’s believe in a competitive railway market (thus ‘*Free market*’ governance structure) and a pricing environment where societal costs are not internalised ($\psi^{user} = 50$, $\psi^{operator} = 50$, $\psi^{society} = 0$). Together, these factors can be summarised under the ‘*1. Liberalisation*’ scenario of *Figure 3.24*.

Table 6.1: Observed KPIs for the estimation of the initial network

KPI	**Number of lines**	**Connected vertices**	**Reachable ODs**	**Total costs**	**User costs**	**Operator costs**	**Societal costs**	**Available seat-km**	**Avg. load factor**	**Avg. line length**
Unit	[−]	[−]	[−]	$[10^6€]$	$[10^6€]$	$[10^6€]$	$[10^6€]$	$[10^6 km]$	[%]	$[km]$
Value	54	89	396	-24.9	-31.0	15.8	-9.7	277	60.5	738

KPI	**Avg. stops / line**	**Avg. freq./line**	**Modal split air**	**Modal split HSR**	**Modal split car**	**Avg. HSR trip dist.**	**Share direct pax**	**Share 1-trf pax**	**Share 2-trf pax**	**Rev. pax-km**
Unit	$[st./li.]$	$[veh/h]$	[%]	[%]	[%]	$[km]$	[%]	[%]	[%]	$[10^6 km]$
Value	4.0	9.2	62.1	14.7	23.2	488	92.0	7.5	0.5	168

The KPIs of the simulated network are stated in *Table 6.1*. An analysis of these number indicates that this scenario has been able to develop itself into a well-functioning HSR system, given its positive cost-benefit ratio of € 24.9 million per day and its considerable trip substitution of 14.7%, resulting in a revenue passenger kilometre (RPK) of $168 \cdot 10^6 km$. However, fluctuating behaviours are observed when visually analysing the network (see also *Figure C.3* in *appendix C*). Firstly, the network is well spread throughout the map, which is also confirmed by the number of connected vertices (89/124). However, despite the introduction of strategic pricing (*section 5.3*), it is still observed that the model experiences difficulties in connecting multiple sub-networks. This is confirmed by the low number of transfer passengers within the network ($t_1 = 7.5\%$, $t_2 = 0.5\%$)

This first simulation is not yet enough to define the typical characteristics of an HSR system, but should rather be seen as a lower boundary for later comparisons. In the two following sections, analyses are performed to discover more about how this system can be influenced. Finally, *subsection 6.4* will recall this experiment to assess the potential improvement that can be made and to define the typical network characteristics.

6.2. Effects of Pricing and Governance Strategies

To test the effect of different pricing and governance strategies, six diverging scenarios were simulated in the second experiment, which was previously defined in ('*Experiment 2*'; *subsection 3.4*). Summarising, the scenarios distinguished for two policy components: the governance structure (expressed in parameter modifications) and the pricing policy (expressed in objective function weights). In *Figure 6.1*, these policies scenarios are briefly revisited. The resulting impacts of the policy strategies - as found by simulation - are displayed in table *Table 6.2*. Here, the top rows briefly summarise the scenarios, after which the KPIs are compared relative to the '*3. Total Welfare*' scenario, for all values are fixed at an index of 100. A more detailed reporting and explanation of these results developments can be found in *appendix C*.

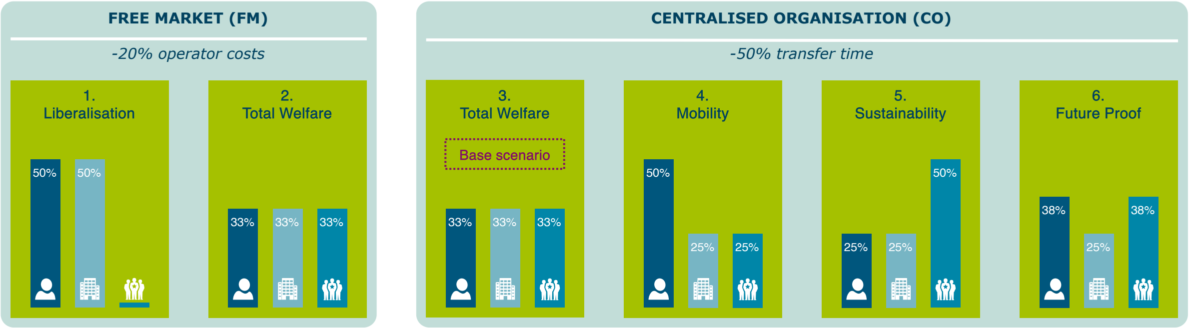

Figure 6.1: Overview of modelled pricing and governance scenarios - *revisit of Figure 3.24*

Effects of different governance structures

The exact difference in impact of the two governance structures was observed by isolating this variable, which can be seen in scenarios '*2. Total Welfare*' and '*3. Total Welfare*'. This comparison indicates a stronger cost-efficiency of a '*free market*' governance structure by a sharp 13% increase of the total benefits. At the same time, it produces a relatively similar network extensiveness with a 2% RPK increase, an equal number vertices connected, and similar performances for the user (-3%) and societal (+1%) benefits, when compared to the '*centrally organised*' network. The benefits of the free market scenario mainly originate in the substantial reduction of operator costs (-16%). However, it should be noted that the magnitude of this difference follows the arbitrary reduction of 20% in operator costs, although this nevertheless indicates a relatively strong increase of efficiency for a small compromise in network performance.

Effects of different pricing policies

Concerning differences in pricing policies, it is seen that the internalisation of external costs induced a strong growth in the network extensiveness - which was measured by increasing values for the ASK, RPK and number of transfer passengers - and the network's costs performance - as seen by the growth of user and societal benefits - for all scenarios. However, these advancements do not always make the networks more cost-efficient, as the ratio between the operator's costs and the cost savings experienced by users and society were not always moving towards a positive development of the total

Table 6.2: Measured effects of pricing and governance strategies

	1. Liberalisation	**2. Total Welfare**	**3. Total Welfare**	**4. Mobility**	**5. Sustainability**	**6. Future Proof**
ψ^{User}	50.0	33.3	33.3	50.0	25.0	37.5
$\psi^{Operator}$	50.0	33.3	33.3	25.0	25.0	25.0
$\psi^{Society}$	0.0	33.3	33.3	25.0	50.0	37.5
	Free market $C^{operator}$ -20%		**Centralised organisation** $t^{transfer}$ -50%			
Number of lines	96	100	100	123	130	143
Connected vertices	93	100	100	105	107	109
Reachable ODs	76	119	100	165	173	169
Centre focused	97	99	100	100	103	102
Total benefits	92	113	100	92	97	97
User Benefits	90	97	100	114	115	117
Operator costs	85	84	100	143	143	143
Societal Benefits	84	101	100	127	134	129
Available seat km	85	105	100	143	143	143
Avg. load factor	97	97	100	95	102	97
Avg. line length	105	108	100	109	99	106
Avg. no. stops / line	100	103	100	108	103	110
Avg. freq. / line	86	92	100	102	107	92
Modal split air	102	100	100	96	94	95
Modal split HSR	85	102	100	125	131	128
Modal split car	105	100	100	92	91	92
Avg. HSR trip dist.	97	101	100	108	110	108
Share direct pax	111	105	100	93	87	96
Share 1-trf pax	48	84	100	129	162	118
Share 2-trf pax	28	40	100	171	155	103
Revenue pax km	82	102	100	136	145	138

- Explanation: Normalised development of KPIs for policy alterations, indexed (100) at 3. Total Welfare (CO) scenario
- More information on value development: see appendix C

benefits. This difference was primarily seen when comparing the '*free market*' with the '*centralised organisation*' structures.

In the free market scenarios (1. Liberalisation and '*2. Total Welfare*'), the inclusion of societal interests in the design considerations leads the development past a design barrier, hence allowing for a more extensive network. This extended network is then able to take advantage of a better integration KPIs (more transfer passengers, higher load factors), which induces a better cost-benefit ratio. For the centralised scenarios, however, different behaviour is seen. Enlarging the interests of users or society leads to the inclusion of lines that are not necessarily most profitable, but that do contribute to the pursued policy goals (sustainability, mobility or social cohesion). The reduction in total benefits is a lot smaller than the increase in user and societal benefits, indicating a positive rate of return. It means that investing in this has an amplifying effect. A more in-depth analysis of this investment will be discussed in *subsection 6.4.3*.

In line with previous findings, all of the active subsidisation/taxation scenarios ('*4. Mobility*', '*5. Sustainability*' and '*6. Future Proof*'), show an improvement of the network extensiveness for a slight reduction of the cost-efficiency (thus total benefits). Regarding this cost-efficiency, it is seen that the '*4. Mobility*' scenario performs worst whilst not offering substantially larger advantages on the network performance (e.g. share HSR trips, RPK or the number of reachable OD's). This indicates that it mainly provided more capacity on larger used lines (as also seen by the lower ANLF), instead of providing a more diverse and extensive network. The opposite is seen for the '*5. Sustainability*' scenario, which is more reserved in operating partially empty trains but which also recognises the added value of connecting more destinations. Finally, the '*6. Future Proof*' scenario shows to be a mix of the two previous scenarios. It finds a balance between both interests and is able to develop into the most diverse option, without losing too much on costs efficiency.

Combining lessons of governance and pricing strategies

Combining the lessons of this experiment, it is derived that internalising external costs for a free market governance - which was simulated by scenario '*2. Total Welfare*' - results in the best cost-benefit ratio hence makes it the most economical solution. A centralised organisation becomes especially attractive when this is combined with the active and balanced subsidisation/taxation for the user and societal interests. This makes that - when aiming for the most extensive solution -, the '*6. Future Proof*' strategy seems most desirable.

6.3. Effects of HSR Vehicle, Line and Passenger Design Variables

The goal of the third experiment (Experiment 3.) - as introduced in *section 3.4* - was to define the importance of multiple design variables (see *Figure 6.2*) for an HSR system. To do this, an analysis was performed in which each of the isolated parameters was tested for a range of values. The main findings of this analysis will be discussed in this section. A more thorough underpinning and explanation this experiment's results are stated in *appendix D*.

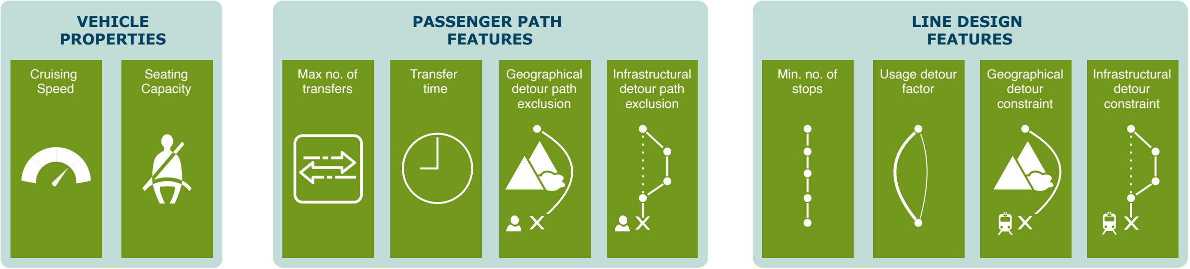

Figure 6.2: Overview of modelled HSR design variable scenarios - *(revisit of Figure 3.25)*

The overall results of this analysis are displayed in *Table 6.3*. In this, the studied parameters are stated on the vertical axis, whereas the effect on KPIs - as related to goals associated with HSR - are stated on the horizontal axes. The relation values in the table indicate the average expected change for the base value of the KPI when changing the design variable by the defined interval. An exemption applies to those values that reached a peak (optimum), which are indicated with a star (*). Here, the KPI changes with the relation value by every interval-step from the peak, the same in both directions.

Alterations of the vehicle's properties

Altering the characteristics of high-speed trains resulted in the unambiguous patterns of the first to rows in *Table 6.3*. Increasing the cruising speed allows for a higher level of service, thus contribution to all policy goals. Opposing this, a higher seating capacity makes it harder for the operator to accurately assign capacity, resulting in a lower performance and a smaller network. Both effects for vehicle speed and capacity an be expected to be tempered in further and more detailed design stages, as faster vehicles increase for example acquisition costs, whilst the inclusion of heterogeneous vehicles or economy of scale advantages might favour larger vehicles.

Alterations of line design features

The most important observation concerning the variables that influence the '*Pool of Lines*' construction in the LGP regards the usage detour. Here it is seen that the inclusion of slightly demand-based lines in the LGP ($fac^{usage} = 0.125$) is beneficial to most user and societal goals,

Table 6.3: Measured relations between HSR design variables and KPIs

Measured relations between HSR design variables and KPI contribution to policy goals

						Operator (cost-efficiency)				User (mobility)			User (social cohesion)			Society (sustainability)		
						Total costs savings	**Operator costs**	**Avg. load factor**	**Share transfer pax**	**User costs savings**	**HSR available seat km**	**Share direct pax**	**No. connect cities**	**Reachable ODs**	**No. of lines**	**Societal costs savings**	**Revenue. pax km HSR**	**Modal split HSR**
	Parameter	**Unit**	**Range**	**Interval**	**Base→ Peak* ↓**	$€\ 2-2.5\cdot10^{7}$	$€\ 2-3.5\cdot10^{7}$	$60-65\%$	$10-20\%$	$€\ 3-4\cdot10^{7}$	$275-625\cdot10^{6}km$	$80-90\%$	$90-115(of124)$	$400-1150(of1300)$	$50-90$	$€\ 1-1.5\cdot10^{7}$	$175-375\cdot10^{6}$ km	$15-30\%$
Vehicle	**Cruising speed**	$[km/h]$	225-375	50	*n/a*	1.276	1.145	1.002	1.213	1.238	1.145	0.946	*Var.*	1.070	1.021	1.090	1.148	1.102
	Seating Capacity	$[seats]$	350-600	50	*n/a*	0.994	0.963	0.994	0.947	0.980	0.963	1.013	0.985	0.937	0.950	0.964	0.958	0.966
Passenger Path	**Max. no. of transfers**	$[trf.]$	0 - 2	1	$\star1$	0.970*	1.087	0.945*	*Var.*	0.968*	1.087	*Var.*	0.990	1.233	0.939*	0.903*	0.887*	1.089*
	Avg. transfer time	$[min]$	15 - 60	15	$\star30$	0.979	0.917	0.997	0.722	0.945	0.917	1.070	0.952*	0.915	1.017	0.931	0.913	0.934
	Geo. detour excl.	$[-]$	1.05-1.25	0.05	*n/a*	1.106	1.107	1.008	*Var.*	1.110	1.107	*Var.*	*Var.*	1.162	*Var.*	1.097	1.117	1.114
	Infra. detour excl.	$[-]$	1.05-1.25	0.05	*n/a*	0.974	1.030	1.003	1.066	*Var.*	1.030	0.983	*Var.*	1.059	1.016	1.022	1.033	1.022
Line Design	**Min. no. of stops**	$[stops]$	2 - 6	1	$\star3$	0.924*	*Var.*	0.955*	0.886	0.962*	*Var.*	1.029	*Var.*	*Var.*	0.925*	0.976*	*Var.*	0.975*
	Usage detour factor	$[-]$	0 - 1	0.125	$\star0.125$	0.987	0.977*	0.996	1.017	0.986*	0.964*	0.996	*Var.*	0.983	0.980	0.983*	0.980*	0.985*
	Geo. detour constraint	$[-]$	1.25-1.75	0.25	*n/a*	1.009	1.017	1.008	0.844	1.015	1.018	1.040	1.048	1.048	1.150	1.013	1.025	1.017
	infra. detour constraint	$[-]$	1.25-1.75	0.25	$\star1.50$	0.984*	0.986*	1.001	0.977	0.985*	0.986*	1.006	0.976*	0.989*	1.050	0.985*	0.987*	0.988*

- *Explanation: Base value is expected to change with the relation factor when increased by the interval of the parameter*
- *Special case - peak*: Base value reaches top at peak and changes with same relation* factor in both directions*
- *Special case - var.: no clear pattern could be identified.*
- *More information on relation factor estimations: see appendix D*

although it also comes at the cost of operator efficiency. Further examination highlights the performance peak when constraining the minimum number of stops to three (two terminal stations and one intermediate) per line, though it should be mentioned that 2-stop lines might still be beneficial when added to the pool of lines, as they currently mostly replace 3-stop lines following the character of the tactical line selection for the reduction of the computational burden, as was explained in *section 3.3*.

The alteration of the infrastructural line detour constraint (*Equation 3.23*), an optimum at the value of $fac^{dt,infra} = 1.50$ was found. Here, a lower factor would mainly exclude beneficial routes (given the reduced network development) and higher factor would result in a lower operator efficiency (given the larger number of lines between a smaller number of vertices). Finally, the geographical line detour constraint (*Equation 3.24*) showed to be non-restrictive when set at $fac^{dt,geo} = 1.50$. Intensifying to $fac^{dt,geo} = 1.25$ resulted in a deterioration of both the descriptive key performance indicators, as well as the cost-efficiency, thus indicating that it is best to disregard this constraint.

Alterations of passenger path features

The validation of *chapter 5* demonstrated the importance of controlling passenger paths thought the network, as to prevent the development of so-called '*separate island networks*'. Performing multiple simulations, it was seen that limiting the maximum number of transfers, altering the transfer time and the introduction of strategic pricing could all be useful tools for increasing the network interactions. To learn more precise effects of these measures, they were included in the analysis of this experiment.

The results of this analysis, as stated in the lower rows of *Table 6.3*, showed the effectivity of intensifying the exclusion of infrastructural detouring passengers to a value of $fac^{SPL,infra} = 1.05$, which was modelled by the constraint of *Equation 3.29*. Opposed to this, the relaxation of the geographical detour exclusion constraint (up until $fac^{SPL,geo} = 1.25$, see *Equation 3.30*) gave better results, meaning that the effectivity of this exclusion strategy cannot be confirmed. Additional to this, the same analysis demonstrated the positive impact of limiting the number of transfers to one, as a peak value is observed for this setting in most financial and network performance indicators. Regarding the alteration of transfer time, no pattern of for strategic passenger selection could be identified.

6.4. Potential Impacts and Characteristics of Improved Design

The final experiment, '*Experiment 4*' as defined in *subsection 3.4*, uses the lessons from previous experiments to determine the typical design characteristics and potential impact of improved HSR line configurations, with which it becomes possible to answer the main research question of this thesis. This experiment is performed by defining two improved scenarios, as will be presented in *subsection 6.4.1*, and by comparing these with the simulation of the initial network from '*Experiment 1.*' (see *section 6.1*). This comparison starts in *subsection 6.4.2*, where the networks of interest are analysed by their layout to find how a typical strong-performing network looks like. *subsection 6.4.3* continues this comparison of networks, by assessing them on their network performance and the potential contribution they provide to the main policy goals.

6.4.1. Proposed synthesised network settings

To assess the characteristics and potential contribution of and enhanced network design, two improved scenarios are proposed. These scenarios find their base in the standard parameterisation of *chapter 4* - as this tried to describe reality as close as possible - but are adjusted for the lessons learned from the previous analyses. First of all, both synthesised scenarios were improved by passenger paths to a maximum of one transfer, whilst the geographical detour path constraint of *Equation 3.24* was released. Furthermore, it was chosen to set the geographical strategic pricing level to the tested upper limit ($fac^{SPL,geo} = 1.25$) and the infrastructural strategic pricing level to the tested lower limit ($fac^{SPL,infra} = 1.05$).

The first scenario, '*Economical*', describes a low-effort solution that aims for a high cost-efficiency. This holds a '*free market*' governance structure (-20% operator costs) with an equal distribution of objective function weights, thus $\psi = 33.3$ for all stakeholders. moreover, this scenarios is characterised by a shortest path-based lines only ($fac^{usage} = 0.00$). The second scenario, '*Extensive*', works from a '*centralised*' governance structure (-50% transfer time), which is actively subsiding for user and societal benefits ($\psi^{user} = 37.5$, $\psi^{operator} = 25.0$, $\psi^{society} = 37.5$). Here, the pool of lines is supplemented with demand based-routes ($fac^{usage} = 0.125$). An overview of the relevant scenario characteristics is provided in *Table 6.4*. The fully simulated scenario results can be found in *appendix E*

Table 6.4: Proposed synthesised scenarios, alterations to the standard parameters

Name Experiment	**Initial** *Experiment 1.*	**Economical** *Experiment 4.*	**Extensive** *Experiment 4.*
Governance structure Characteristic	**Free market** *-20% operator costs*	**Free market** *-20% operator costs*	**Centralised** *-50% transfer time*
Pricing policy	**Liberalisation**	**Total Welfare**	**Future Proof**
ψ^{user}	50.0	33.3	37.5
$\psi^{operator}$	50.0	33.3	25.0
$\psi^{society}$	0.0	33.3	37.5
Parameters	**Standard**	**Improved**	**Improved**
max no. of transfers	2	1	1
$fac^{dt,geo}$	1.5	*n/a*	*n/a*
$fac^{SPL,geo}$	1.10	1.25	1.25
$fac^{SPL,infra}$	1.10	1.05	1.05
fac^{usage}	0.00	0.00	0.125
Simulation results	*appendix E.1*	*appendix E.2*	*appendix E.3*

6.4.2. Network design characteristics

Simulating the two new scenarios and recalling the simulation of *section 6.1*, resulted in three developed networks which are assessed on their design characteristics in this subsection. All scenarios resulted in functional high-level networks with similar shapes, although deviating in more characteristic details. As expected, the '*Initial*' scenario remained relatively underdeveloped, when compared to the '*Economical*' and '*Extensive*' scenarios. A clear expression of this is seen in the top three rows of *Table 6.5*, where the number of lines, number of connected vertices and reachable OD's show substantial growth for enhanced design. In this, the larger network for the '*Economical*' scenario highlights the model's ability to benefit from network effects.

A visualisation of the '*Extensive*' network's line configurations is provided in *Figure 6.3*, where colours are used to distinguishes for lines and where widths indicate their associated frequencies. This map is used as a basis to analyse the design characteristics, as each of the scenarios had a similar layout, independent of their extensiveness. The map provides insights in the shape, dimensions and focal points of the network. One of the first general findings is the majority of lines that are visiting multiple countries, which indicates the importance of interoperability and cross-border cooperation. In the paragraphs below, a further assessment of the general network's characteristics and line characteristics is performed.

Layout characteristics of the network as a whole

Visually analysing the three scenarios, it was seen that all simulations were capable of designing lines throughout the map, meaning that all parts of the continent were served to some extent. In general, three main behavioural aspects were identified. Initially, it is seen that network density increases towards the geographical centre of the map, in this case Germany. Within this, especially Munich was consistently assigned with a hub function, followed by the other predominant German cities and more peripheral focal points like London, Lille, Bordeaux, Bologna, Copenhagen, Zurich, Warsaw, Budapest and Bucharest. This indicates that hubs are not only the largest cities but also those strategically located.

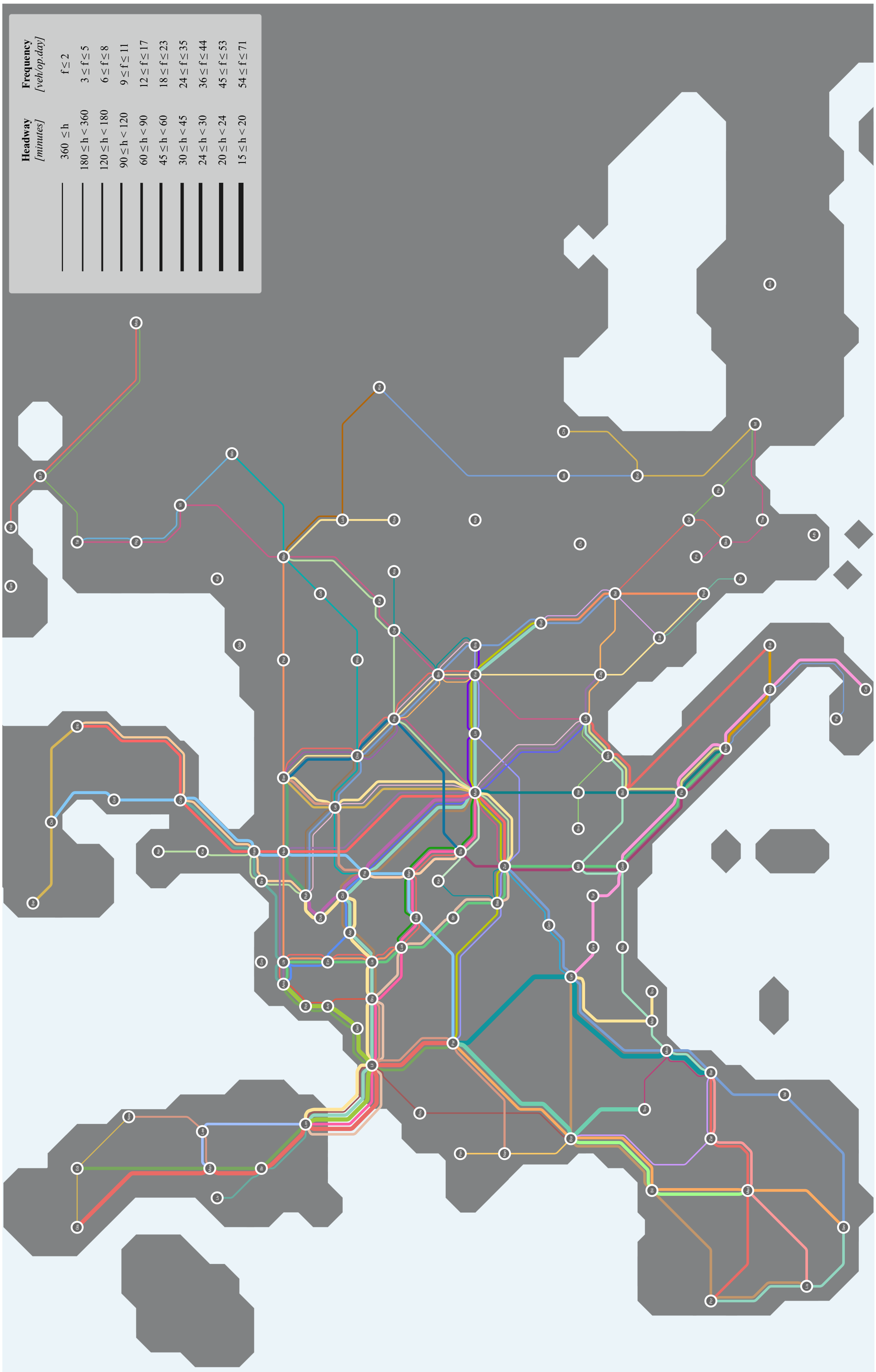

Figure 6.3: Transit map of the extensive high-speed rail network

Following this, a second (2) effect was observed in the unequal distribution of the network, as its extensiveness and density are slightly skewed to the west, which is explained by the lower demand in Eastern Europe. Finally (3), it was seen that frequently unvisited cities are those with a lower demand which are not located between at least two higher demand cities (e.g. Rouen, Toulon & Gdansk). This explains that these cities do not provide enough aggregated demand to justify a separate line, but should also be sought in the model's limitation of mainly working with lines between key-cities.

Characteristics of the lines that compose the network

The networks consists of a variety of lines, as visualised for the '*Extensive*' scenario in *Figure 6.4* (line length), *Figure 6.5* (line frequency), and *Figure 6.6* (number of stops per line) and as numerically represented for all scenarios in the middle rows of *Table 6.5*. The line characteristics already provide insights in the typical design layout, but should also be seen in the context of the network

Combining the network layout with the line characteristics, four recurring line types were distinguished. The first (1) and most distinct category was found in the so-called '*main arteries*', as all networks accommodate 5-20 (depending on the extensiveness) relatively long lines (length > 1000km; number of stops > 6) that can frequently sustain hourly services (≈18 veh/dir/day). These lines were selected during the early phase of development and follow routes with relatively high and stable demands along the visited vertices, such that they benefit from roof tile effects that allow for large traffic flows along the lines.

Following this, the majority of lines have a shorter profile (length < 1000km). These shorter lines can be further subdivided into three categories. The second (2) type of line strategically connects to the main arteries, such that new cities are linked to the network. A decision which is justified by the aggregated demand related to these newly introduced cities. The third (3) line category concerns lines that produce enough demand by themselves, which means that they are found in both low- and high-density areas. Finally, a fourth (4) category are additional lines, which primarily follow a one or a few legs of a main artery, to allow for the more specific assignment of seating capacity.

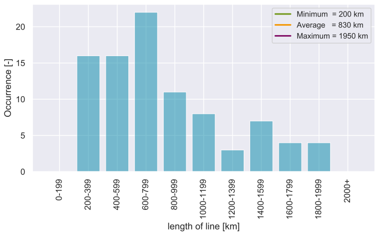

Figure 6.4: Distribution of line lengths (sc. '*Extensive*')

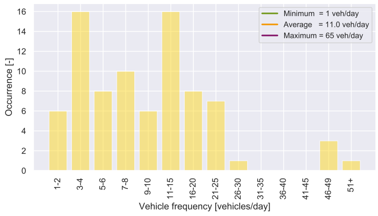

Figure 6.5: Vehicle frequency per line (sc. '*Extensive*')

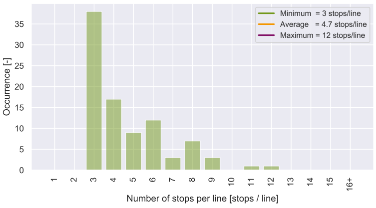

Figure 6.6: Distribution of typical Number of stops per line (sc. '*Extensive*')

6.4.3. Network performance and potential contribution

The three developed networks inherently come with differences and resemblances on the performance they manage to reach by their design. To find these, the networks were partially assessed on their overall network key performance indicators - of which an overview is provided in lower rows of *Table 6.5* - and partially assessed on the city and edge specific statistics, as displayed for the '*Extensive*' scenario in *Figure 6.7*. This last map displays the daily vehicle loads per edge, magnitudes of HSR traffic per city and modal split changes.

Resemblances in performance between network strategies

In search of resemblances, it was seen that the maps of network characteristics (like *Figure 6.7*) showed three striking and recurring behaviours. Firstly (1), the increased edge loads towards geographical bottlenecks like the Iberian Peninsula, Great Britain, Scandinavia; secondly (2) the relatively high HSR

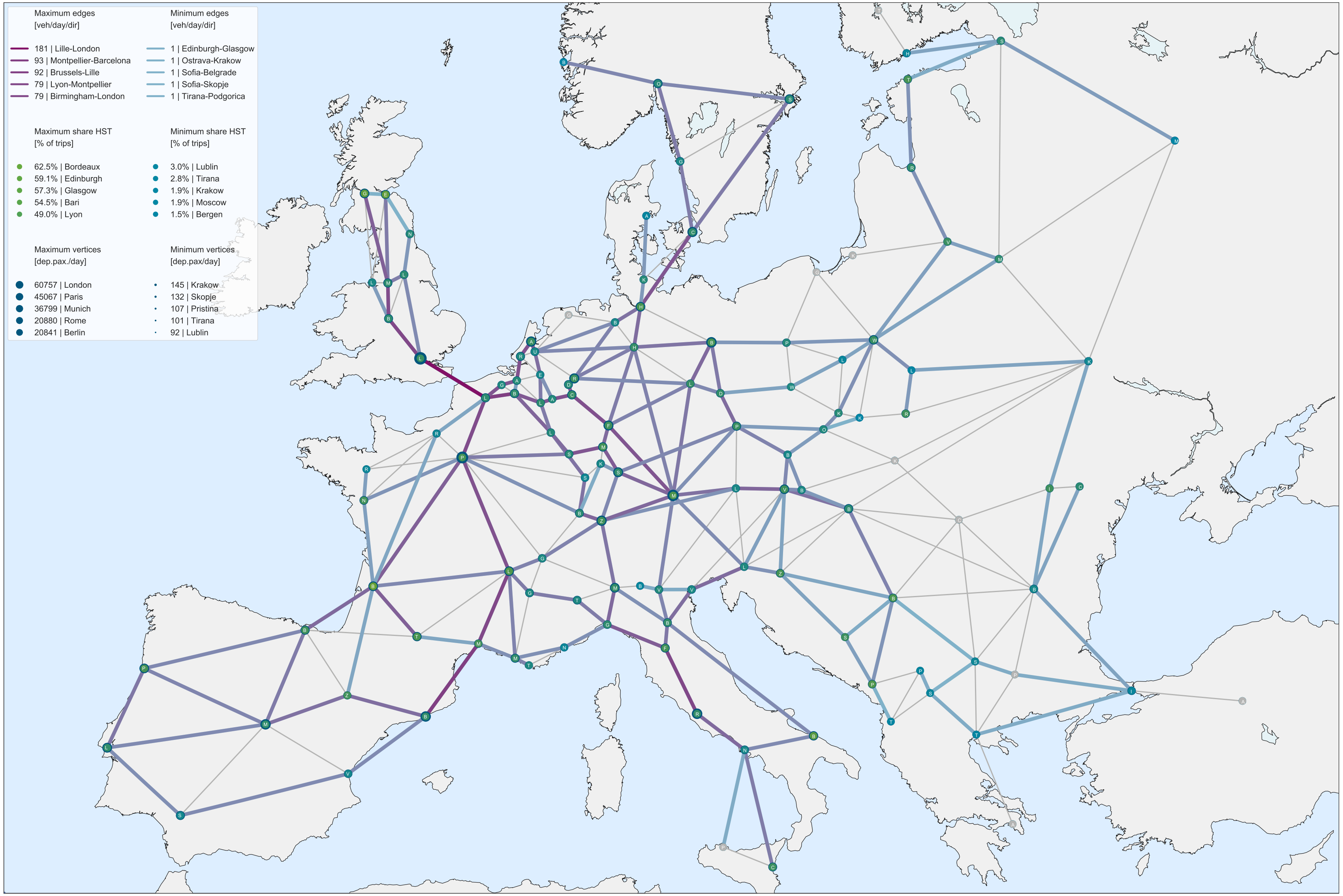

Figure 6.7: Map with vertex and edge characteristics of the ‘*Extensive*’ HSR network

market share for intermediate cities (Bordeaux, Edinburgh, Glasgow, Bari and Lyon), which can be explained by the more locally-oriented demand patterns whilst being large enough to attract multiple lines; and thirdly (3) the smallest vertices, which have flows that are considerably smaller than the capacity of one train (Lublin, Tirana, Pristina). The fact that these smaller cities being connected can be partially explained by roof tile effects in line occupation, but should also be sought in the model's limitation of having a somewhat limited pool of lines (where the line would ideally be one leg shorter, but which is not available) and the neglection of the smallest demand flows.

Differences in performance between network strategies

Differences in the three networks were mainly identified by extracting and assessing the descriptive KPIs, as presented in *Table 6.5*. Below, the networks are discussed on the induced level of service that each of them is able to provide and the modal shift that they realise with this level of service.

Table 6.5: Descriptive characteristics of the developed synthesis networks

	Unit	Initial	Economical	Extensive
Number of lines	[-]	54	83	91
Connected vertices	[-]	89	110	116
Reachable ODs	[-]	396	944	1148
Avg. line length	$[km]$	738	834	831
Avg. no. stops / line	$[seats]$	4.0	4.61	4.68
Avg. freq. / line	$[veh/day]$	9.2	9.12	11.04
Available seat km	$[10^6 km]$	277	499	633
Revenue pax km	$[10^6 km]$	168	300	378
Avg. load factor	[%]	60.5	60.0	59.7
Modal split air	[%]	62.1	56.5	53.5
Modal split HSR	[%]	14.7	25.0	29.9
Modal split car	[%]	23.2	18.5	16.7
Avg. HSR trip dist.	$[km]$	488	558.3	589.9
Share direct pax	[%]	92.0	87.5	77.8
Share 1-trf pax	[%]	7.5	12.5	22.2
Share 2-trf pax	[%]	0.5	*n/a*	*n/a*

Level of service provided per strategy:

The results in the lower rows of *Table 6.5* show unambiguous results for a further network development along the scenarios. This is primarily confirmed by the increased revenue passengers kilometres (RPK; +26%) and available seat kilometres (ASK; +27%) when comparing the '*Economical*' to '*Extensive*' strategies; effects that are even bigger when comparing the '*Initial*' to '*Extensive*' scenarios, with a growth of +125% for the RPK and +129% in ASK.

The higher connectivity values (number of lines, connected vertices and reachable OD's), as well as the increased share of transfer passengers, indicate that the above growth comes from a more wide-spread and integrated network. More transfer passengers would logically have positive results on the train occupation. However, a slight decrease of the average network load factor (ANLF) is observed ('*Economical*': -0.8%; '*Extensive*': -1.3%). This behaviour explains that the model has accepted less profitable routes (thus less competitive with other modes or fewer justification of train capacity) when internalising external costs, as it prioritises the benefits of users and society over the operator's interests.

Induced modal shifts per strategy:

Considering the competition with other modes, the simulations showed an HSR trip substitution potential of 14.7% ('*Initial*'), 25.0% ('*Economical*') and 29.9% ('*Extensive*') respectively. The market share per distance distribution of this substitution is plotted in *Figure 6.8*, which shows that the HSR is especially competitive between 400-600 km. A comparison of the '*Economical*' and '*Extensive*' scenario shows that the latter is relatively strong on longer distances (600-1000 km), thus more competitive with air travel. Something which is confirmed by the increased average HSR trip distance (+5.7%) in *Table 6.5*. This behaviour can be explained by the better network integration and coverage, which allows for ease of travel on longer trips, but should also be sought in the underlying costs aspects. Therefore, further analysis of these costs is done in the paragraph below.

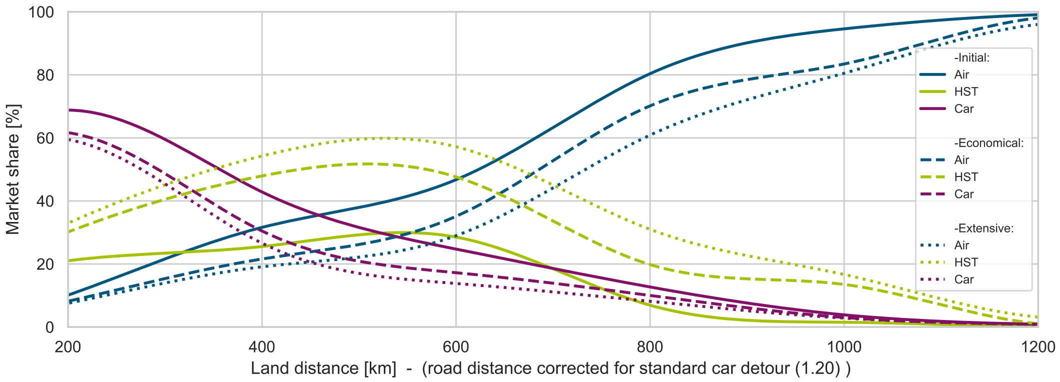

Figure 6.8: Measured modal split per distance for different network strategies

Cost aspects and benefits as experienced stakeholders

To assess the underlying costs aspects, the total expenses and benefits were separated for each stakeholder and further divided into sub-components. The resulting costs components of all scenarios are numerically stated in *Table 6.6*. Furthermore, the developments of these costs during the simulation of the '*Extensive*' scenario have been plotted in *Figure 6.9* (total), *Figure 6.10* (user), *Figure 6.11* (operator), and *Figure 6.12* (society).

Table 6.6: Stakeholder-financial characteristics of the developed synthesis networks

		Initial	**Economical**	**Extensive**
			All in [10^6 € per day]	
User	**Access & Egress**	3.0	4.0	5.1
	Waiting	-19.4	-28.7	-36.1
	In-vehicle	-16.5	-28.0	-30.0
	Transfers	1.9	4.7	5.4
	Sub-total	**-31.0**	**-48.0**	**-55.5**
Operator	**Operational**	14.7	25.8	41.0
	Maintenance	1.1	2.7	4.0
	Sub-total	**15.8**	**28.4**	**45.0**
Society	**Accidents**	-3.2	-5.1	-6.2
	Air pollution	-0.7	-1.2	-1.5
	Climate	-2.5	-4.4	-5.5
	Noise	-0.3	-0.5	-0.5
	Congestion	-3.1	-5.0	-6.0
	Well-to-tank	-0.5	-1.0	-1.2
	Habitat damage	0.6	1.0	1.5
	Sub-total	**-9.7**	**-16.2**	**-19.4**
	Total costs	**-24.9**	**-35.8**	**-29.9**

Separate stakeholder perspectives:

From the user's perspective, benefits are primarily found for time savings in waiting (fewer air travel) and in-vehicle (fewer road travel) duration. Both factors strongly outweigh the newly introduced transfer times and increased access/egress times. This balance is again shifted towards longer HSR trips when applying the extensive scenario, as the costs associated with waiting times increase the most.

Concerning the societal (external) costs, the most substantial benefits of substitution towards HSR are found within the fields of accidents, congestion and climate. Especially the first two of these have a strong relation to the modal shift from the car, as high costs on these factors are characteristic of road traffic. This is confirmed when categorising the societal benefits per mode, as can be seen in *Figure 6.12*. This resulted in a reduction of external costs that was mainly induced by substitution from car traffic (72%) as opposed to air traffic (28%).

Together, the above indicates that, when aiming for larger societal benefits, most is to be won in the competition with automobile traffic. This also leads to the finding that most societal benefits are won in externalities of car traffic, which are not only environmentally related. *Table 6.6* shows that for a developed HSR network, only 31% of societal benefits can be explained by environmental factors of air pollution, climate, habitat damage, noise. It leads to the conclusion that HSR can have an even broader impact on society than what is most frequently argued.

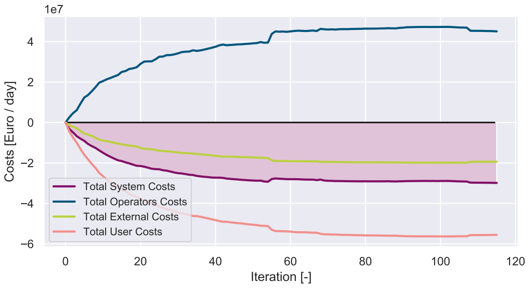

Figure 6.9: Total costs development (sc. '*Extensive*')

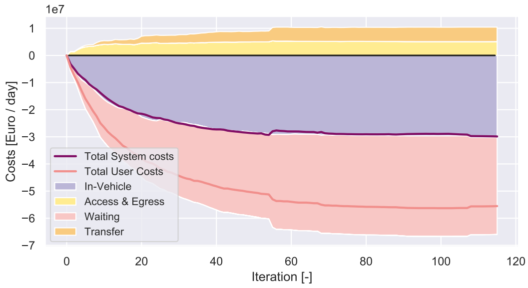

Figure 6.10: User costs development (sc. '*Extensive*')

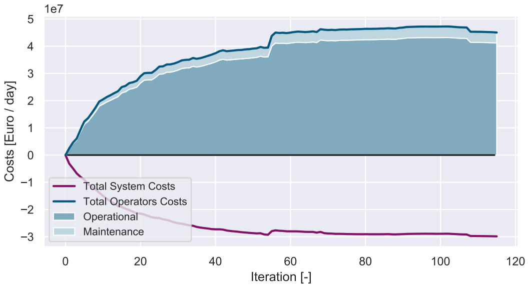

Figure 6.11: Operator frequency per line (sc. '*Extensive*')

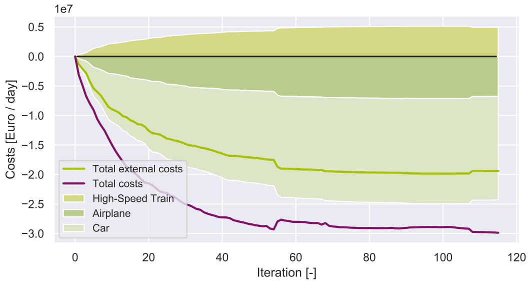

Figure 6.12: Societal costs development (sc. '*Extensive*')

Overall societal cost-benefit developments:

Finally, the benefits of user and societal interests come at the expenses of the operator, who is usually able to pass these costs through by the pricing of tickets. Aiming for policy goals (mobility, social cohesion or sustainability) rather then cost-efficiency, the '*Extensive*' scenario provides a less-beneficial cost-benefit ratio to the '*Economical*', mainly due to a sharp increase of operator costs, though still better than the '*Initial*'. This reduction compared to the '*Economical*' scenario is primarly explained by the lower load factor and the inclusion of less profitable lines.

Comparing the overall costs of the two improved scenarios, it is seen that the increase of user and societal benefits reaches 10.7 million euros per day. At the same time, this comes with a deterioration of 5.9 million euros per day on the cost-benefit ratio. Combining these two values gives a rate of return reaching 1.81 when opting for active subsidisation with the defined weights and a centrally organised network. This effect is expected to be even more substantial when considering secondary benefits of these policy goals. Concluding on that, it means that it should be a political decision whether the advantages outweigh the increased subsidisation costs and efforts for centralising and taxing.

7
Conclusions

This chapter concludes the performed research of this thesis using multiple phases. First, *section 7.1* builds towards an answer to the research questions in a step-wise manner. This is then followed by a reflective view of the interpretations and implications in *section 7.2*, to place the findings in their context. To conclude, *section 7.3* discusses the limitations of the research, which then also lead to suggestions for future research.

Research restatement

In *chapter 1* (‘*Introduction*’) it was found that, despite the potential advantages of high-speed rail, the active encouragement by governments and the continuous growth of demand for long-distance transport, no real European HSR network has been realised yet. The origin of this under-performance was found to be two-fold, as a (1) lack of knowledge on the design of line configurations, (2) prioritisation of national interests in combination with the belief in a free market led to a patchwork of smaller networks without strong cross-border coordination. This research aimed to assess the potential improvement that can be made by addressing the two problems, which was encapsulated in the following research question:

”To what extent can the user, operator and societal performance of a European high-speed rail network be improved by centrally designed line configurations as well as pricing policies and how would such networks look like?”

To be able to answer this multi-aspect question, four objectives were formulated in which knowledge was to be gained: (1) the design characteristics of HSR networks that provide a high contribution to mobility and sustainability-related policy goals; (2) the relative importance of vehicle characteristics, passenger paths restrictions and line design features; (3) the impacts of different pricing policies and governance structures; and (4) the ideal combination of previous settings for different network ambitions.

Considering the size, complexity and limited qualitative knowledge in the topic of HSR network design, it was chosen to develop a quantitative and generic approach that simulates the network planning process for HSR line configurations, whilst continuously considering opposing stakeholder interests and interactions. Implementing this for the European case, performing different scenarios and interpreting the trade-offs in the quality of service (e.g. network coverage and directness), but also the economic profitability and societal impact, lessons were extracted to contribute to the research’s objectives.

7.1. Key Findings of this Research

The key findings and the road to an answer to the main research question are divided into three steps. First, *subsection 7.1.1* describes the development towards a model as outlined above; following this, *subsection 7.1.2* discusses the lessons that were learned from exploratory experiments that had the goal to learn more on HSR network design; and finally, *subsection 7.1.3* answers the main research question by assessing the potential improvement that can be made and describing how such networks look like.

7.1.1. Research field analysis of the problem

From the initial ‘*literature review*’ of *chapter 2* on ‘*Transit Network Planning Problems*’ - a field of research that concerns the design of transit systems - it was found that the problem described by this specific study should be classified as a '*Transit Network Design and Frequency Setting Problem*' (TNDFSP). This, as it has a strategic character that searches for a strong performing network - considering multiple stakeholder interests - by controlling the selection of lines and their associated frequencies. It was found that an abundance of research has been done in the fields of TNDFSPs and high-speed rail in general, though the interface of these research fields is still unexplored, hence leaving a scientific knowledge gap.

Modelling the unique characteristics of the high-speed rail environment
From further inspection in this chapter, it was concluded that the problem and its solution strategy required a customised approach to address the unique characteristics of long-distance transport. The most impactful characteristics were found to be the (1) representation of stakeholder interests, the (2) deviant passenger behaviour with associated transport demand patterns and (3) the specific infrastructural and mode-specific properties.

Each of these unique characteristics had to be covered to reach a minimum level of accuracy, which was done in *chapter 3* on the methods and *chapter 4* on the parameterisation of the case study. The first (1) factor was addressed by including a societal stakeholder that aimed for external costs minimisation, besides the typically included user and operator. The second (2) challenge was resolved by using revealed data of air traffic between airports that allowed for an estimation of demand between cities. Finally, the third (3) requirement was taken on by separately modelling each of the modes, whilst keeping the constraints for HSR designs to a minimum given the currently limited knowledge on this field.

Development of a solution strategy for the complex problem
In previous literature, it was determined that the TNDFSP is an NP-hard problem. Combining this with the substantial scale of this study (124 vertices), it was concluded that the problem could not be solved analytically or with conventional methods. Considering the model's objectives (light-weight, flexible, few starting assumptions & reasonable performance) and frequently used solution strategies (including mathematical programming, heuristic and meta-heuristic techniques) it was concluded that a greedy hill-climbing heuristic, starting with the generation of lines and selecting them by sequential (de)activation, would be most suitable. The test runs of *section 5.1* showed that this model was able to decrease the calculation time 96.4% (compared to an exhaustive search) whilst still reaching the global optimum for a smaller problem. Real scale problems could be solved in 3-5 days, depending on their level of extensiveness.

7.1.2. Evaluation of high-speed rail system design aspects

Having defined the HSR-specific TNDFSP, formulated a solution strategy and parameterised to the context of the European case, it became possible to perform multiple experiments, of which the outcome's interpretations would allow to answer the research question.

Necessity of passenger path control
Before starting the experiments, the prior validation of *section 5.2* showed the necessity for the passenger path control, as unprofitable passenger flows (thus low user benefits at high operator costs) would force the network to a state of multiple not-connected sub-networks. It was found that this effect could be neutralised by strategically spilling those passengers with more than 5% infrastructural detour (in time and distance) of their shortest path through the network and by setting a maximum of one transfer per path. In addition to this, no indication for effects of spilling geographically detouring passengers or the alteration of transfer time were found.

Benchmark setting for the initial network performance
In the first experiment, a benchmark of the current network's potential was made in *section 6.1*, which was described by a free market governance without the consideration of external costs and named as '*Initial*'. The model developed lines in all regions of the map and reached a positive cost-benefit ratio, although it was characterised by a limited level of extensiveness and integration, resulting in

few transfer passengers (<10%) and an overall HSR modal split shift reaching 14.7%, suggesting that improvement could be made.

Impacts of different pricing and governance strategies

Performing an analysis on different pricing and governance strategies in the second experiment of *section 6.2*, it was found that the internalisation of the actual external costs results in an improvement of the network performance and policy goals of enhanced mobility, social cohesion and sustainability. Performing this in a free market governance structure results in the best societal cost-benefit ratio, which is in line with the EU's believe in a competitive railway market.

However, centrally designing and organising the HSR network - in combination with actively subsidising and taxing for the user and societal interests - significantly increases the network performances and contribution to the previously stated policy goals. This latter decision comes with a reduced cost-benefit ratio - thus requiring governmental investments - but also allowed for a growth of user and societal benefits approximating 1.8 times this investment, hence resulting in a positive rate of return. This value is bounded by the model's inability to monetise the required efforts for subsidisation/taxation plans and a centralised governance, though it does show a substantial margin to work with.

Effects of HSR vehicle, line and passenger design variables

In planning HSR systems, several design decisions can be made, of which the effects were not previously known. In *section 6.3* on the third experiment, an analysis was performed on the vehicle's properties, line design features and previously mentioned passenger control strategies. This experiment demonstrated the unambiguous positive impact of increasing cruising speed and decreasing seating capacity of vehicles, although this should be seen in the light of expected indirect costs following additional infrastructural or staff expenses. In that setting, these numbers are especially useful to assess whether these raised costs outweigh the induced benefits.

Concerning the design of lines, it was seen that the partial inclusion of demand-based lines (as opposed to shortest-path-based lines only) is especially interesting from the passenger's and societal perspective, meaning that they can be considered when aiming for increased mobility and sustainability goals. Furthermore, this experiment demonstrated that a minimum of three stops per line increases the overall performance and that no indication was found to exclude geographically detouring lines.

Proposed strategies for network improvements

Using the lessons of the above experiments, two new strategies in HSR network design were proposed. One pursuing an '*Economical*' solution that developed towards the highest cost-benefit ratio and that was characterised by a free market governance, the internalisation of actual external costs and lines based on shortest paths; and one '*Extensive*' solution that developed towards a strong contribution on sustainability and mobility-related policy goals by a centralised governance, the active subsidisation/taxation of external costs and the partial inclusion of demand-based lines.

Additionally to the above, the previous analyses led to conclusions that both improved networks should limit the maximum number of transfers per passenger to one, that geographically lines are not to be excluded and that strategic pricing - the exclusion of undesirable passengers - should target infrastructurally detouring passengers specifically.

7.1.3. Potential performance improvements and how to reach them

To provide an answer to the research question, the fourth experiment of *section 6.4* was concerned with the simulation of the '*Economical*' and '*Extensive*' scenarios, after which they were assessed on their lay-out and compared on their multi-aspect performance to each other and to the previously simulated '*Initial*' scenario.

Lay-out features of networks with high policy contributions

from these simulations, it was concluded that both improved scenarios again served all regions of the map to some extent and that - independent of their level of extensiveness - they were structured in a comparable manner. The resulting networks had an increase of line density towards the geographical centre, the variation in the total transport demand made them slightly west-skewed, and especially lower-demand cities which were not geographically located between larger metropolises frequently ended up being unconnected. The last of these requires further underpinning, as the current generation of lines is biased due '*Pool of Lines*' reduction based on terminal-cities.

Regarding the lines that compose the network, it was seen that approximately 80-90 lines were used, of which about 10-20 longer ones (1000km-2000km) that could sustain hourly services (≈18 veh/h). The network was then supplemented by a set of shorter lines that could be justified when connected to the network, a set of lines that have enough demand themselves and a set of lines that largely overlap longer lines, such that capacity is assigned more accurately. As said, the main difference in network design was found to be their extensiveness, which became especially meaningful in assessing the performances.

Potential performance improvement for users, operators and society
The improved simulations ('*Economical*' and '*Extensive*') indicated that combinations of external costs inclusion and centralised governance structure could be used to achieve further enhance network extensiveness and integration, as was seen by an increase of the number of cities connected (+24% to +30%) and reachable OD-pairs (+138% to +189%) compared to the '*Initial*' scenario. Both improved networks demonstrated to be beneficial to all stakeholders, albeit with a different extent and emphases.

From a user's perspective, the largely extended network led to a sharp increase of HSR trip substitution from 14.7% ('*Current*') to 25.0% ('*Economical*') and 29.9% ('*Extensive*'). The great benefit of this is a lower travel time and the costs associated, as travellers were able to save to 54.8% ('*Economical*') and 79.0% ('*Extensive*') more on their travel expenses when compared to the current situation. Similar results were seen from a societal perspective, as this stakeholder benefits from the modal shift due to the relatively low external costs of HSR. The internalisation of this factor led to a relative reduction 67.0% ('*Economical*') on the societal costs when compared to the current situation and 100.0% when active subsidisation/taxation and a centralised governance were performed. Additionally, these benefits were primarily gained by the substitution from car traffic (72%) rather than air traffic (28%).

Operator wise, both an '*Economical*' and '*Extensive*' strategy were found to be beneficial, although in a different manner. The network analyses proved that the active subsidisation/taxation led to the inclusion of less profitable lines, which was especially beneficial to the other stakeholders than the operator. This made the increase of cost-benefit ratio higher for the '*Economical*' strategy (+43.8%) than the '*Extensive*' strategy (+20.0%), which meant that they are still better than the current situation.

Overall, the benefits of an '*Extensive*' strategy compared to an '*Economical*' strategy require a more considerable governmental effort, as a centralised governance is to be set up, an active subsidisation/taxation policy has to be introduced, and the financial gap in cost-benefits has to be covered. It was found that filling this financial gap requires an investment of € 2.2 billion per year whilst providing € 3.9 billion per year on the user and societal benefits, thus resulting in a rate of return of 1.81. This number does not yet consider the efforts and indirect costs that would come with such a policy and governance transformation, though it does indicate the margin to work in. Concluding to this, it remains a decision on whether the above-described benefits are worth the efforts.

7.2. Interpretations and Implications

By formulating a customised version of and solution methodology for the '*Transit Network Design and Frequency Setting Problem*' (TNDFSP) in for high-speed rail, this study aimed to gain insights into (1) the design characteristics of HSR networks that provide a high contribution to mobility and sustainability-related policy goals; (2) the relative importance of vehicle characteristics, passenger paths restrictions and line design features; (3) the impacts of different pricing policies and governance structures; and

(4) the ideal combination of previous settings for different network ambitions. This, to ultimately assess the potential improvement of the current HSR system. Performing the above, this study contributed to the current state of knowledge in the practical field of strategic-to-tactical HSR network design and to the scientific field of TNDFSP studies.

Interpretation of the overall results
The observation that a more extensive network can result in improved benefits for all stakeholders proved that both the inclusion of external costs as well as the centrally designed governance structure are useful tools in pursuing the EU's policy goals of mobility, social cohesion and sustainability. Furthermore, it was seen that argumentation of this extended network development could be politically argued from each of these policy goals, as they show a strong interrelationship. However, it is worth mentioning that a great part of the demonstrated benefits stand with the control of secondary effects, such as the generation of newly induced transport demand or the released airport capacity, as these have a substantial impact on the final outcome.

Implication of the results and practical guidelines for authorities
The results of this work show that - in contrast to the EU's believe and the current practice - a completely free and competitive railway market is not the ideal strategy when aiming for the maximisation of stakeholder benefits and the contribution to policy goals. The most substantial step can be made by the inclusion of actual external costs when continuing the current free market. This, because it benefits the cost-efficiency of private parties but also allows the network to develop past an expensive threshold of connecting multiple sub-networks. Despite being highly effective, it should be noted that this cost-neutral solution requires the politically sensitive taxation of the airline industry and road users, whilst subsidising private railway undertakings. It is expected that this will already raise substantial difficulties.

When aiming for the maximum achievable stakeholder and policy benefits, the government in charge should apply a centralised governance structure in combination with the active subsidisation/taxation of external costs. The organisational advantage of this follows from the subsidisation flows remaining within the own governmental organisation, although the taxation schemes for other transport modes would be even harsher and would therefore require a strong political will. Other than that, this solution also requires the acceptance of large investments with public funds, the willingness of member states to (partially) sacrifice sovereignty and the subordination of national interests.

Together, the policy schemes, as described above, mostly represent two extreme sides of the spectrum. In reality, it could also be opted to find solutions that stimulate cooperation by an in-between or alternative solution, such as private-public partnerships or a concession system. Despite not being specifically tested in this study, the results show an abundance of arguments that would favour improved cooperation. On one side, the great number of border-crossing lines or lines reaching significant lengths indicates the importance of a cross-border view. On the other side, the importance of passenger path control, frequently overlapping lines, usage right of critical infrastructure, exclusion of unimportant cities or the operation of major hubs all benefit from some overarching view.

All in all, the findings of this study shed a new light on the current practice and provide political discussion with additional arguments on how to design the most successful European HSR system. The final decision for different governance structures, pricing policies or any cooperation strategy can be argued from many perspectives. Currently, being in a rather 'low-effort' solution, all changes require a practical effort, but whether the demonstrated benefits outweigh these efforts for policy goals and stakeholders remains a political decision.

7.3. Limitations and Recommendations

The experiments - as performed in this study - are a representation of reality, though assumptions and simplifications are inevitable when considering the available time and computational possibilities. It means that these modelling decisions have an impact on the quality of the findings and the ability to answer the research question. This section discusses the limitations of the research and - based on these limitations - proposes recommendations for future research, which can be either of improving or expanding nature. A comprehensive overview of the identified limitations is presented in *Table 7.1*. A deepened analysis per group is performed in the four paragraphs below. Concluding, a brief statement on proposed ideas for future trends is provided.

Scope limitations by computing and time restrictions
The first set of limitations can be primarily assigned to the structure of the research, as these scope-boundaries were mainly set by time and computational restrictions. Bounding the number of cities and possible lines - as these go hand in hand with each other - is an effective way of reducing the size of the problem, though it also impacts the accuracy and ability to interpret results. Proposed ways to tackle these problems in future studies are to: (1) use the newly found networks as a starting point; (2) allow line adjustment phases, such that improvement dependent of extra lines; and (3) perform step-wise simulations in which insignificant cities are eliminated in earlier phases.

Modelling of high-speed rail
The '*modelling of high-speed rail*' category mainly connects to the level of '*Transit Network Planning Problem*' (TNPP) that is chosen, as was explained by *Figure 2.1* in *subsection 2.1.1*. This specific study, being in-between the strategic and tactical levels, had to make compromises on both sides (strategic: infrastructure/acquisition; tactical: operational aspects). The fewer restrictions allowed the model to have more freedom in its possible solutions, which was more suitable for this first exploratory study on line configurations. Now that more is known, it is well possible to use these lessons in future studies.

From a strategic perspective, it could be interesting to investigate the potential of infrastructural components. This model was already able to determine the loads per edge and vertex, so expansion of this could allow for incorporating the decision for construction. Concrete, these prospective studies could include the construction costs of infrastructure, try to navigate flows over preferred links or exclude links that have a minimal contribution.

Moving to the tactical side of the problem, it could be interesting to learn more about the operational aspects. Currently, the frequency constraints only ensured basic feasibility rules, which led to the possibility of 180 trains per day per direction through the Canal tunnel: a substantial challenge. More detail could be added by restricting such bottlenecks to a maximum, allowing for vehicle differentiation or operational strategies like the merger of trains, stop-skipping or short-turning.

Modelling of passenger demand and behaviour
The research field of long-distance transport demand modelling remains very limited, which led to the decision of using revealed data of air passengers between airports to estimate a total demand between cities. Regardless of the exact methodology, this decision comes with three main drawbacks. First (1), it is not possible to accurately model shorter distance (<200 km) demand, as the is typically not or very minimally served by air travel; second (2), it is not known by what type of passengers these trips are made, which can be important for modelling their decisions; and thirdly (3), it is not possible to see whether these passengers are through going from their destination (thus making a transfer) or not.

Of these problems, especially the first is considered to have a substantial impact, as these short-distance passengers will also be most likely to use the designed network for shorter distances. In this case, it is expected that the introduced error makes the model rather conservative, given that this extra demand could only provide a stronger justification of lines. To improve this problem in future research, an attempt could be made to include data from bus or conventional rail services.

Secondary responsive effects
The current model considers a stable and unresponsive environment to work in, which in reality is not necessarily to be expected. Introducing a new and extensive HSR network, it is very likely that the

surroundings will respond to this. The effect predicted to be the most substantial concerns the generation of new demand due to the increased level of service. When aiming for enhanced mobility, a positive factor, but not necessarily when aspiring benefits in sustainability. To gain insights into this effect, further knowledge on the travel motives and trade-offs are required. Gaining these in a separate research and incorporating these in this work would significantly contribute to the accuracy of this study.

Even further out of control is the behaviour of the aviation industry, as this expected to respond like communicating vessel. The restrictive growth of air travel will allow the released seat capacity to be quickly filled up again, whilst the released take-off/landing slots at an airport might be used for longer flights, now that the airline's feeding function might be performed by the high-speed rail system. Both having again having a positive effect on mobility and a negative effect on sustainability goals, it is essential to understand more on this. Future research investigating the effect of policy measures that control this behaviour could be of great value.

Proposed ideas for a future hyperloop trend

In this time of rapid technological advancement, new developments are always closeby. One of the most compelling topics with an interface to this study concerns the concept of '*Hyperloop*'. Connecting a continental system with pods travelling near the speed of sound could be the next step for transportation. Having very similar characteristics as high-speed rail - but even larger sunken investments, more uncertainties and fewer proof of concept - improved knowledge is definitely desirable.

The model of this study could be applicable to a hyperloop scenario, although it requires a few adaptions and remarks. It is likely that pods will emphasise more towards point-to-point traffic, which follows from lower vehicle seating capacity, but also the increased relative burden of a stop due to its high cruising speed. It makes that it might be less important to think from a corridor perspective when compared to the train. However, this model could still be beneficial - as it would identify essential infrastructural elements - though there might be solutions with fewer computational requirements.

An additional factor to this could be identified in the hyperloop's (non-)flexibility. With a more individual character per pod, it would be easier to swiftly adapt lines and connections, although this is also partially counteracted by significantly higher infrastructural investments. It means that the main contribution of translating this work to a hyperloop scenario can be found when incorporating the decision to buy infrastructure, as this would allow to compare the required monetary investments to the multi-stakeholder interests.

Table 7.1: Overview of the research's limitations

Category	Limitation	Impact	Description
Scope limitations by computing and time restrictions	**Size pool of lines**	large	The size was bounded by the computational ability of the heuristic in the given time. Sub-optimal (too long, largely empty) lines were still observed
	Number of cities considered	medium	124 strategically selected cities provide good insights in general line design, but not so much on the exact stopping patterns in specific regions or along lines
	Possibility for line adjustment	medium	This was not included, but could address the above problem of the pool of line size and increase accuracy
	Multiple case studies	medium	the characteristics of the case (e.g. geographical bottlenecks, demand differences) were of great importance for the final design. Other cases could provide new insights
	Limited validation	medium	The size of the model and the available time did not allow for more extensive validation of the heuristic model and its perform ace of the large network
Modelling of high-speed rail	**Interoperable infrastructure**	large	Large efforts are required to harmonise current technologies
	Homogeneous vehicles	large	Differentiation allows more accurate capacity assignment and inclusion of smaller lines
	Uncapacitated infrastructure	medium	Some infrastructure is already heavily used by other (conventional) rail, but this approach allows to identify important stations and connections
	Availability of infrastructure	medium	Some infrastructure will never be built, but this approach allows to identify important stations and connections
	Vehicle interactions	medium	Interaction with vehicles of same and other modes has a substantial impact on the design, but considered in later design phases
	Operational strategies	medium	Strategies like stop skipping and short-turning are expected to increase accuracy and performance
	Frequency determination (1)	small	The operator bases its frequency on the entire demand, this could be more strategic by spilling the last half-empty train
Modelling of passenger demand and behaviour	**No demand under 200 km**	large	Unable to estimate using air travel. Current model is rather conservative as this traffic will increase demand along lines
	No transfers passengers	medium	Air traffic was used to estimate the total transport demand. No distinction was made between point-to-point and transfer passengers, although they will have interests in reality
	Deterministic HSR trip assignment	medium	Passengers currently opt for the (equally) best path(s) within the HSR network. In reality, it can be expected that they will also use close-to-best paths that could be modelled stochastically
	Different passenger types	medium	Different passengers (e.g. business / leisure) prefer different service attributes and assign other monetary values to their time.
	Neglecting lower level modes	medium	Long-distance busses and conventional trains were not considered, as their share in this transport-scope is rather small
	Multi-modal trips	medium	The model did not consider multi-modal trips. These are theoretical possible, although less likely on continental scale (when compared to intercontinental)
	Maximum of two transfers	small	A maximum of two transfers was considered. In reality, a small portion will use more, but simulations showed that two-transfer paths - when allowed - were already rare and undesirable from a network perspective.
	Symmetrical demand	small	In reality, passengers will also make more complicated tours, resulting in unsymmetrical demand.
Secondary responsive effects	**Generation effects**	large	Improved HSR networks will induce additional demand
	Restrictive aviation growth	medium	Restrictive growth of air travel will fill the released air capacity
	Released airport slots	medium	Short-haul flights might be substituted with long-haul flights hence resulting in an increase external costs and mobility
	Frequency determination (2)	medium	Including the line frequency as a service attribute is more accurate but requires an iterative process to cover supply-demand interactions, thus bringing an associated computational burden

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A
Research Article

The research article starts at the next page

A Unified Design of the European High-Speed Rail Network

Impacts of Design, Pricing and Governance Strategies

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Master thesis

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Master of Science in Transport, Infrastructure and Logistics at Delft University of Technology, The Netherlands

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Abstract — High-speed rail (HSR) is frequently seen as a promising alternative for long-distance travel by air and road, given its environmental advantages whilst offering a competitive level of service. However, due to a lack of knowledge on the design of HSR specific line configurations and the prioritisation of national and railway company interests, no real European HSR network has been realised yet. Together, these lead to a sub-optimal performance from a user, operator and societal perspective.
This research is the first attempt to apply the more frequently used '*Transit Network Design and Frequency Setting Problem*' (TNDFSP) in an HSR setting, which searches the ideal set of lines and associated frequencies in a given network. To do so, this study developed a novel HSR generic model and solution algorithm, which were then parameterised for the European case. By benchmarking the current situation; analysing the relative importance of vehicle, passenger path and line design variables; evaluating pricing and governance strategies; and finally proposing improved settings; it was possible to assess impacts of improved design. The experiments showed that benefits for all stakeholders could be simultaneously enhanced when implementing a centralised governance and internalisation of external costs. This allowed the HSR market share to evolve from 14.7 % to 29.9 %, whilst also improving the societal cost-benefit ratio by 20.0 %. The governmental investment which is required to fill the gap from the most economical to the most extensive solution equals € 2.2 billion per year, but also provides a positive rate of return of 1.8 for the combined user and societal benefits. Additionally, the model demonstrated the necessity of spilling unprofitable passengers and the importance of improved cooperation. These followed from the strong network integration with overlapping and border crossing lines of substantial lengths, the contradiction between national and international interests and the high number of critical infrastructural elements.
All in all, this study demonstrated the possibility of using the TNDFSP in an HSR setting, which opens ways for further understanding of HSR network design. For this specific research, it allowed the identification of substantial opportunities for mobility and sustainability. These can be reached by improved design choices, internalisation of external costs and by relaxation of the desires for a competitive railway market and national sovereignty; all newly underpinned arguments for the discussion on how to design a successful (European) HSR system. Future research could greatly contribute by incorporating the construction of infrastructure, including timetabling or operational aspects, assessing different case studies in size and geography or introducing new technologies.

Keywords — High-Speed Rail , Europe , Network Design , Line Configurations , TNDFSP , Pricing , Governance

Full report — An electronic version of the full report is available at: https://repository.tudelft.nl/

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1. INTRODUCTION

Over the last century, long-distance travel has become more and more common (The World Bank, 2020). Bringing many advantages by enhanced mobility, it also comes at the cost of externalities, such as the depletion of finite natural resources, noise pollution and the contribution to climate change (Janić, 1999). Frequently, High-Speed Rail is considered as a promising alternative for short-haul flights (<1500 km) and long-distance car travel (>200 km), by providing competitive services against fewer environmental disadvantages (Givoni, 2006; Albalate and Bel, 2012; Pagliara et al., 2012; Donners and Heufke Kantelaar, 2019). With this knowledge, great encouragements and investments have been made for a European HSR network (European commission, 2020).

Despite the combination of seemingly favourable circumstances, no real European HSR network has been realised yet. The infrastructure is largely existing, but the current network is a patchwork of poorly connected sub-networks without a good cross-border coordination (European Court of Auditors, 2018). Two main underlying problems cause this suboptimal state: (1) a lack of knowledge on design of line configurations for High-Speed Rail from a network perspective and (2) a reduced network integration due to prioritisation of national and railway company interests. (Vickerman, 1996; Laperrouza and Finger, 2009). This study initially focuses on the first, but with that also gains insights into the second.

To determine how these problems can be addressed, a quantitative study on the line configurations of HSR networks, based on the '*Transit Network Design and Frequency Setting Problem*' (TNDFSP) (Guihaire and Hao, 2008), was performed in this study. This research is the first attempt to transform and solve this problem, that is typically used in conventional transit systems, into an HSR setting. By generically defining this HSR-adapted problem, formulating a novel solution algorithm and modelling the case-specific European environment, this paper aims to gain insights into HSR network design. This, to ultimately answer the main research question:

'"To what extent can the user, operator and societal performance of a European high-speed rail network be improved by centrally designed line configurations as well as pricing policies and how would such networks look like?"'

The remainder of this paper is organised in the following structure: *section 2* reviews a brief overview of relevant studies and their link to the HSR environment. Following, an elaboration of the exact problem, the methods used to solve this, the parameterisation of the European case and model implementation are discussed in *section 3*. Continuing, *section 4* presents the results of the performed simulations and the extrapolated lessons of these, after which the final conclusions are drawn in *section 5*.

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2. LITERATURE

Public transport systems are often advocated for due to their potential mobility and environmental benefits. However, to reach an effective state for such systems, a balance has to be found between the quality of service for users, the costs for operators and the impact on the system's surroundings (Guihaire and Hao, 2008; Farahani et al., 2013). The sections below perform an assessment of the literature in the field of strategic transit design. This, to identify available techniques, their potential for an HSR environment and the challenges to be expected.

2.1. Transit Network Optimisation Fields

Ideally, all aspects of a transit network would be designed simultaneously (Gallo et al., 2011). However, due to the highly complex working environment and stakeholder interests, the problem is frequently divided into smaller sub-problems (Desaulniers and Hickman, 2007; Ibarra-Rojas et al., 2015). A commonly used division considers six subsequent phases: (1) '*Network Planning*', (2) '*Line Planning*', (3) '*Timetable Generation*', (4) '*Vehicle Schedules*', (5) '*Crew Schedules*' and (6) '*Real-Time Management*' (Bussieck, 1998; Lindner, 2000; Lusby et al., 2011). The problems that quantitatively describe these phases can be encompassed under the name '*Transit Network Planning Problem*' (TNPP), as defined (Ibarra-Rojas et al., 2015). Because of cross-level relations between the sub-problems of the TNPP, works in this field often favou to combine several subproblems into one. Guihaire and Hao (2008) defined a framework of these combined problems. Pairing this framework the topic of this specific study on centrally designed HSR line configurations, it is established that the problem of this research can be classified in the category of '*Transit Network Design and Frequency Setting Problems*' (TNDFSP).

2.2. Transit Network Design and Frequency Setting Problem for HSR

The TNDFSP combines a (1) '*Design Problem*' (which determines a set of lines, consisting of terminal stations and intermediate stops) with a (2) '*Frequency Setting Problem*' (that finds adequate time-specific frequencies) for a given demand. The resulting output of the two combined problems consists of a '*Line Plan*' (the set of chosen lines) and their associated '*Frequencies*'. Together, they form the '*Line Configuration*' (Kepaptsoglou and Karlaftis, 2009; Schöbel, 2012). In search of previous literature, no studies applying this problem in an HSR environment were found. To learn about this, the sections below perform an assessment of existing TNDFSP studies for conventional transit and other relevant HSR studies.

Objectives: The objective function is the mathematical expression that reflects a goal which can either be minimised or maximised (Hillier and Lieberman, 2015). As the TNDFSP makes a trade-off in the interests of multiple stakeholders, it is classified as a multi-objective problem. Typically, transit planning has two main partners involved: the operator wishing to minimise its costs (e.g. acquisition, operational and maintenance) and the user desiring a maximisation of its benefits (e.g. travel time, costs) (López-Ramos, 2014; Owais et al., 2016). Frequently, studies expand these stakeholder interests by incorporating a broader set of goals, such as the minimisation of external costs, transfer traffic, travel time and fuel consumption, or the maximisation of capacity or total (societal) welfare.

TNPP studies in the field of HSR show similar objective types: Yue et al. (2016) consider the maximisation of profit for a given fleet, Sun et al. (2014) try to minimise the travel times for trains, Gallo et al. (2011) separate car from transit users and Li et al. (2013) introduce a green perspective by incorporating the minimisation of energy use and carbon emissions. The analysis shows that most differences are not necessarily found in the types of objective functions, but rather the specification of the parameters, given their deviant characteristics when compared to conventional transit.

Decision Variables: Decision variables are the representations of quantifiable decisions to be made (Hillier and Lieberman, 2015). In general, two main decision variables are used for the TNDFSP: the (1) '*line selection*' and (2) '*line frequencies*', although sometimes expanded by the '*vehicle type*' (Kepaptsoglou and Karlaftis, 2009). However, implicitly many more decision variables are taken into account, as the selection of a specific line comes with its own characteristics, such as covered lengths, stop locations, directness or the lack of that (Fan and Machemehl, 2008).

From the perspective of HSR, many resemblances with other transit modes can be found. This, because the mentioned decision variables are all focused on the high-level network and passenger flows, rather than operational factors. It makes that the decision variables do not require further expansion for this study.

Network Characteristics: A standard TNDFSP network consist of '*vertices*' (stops or stations), '*edges*' (direct connection between vertices), '*lines*' (passenger services residing a sequence of connected edges) and '*paths*' (passenger courses between two vertices following one or more lines) (Schöbel, 2012). In general, these networks come in three typical structure types: '*simplified radial structures*', '*simplified rectangular grid structures*' and '*realistic irregular grid*' structures (Kepaptsoglou and Karlaftis, 2009). Furthermore, a distinction can be made in the modes available (uni- or multi-modal) as well as the ability for traffic to interact with vehicles of the same or other modes. (Farahani et al., 2013).

Regarding other network optimisation research in the field of HSR, it is seen that most studies (e.g. Allard and Moura (2014) and Lovett et al. (2013)) use a realistic irregular (grid) structure, as the spatial geography on longer distances typically follows an irregular pattern when compared to urban regions. However, the size of these structures remains relatively limited, reaching a maximum of 10 vertices. Following this, (Jong et al., 2012) acknowledges the infrastructural limitations of (high-speed) rail infrastructure by combining a strategic frequency setting problem with a tactical timetabling problem.

Demand Characteristics: From literature, three main aspects of demand modelling in TNDFSPs are found. Firstly (1), two distinctive '*Spatial patterns*' are identified by Kepaptsoglou and Karlaftis (2009): a '*one-to-many*' demand pattern (used when focus is at one vertex, e.g. Chien and Schonfeld (1998)) and a '*many-to-many*' demand pattern (emphasising flows on a network scale, e.g. Zhao and Zeng (2007) and Hassan et al. (2019). Secondly (2), the '*time scope*' varies between years for highly discrete problems concerning the construction of infrastructure and minutes for tactical and operational problems (Farahani et al., 2013; Ibarra-Rojas et al., 2015). Finally (3), differences in '*dynamic demand responses*' are observed. These can be subdivided into '*fixed or elastic total demand*' (when considering generation effects, e.g. Cervero (2002), Laird et al. (2005), Di Giacinto et al. (2012) and Beaudoin and Lin Lawell (2018)) and '*fixed or elastic mode specific demand*' (when evaluating mode substitution, e.g. Janić (1996))

For a TNDFSP in the HSR domain on the European continent, it is considered that '*many-to-many*' demand pattern and a relatively longer '*time-scope*' are required. Furthermore, considering '*elastic demand patterns*' could strongly increase the accuracy. However, the most characteristic difference in the demand for an HSR problem is not mentioned above. Many of TNDFSPs for conventional transit systems assume demand to be generated by residential zones (e.g. Fan and Machemehl (2008) and Heyken Soares et al. (2019)). For long-distance transport, however, the generation of demand must be sought in other factors. The implementation of this will be discussed more elaborately in *section 3.3*

Constraints: Imposing constraints on any optimisation problem ensures realistic solutions, but it also contributes to the reduction of computational requirements (Bussieck, 1998). In a search for unification of fundamental line planning models, Schöbel (2012) identified constraints which mainly concern budget, capacity and connectivity requirements. Including more practical works, López-Ramos (2014) also recognises express services, the inviolability of existing lines and time horizon to finish tasks. Additionally, Zhao and Zeng (2006) focusses on classical bus systems and finds the importance of line design constraints, such as directness, length, shape, and load factor requirements.

Characteristic of rail transport is the relative dependence on its infrastructure and the subsequent requirements (Bussieck, 1998). In this category, especially constraints for operational factors (physical interoperability and safety systems, more complex station or edge capacities and difficulties in overtaking) and political factors (divergent governance or international political conflicts) play an important role (Ahuja et al., 2005; Yue et al., 2016). However, their complicated nature makes that they cannot always be quantified (Bussieck, 1998). Given the strategic character of this research, it means that the emphasis should be laid upon line design or potentially political constraints, rather than operational.

2.3. Solution Strategies

TNDFSPs are seen as relatively complex problems. In Baaj (1990) and Fan and Machemehl (2004), six main factors of complexity were identified: (1) the expression of decision variables and objective functions, (2) frequently occurring non-convex and non-linear costs, (3) NP-hardness due to a discrete nature bringing combinatorial complexity, (4) conflicting stakeholder objectives, (5) designing operationally feasible lines that obey design criteria and (6) the nature of variable transit demand. Combining this with the observation of (Schöbel, 2012), that this problem often has an application-driven character, results in a variety of problem formulations and solution approaches.

Kepaptsoglou and Karlaftis (2009) defines the two most fundamental strategies as the '*Line Generation & Configuration*' method (where a set of candidate lines is generated, after which a sub-selection of these lines are selected for the final network) and the '*Line Construction & Improvement*' method (which starts with an initial line plan that is step-wise improved by altering lines). The processes to guide and solve these problems follow one of two main techniques: either '*conventional techniques*' (analytical and mathematical programming) or '*heuristic techniques*' (heuristics and meta-heuristics) (Kepaptsoglou and Karlaftis, 2009; Iliopoulou et al., 2019). However, the application of conventional techniques is generally considered less suitable. For the analytical options, this follows from the problem being NP-hard and the results being opaque. For the mathematical programming, this follows from the inability of realistically representing the structure of lines (Ceder, 2001; Youssef et al., 2001; Fan and Machemehl, 2004; Iliopoulou et al., 2019).

Concerning the heuristic techniques, it is seen that a variety of procedures are applied. Regular heuristics mostly use '*constructive strategies*' (skeleton, end-node assignment and network), which are applied either in successive or simultaneous order (Sonntag, 1977; Quak, 2003). In meta-heuristics, a threefold division is found: '*single-solution*' (e.g. Tabu Search, Simulated Annealing or GRASP), '*population based*' (e.g. Evolutionary algorithms or swarm intelligence such as Ant or Bee colonies) and '*hybrid*' forms Iliopoulou et al. (2019). The wide variety of applied techniques indicates the importance of customised approaches.

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3. METHODOLOGY

The main goal of this research is to assess to potential improvement that can be made in the design of HSR networks and to learn on the characteristics of such improved networks, as was formulated in the '*Introduction*' (*section 1*). Given the size, complexity and limited qualitative knowledge in the topic of HSR network design, it was chosen to use a quantitative approach. In *section 2*, it was found that a problem like this is numerically described by the '*Transit Network Frequency and Design Setting Problem*' (TNDFSP), which is more frequently used for conventional public transport systems. However, to make this applicable for this study, a range of adaptions had to be made. This chapter covers the methodological elaboration of this adapted problem, which is built upon a three-step approach: a generic '*problem formulation*', a generic '*solution strategy*' and a case-specific '*parameterisation*'. Additionally, the model is implemented to make it usable. An overview of this overall approach is presented below.

Methodological approach and chapter structure: The first step (1) (*subsection 3.1*) was to define a customised version of the TNDFSP, such that this quantitatively describes the problem of optimising HSR line configurations in a generic setting. The inherent complexity of these TNDFSP problems (as discussed in *section 2.3*), makes that these cannot be solved using conventional techniques. Because of this, the second step (2) (*section 3.2*) was to formulate a novel heuristic that strategically searches the solution space for strong performing results in a reasonable time. The final development step (3) (*section 3.3*), was to parameterise the newly described problem for the European case study, such that the simulation takes place in a realistic situation. By implementing the previously described model and constructing multiple experiments, as stated in *section 3.4*, it became possible to simulate multiple scenarios. Interpreting the outcomes of these different simulations allowed to ultimately assess the potential network improvement design characteristics of a unified HSR design.

Modelling choices: Several modelling choices were made to match the strategic character of the research, simplify the problem and emphasis the research goal. The study considers a continuous state perspective, such that the expenses for the construction of infrastructure or the acquisition of vehicles are not considered. The associated time-span of this continuous state equals one operational day of eighteen hours. In this state, all costs components are considered relative to a situation with no HSR whatsoever. Additionally, the network's infrastructure is uncapacitated to provide the problem with solution freedom. Below, an overview of further modelling assumptions is stated:

- The total demand is fixed (thus no generation effects)
- The mode-specific demand is elastic, based on the level of service and assigned assuming a stochastic uncongested user equilibrium
- The network is symmetric for each OD-pair (demand, level of service)
- Vehicles of the same mode are homogeneous
- Vehicles do not interact whatsoever
- No operational strategies (e.g. deadheading or short-turning) are considered
- HSR infrastructure is interoperable throughout the network and not capacity or operationally restrictive
- HSR allows for a maximum of two transfers per path; air travel assumes direct trips only

3.1. *Problem Definition*

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*' $V=\{v_1,v_2,\dots,v_{|v|}\}$ and a finite set of connections between these cities that are represented as '*edges*' $E=\{e_1,e_2,\dots,e_{|E|}\}$. Furthermore, different ways of transport are distinguished by '*modes*' $M=\{m_1,m_2,\dots,m_{|q|}\}$. Following this given graph, a '*line*' can be defined as a service that is a sequence of directly connected vertices: $l=\{v_{first},\dots,v_{last}\}$. Combining multiple of these separate line together results in a '*set of lines*' $L=\{l_1,l_2,\dots,l_{|L|}\}$. 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 so-called '*transfer path*' p^t. Together, these paths form the set of paths $P=\{p_1,p_2,\dots,p_{|P|}\}$, where each pair of vertices has only one such path. An overview of sets and indices is presented in *Table 1*

TABLE 1: OVERVIEW OF SETS AND INDICES

Notation	**Description**
$i,j\in V$	Vertices (cities & stations)
$c\in E$	Edges
$k\in L$	Lines
$q\in M$	Modes
$p^d\subset P$	Direct path
$p^t\subset P$	Transfer path

3.1.1. *Parameters*

The succeeding steps of the problem definition use a range of parameters and variables to describe different components within the model. An overview of this is displayed in *Table 2*.

3.1.2. *Decision Variables*

The typical TNDFSP knows two main decision variables, which are also used for this study: the '*set of lines*' $L=\{l_{k=1},l_{k=2},\dots,l_{k=L}\}$, where it is defined which selection of lines are to be activated, and the associated '*frequencies*'

TABLE 2: OVERVIEW OF PARAMETERS AND VARIABLES

Notation	Unit	Description
V	[-]	number of vertices v
$t^{acs}_{v,m}$	$[min]$	access time of vertex v for mode m
$t^{egs}_{v,m}$	$[min]$	egress time of vertex v for mode m
E	[-]	number of edges e
$ds^{gc}_{i,j}$	$[m]$	greater circle distance between vertices v_i and v_j
$ds^{land}_{i,j}$	$[m]$	land distance between vertices v_i and v_j (road distance corrected by standard car detour factor)
$ln^{str}_{e,m}$	$[m]$	stretching length of edge e for mode m
fc^{dt}_{m}	[-]	detour factor of transport mode m
$t^{rid}_{e,m}$	$[s]$	total riding time at edge e for mode m (incl. dwell time HSR; incl. taxi and take-off/landing air)
$ln^{str}_{l_k}$	$[m]$	stretching length of line l_k
$ln^{l_k,min}$	$[m]$	minimum line length for any route
cp_m	[-]	vehicle capacity of mode m
t^{trf}_{m}	$[min]$	transfer time for mode m
fc^{loa}_{m}	[-]	design load factor of mode m
$t^{l_k}_{i,j}$	$[s]$	total travel time between vertices i and j on line l_k
$t^{t_r}_{i,j}$	$[s]$	total travel time between vertices i and j along transfer path pt_s
$t^{rt}_{l_k}$	$[s]$	round trip time of line l_m (incl. buffer time)
$n^{veh}_{l_k}$	[-]	number of operating vehicles of mode m required on line l_k
$dm^{tot}_{i,j}$	$[pax/day]$	Total travel demand between vertices i and j
$dm^{m}_{i,j}$	$[pax/day]$	travel demand between vertices i and j for mode m
$dm^{l_k}_{e_c(a,b)}$	$[pax/day]$	travel demand between vertices i and j on line l_k ;
$dm^{pd_r}_{i,j}$	$[pax/day]$	travel demand between vertices i and j along direct path pd_r
$dm^{pt_s}_{i,j}$	$[pax/day]$	travel demand between vertices i and j along transfer path pt_s
$q^{v,m}$	$[pax/day]$	number of passengers using vertex v with mode m
$q^{e,m}$	$[pax/day]$	number of passengers using vertex e with mode m
$q^{max}_{l_k}$	$[pax/day]$	maximum number of passengers using on the line l_k

$F = \{f_{l_{k=1}}, f_{l_{k=2}}, ..., f_{l_{k=L}}\}$ for each of the activated lines. An overview of this is given in *Table 3*. It should be noted that indirectly, the decision for these two variables also represents other design variables, as each lines comes with its own characteristics (Fan and Machemehl, 2008).

TABLE 3: OVERVIEW OF DECISION VARIABLES

Notation	Unit	Description
$L = \{l_{k=1}, l_{k=2}, ..., l_{k=L}\}$	[-]	set of lines
$F = \{f_{l_{k=1}}, f_{l_{k=2}}, ..., f_{l_{k=L}}\}$	[veh/d]	frequency on line l

3.1.3. Objectives and costs components

Based on the analysis of *section 2.2* and the character of the HSR environment, it is chosen to define the objective as the minimisation of the weighted (ψ) costs (C) as experienced by three main stakeholders: '*Users*', '*Operator*' and '*Society*'. Here, the weights are introduced to reflect the pricing policy trade-offs. The comprehensive objective function is presented in *Equation 1*. The separate stakeholder costs components are further expanded in *Equation 2* (user), *Equation 3* (operator) and *Equation 4* (society).

$$Min.\ \ Z = (\psi^{user} \cdot C^{user}) + (\psi^{ope.} \cdot C^{ope.}) + (\psi^{ext.} \cdot C^{ext}) \qquad (1)$$

where:

Z = Objective function value
ψ_x = weight for stakeholder x
C_x = Total costs for stakeholder x

User costs The user costs follow from the time spent on travelling and the associated monetary value that is given to this time (Value of Time, indicated as VoT). With this, it follows that the user's objective is to minimise its travel costs. Dependent on the mode, a trip can consist of five elements: the (1) '*access time*', (2) '*waiting time*', (3) '*in-vehicle time*', (4) '*transfer time*' and (5) '*egress time*'. The overall user costs are determined by summing number of passengers q that spend a time t at a specific point. The formula describing the user costs is given in *Equation 2*.

$$C^{user} = c^{access} + c^{waiting} + c^{in-vehicle} + c^{transfer} + c^{egress} \qquad (2)$$

where:

$$\begin{aligned}
c^{access} &= VoT^{acs}\left(\textstyle\sum_m \sum_v \left(q^{acs}_{v,m} + t^{acs}_{v,m}\right)\right)\\
c^{waiting} &= VoT^{wai}\left(\textstyle\sum_m \sum_v \left(q^{wai}_{v,m} + t^{wai}_{v,m}\right)\right)\\
c^{invehicle} &= VoT^{inv}\left(\textstyle\sum_m \sum_e \left(\left(\sum_{p_d}\left(q^{e,m}_{p_d,e}\right) + \sum_{p_t}\left(q^{e,m}_{p_t,e}\right)\right) \cdot t^{inv}_{e,m}\right)\right)\\
c^{transfer} &= VoT^{trf}\left(\textstyle\sum_m \sum_{p_t}\left(\sum_{i,j} q_{m,p_t} \cdot \left(n^{trf}_{p_t} \cdot t^{trf}_{m}\right)\right)\right)\\
c^{egress} &= VoT^{egr}\left(\textstyle\sum_m \sum_v \left(q^{egr}_{v,m} + t^{egr}_{v,m}\right)\right)
\end{aligned}$$

Operator costs The operator is responsible for running the HSR network, which means it has an interest in minimising these costs. The main costs components for operating a high-speed rail system, as defined by Campos and de Rus (2009) and Zschoche et al. (2012), are covered in the (1) '*operational*' and (2) '*maintenance*' expenses, which are expressed in cost per seat-kilometre. The numerical formulation of the operator cost components are further defined in *Equation 3*.

$$C^{operator} = c^{operational} + c^{maintenance} \qquad (3)$$

where:

$$\begin{aligned}
c^{operational} &= \textstyle\sum_{l_k \in L}\left(2 \cdot ln^{str}_{l_k} \cdot f_{l_k} \cdot cp_{hsr}\right) \cdot c^{oper.,marg}\\
c^{maintenance} &= \textstyle\sum_{l_k \in L}\left(2 \cdot ln^{str}_{l_k} \cdot f_{l_k} \cdot cp_{hsr}\right) \cdot c^{main.,marg}
\end{aligned}$$

Societal costs The societal costs follow from indirect effects that are not paid by the actual user or operator, but rather by society. Internalising these so-called '*external*' costs is done by *Equation 4*, where the flow of passengers is combined with the mode-specific overall external costs per passenger-kilometre.

$$C^{society} = c^{external} \qquad (4)$$

where:

$$c^{external} = \textstyle\sum_m \sum_e \left(\left(\sum_{p_d}\left(q^{e,m}_{p_d,e}\right) + \sum_{p_t}\left(q^{e,m}_{p_t,e}\right)\right) \cdot ln^{str}_{e} \cdot c^{ext,marg}_{m}\right)$$

3.1.4. Constraints

The objective function of *Equation 1* is subject to a range of constraints. This, to ensure feasible results and to restrict the solution space thus associated computational burden of the problem. The constraints are divided into three categories: ‘*Line Design constraints*’, ‘*Line Frequency constraints*’ and ‘*Passenger path constraints*’.

Line design constraints: The formulas below present the line design constraints. The constraints concerning the ‘*minimum line length*’ (*Equation 5*) and ‘*minimum number of stops*’ (*Equation 6*) prevent nesting with conventional rail and assure a network function. Following, the ‘*round trip time*’ (*Equation 7*) imposes that all trains should be able to return to their home station within one operational day, to keep balance and allow for practicalities like maintenance. Next, the ‘*line symmetry*’ (*Equation 8*) says that all lines should be identical both directions and finally, *Equation 9* and *Equation 10* prevent the inclusion of strongly detouring lines, mainly to reduce the computation time.

Minimum Line Length:

$$ln^{str,min}_{l_k} \leq ln^{str}_{l_k} \qquad \forall \qquad l_k \in L \tag{5}$$

Minimum Number of Stops:

$$n^{s_l,min} \leq n^{s_l} \qquad \forall \qquad l_k \in L \tag{6}$$

Round Trip Time:

$$t^{rt}_{l_k} \leq t^{rt,max}_{l_k} \qquad \forall \qquad l_k \in L \tag{7}$$

Line Symmetry:

$$l_k(i,j) = (\ l_k(j,i)\ )^{-1} \qquad \forall \qquad i,j \in V \tag{8}$$

Infrastructural detour (time & distance):

$$ln^{str}_{l_{k(i,j)}} \leq fac^{dt,infra} \cdot p^{d,min}_{i,j} \tag{9}$$

Geographical detour:

$$ln^{str}_{l_{k(i,j)}} \leq fac^{dt,geo} \cdot ds^{gc}_{i,j} \tag{10}$$

Frequency constraints: Below, the frequency constraints are presented. Given the strategic character of this study, they are mainly responsible for safeguarding feasible solutions, rather than user and operator friendly timetables. The ‘*minimum frequency*’ (*Equation 11*) ensures non-negativity and prevents ghost lines, which are active but have no trains. The ‘*integer frequency*’ (*Equation 12*) restricts the model from using partial trains. Finally, the ‘*frequency symmetry*’ (*Equation 13*) guarantees the continuity of trains by making sure the frequency is identical in both directions of a line.

Minimum Frequency:

$$f_{min} \leq f_{l_k} \qquad \forall \qquad l_k \in L \tag{11}$$

Integer Frequencies

$$f_{l_k} = \mathbb{Z} \qquad \forall \qquad l_k \in L \tag{12}$$

Frequency Symmetry

$$f_{l_k(i,j)} = \Big(\ f_{l_k(j,i)}\ \Big)^{-1} \qquad \forall \qquad i,j \in V \tag{13}$$

Passengers path constraints: The passenger’s ability to travel through the network is bounded by the constraints as presented below. Firstly, *Equation 14* limits the maximum number of transfers per path. This constraint is mainly for computational reasons, but it is also an essential tool for the design and performance of the network, as will be found in *section 3.4.2* and *section 4.3*. Similarly, *section 3.4.2* proves the necessity of excluding unprofitable passengers from the system, which is quantitatively described by the strategic pricing levels of *Equation 15* and *Equation 16*.

Maximum number of transfers:

$$n^{trf}_{p^t} \leq n^{trf,max}_{p^t} \qquad \forall \qquad p^t \in P \tag{14}$$

Infrastructural Strategic Pricing Level:

$$p(i,j) = \begin{cases} feasible, & \text{if } t^{inv\&trf}_{p(i,j)} \leq fac^{SPL,infra} \cdot t^{inv,min}_{p^d(i,j)} \\ infeasible, & \text{otherwise} \end{cases} \tag{15}$$

Geographical Strategic Pricing Level:

$$p(i,j) = \begin{cases} feasible, & \text{if } ln^{str}_{p(i,j)} \leq fac^{SPL,geo} \cdot ds^{gc}_{i,j} \\ infeasible, & \text{otherwise} \end{cases} \tag{16}$$

3.2. *Solution Strategy*

The fundamental solution strategies of Kepaptsoglou and Karlaftis (2009) (as discussed in *subsection 2.3*) require either a starting network of which the lines can be altered (Line Configuration & Improvement; LCI) or a set of lines from which a selection can be made (Line Generation & Configuration; LGC). Given the currently limited available knowledge on how such networks or lines should look like, it is chosen to use the latter option (LGC) and provide the system with a diverse palette of lines. In *subsection 2.3*, it was found that conventional solution strategies are non-sufficient for real-scale problems due to six characteristic difficulties of TNDFSP, which makes the problem reliant on (meta-)heuristics. In search of a suitable method, multiple techniques were considered. Aiming for a light-weight model (to perform multiple tests), which uses few starting assumptions (due to limited knowledge on line configurations) but also comes to reasonably optimal solutions, it was chosen to develop customised hill-climbing heuristic approach starting from a fully deactivated pool of lines. *subsection 3.2.1* briefly discusses the high-level structure of the ‘*line generation and configuration*’ procedure, which is then followed by a further elaboration of its components.

3.2.1. Line Generation and Configuration

A visualisation of the high-level ‘*Line Generation and Configuration*’ approach is presented in *Figure 1*. The figure consists of five main components. As ‘*Input*’, it receives the definition of the initial problem definition as discussed in *section 3.1* and the parameters of *section 3.3*. Together, these make an environment to work in. Executing a range of procedures, it works towards the ‘*Output*’. This output consists of a resulting line configuration (thus set of lines and frequencies) with their associated performance details.

To reach this state, three main procedures are used. Firstly, the ‘*Line Generation Procedure*’ (LGP) builds a pool of feasible and strategically designed lines. These lines are then transferred to the ‘*Line Configuration Procedure*’ (LCP). This procedure guides the search towards a strong performing solution by strategically selecting multiple sets of lines. The proposed configurations are simulated and assessed on their performance in ‘*Network Analysis Procedure*’ (NAP). Following this, the LCP decides which next move is most suitable, meaning that the latter two are in continuous consultation with each other.

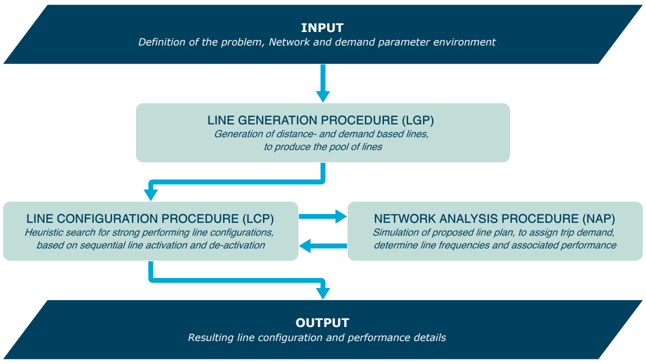

Fig. 1: High-level Line Generation and Configuration approach

3.2.2. *Line Generation Procedure*

Figure 2 provides an overview of the steps within the LGP. This procedure uses five operations to work towards the construction of two line types: Those based on shortest paths and those that are allowed to detour along edges with expected higher demands. Starting in ‘*Operation 1.*’, Dijkstra’s algorithm (based on travel times) is applied to find the shortest path between each OD-pair (Dijkstra, 1959). From this, all of the resulting paths are stored as potential lines.

Continuing, the demand-based lines are produced using the ‘*shortest-path-usage map*’ technique, as defined by Kiliç and Gök (2014) and further developed by Heyken Soares et al. (2019). Here, the potential demand per edge follows from the assumption that all passengers would ideally follow their shortest path through the graph, which is done in ‘*Operation 2.*’ by counting the expected traffic. Next, ‘*Operation 3.*’ transforms the weights of the edges in the graph by combining the travel times and expected demand (by ratio $fac^{dt,dm}$), such that high-demand edges have relatively lower weights. In the succeeding ‘*Operation 4.*’, Dijkstra’s shortest-path algorithm is once again applied, but now with the new edge weights. This operation then presents the resulting demand-based paths to the set of potential lines.

Finally, the set of potential lines is reduced by enforcing the line design constraints of *subsection 3.1.4* in ‘*Operation 5.*’ upon the set of potential lines, such that infeasible lines are excluded. This makes that the remaining lines constitute the ‘*Pool of Lines*’. However, the previous operations make that this pool could theoretically contain $2 \cdot \left(V^2/2\right)$ unique lines. The exponential character of this pool size makes that the problem becomes impracticable for larger networks, as will also be demonstrated in *section 3.4.1*. To further reduce the set of lines, two measures were taken: firstly, the designation of key-cities, which are the only vertices where lines can begin or terminate; and secondly the strategic elimination of lines, where a selection is made based on the closeness, highest demand destinations and highest expected line usage, to maintaining a diverse palette of lines.

3.2.3. *Line Configuration Procedure*

The Line configuration Procedure (LCP), as illustrated in *Figure 3*, is the heuristic that guides the search towards a strong performing solution by proposing possible line plans and comparing their performances. The LCP has a greedy hill-climbing character, and it consists of five operations. These operations are based on the activation, deactivation or substitution of the current line configuration.

The heuristic starts with an empty line plan. The first two steps (‘*Operation 6.*’ and ‘*Operation 7.*’) are concerned with activating lines from the ‘*pool of lines*’. In every iteration, the solution space is defined as the individual activation of all currently non-activated lines, which bounds the number of iterations by the triangular number T_n, with n being the size of the ‘*Pool of Lines*’. Following this, the entire iteration solution space is presented to the NAP, where all moves are simulated separately. With its greedy character, the LCP selects the best performing move. ‘*Operation 6.*’ then repeats this process until no further improvement is found. To reduce the risk of ending at a local optimum, ‘*Operation 7.*’ repeats the same process, but with the ability to accept a maximum number of s temporary deteriorating iterations ($s = 10$ for this study). Finding a delayed improvement, the line configuration is updated and ‘*Operation 6.*’ is restarted. If no further improvement is found, a continuation towards ‘*Operation 8.*’ is made.

‘*Operation 8.*’ and ‘*Operation 9.*’ are identical to the previous operations 6. and 7., although they work from the opposite perspective. Considering the current configuration, their solution space is defined as the deactivation of all currently active lines. Again, each best possible move is selected in Operation 8. and temporary skipping procedures are performed in Operation 9..

Finally, Operation 10. concerns the substitution of lines. Here the solution space is defined as the modification of all lines (active $\Longleftrightarrow$ non-active) and temporary deteriorations are accepted within an iteration. in the first sub-iteration, the n^{th} best move is selected ($n^{max} = 18$ for this study). In the following sub-iteration, three branches are constructed by selecting the 1^{st}, 2^{nd} and 3^{rd} performing moves. These branches were then deepened by performing a greedy search for three more levels. This sequence of sub-iterations is repeated for n^{max} times until an improvement is found. If this does not happen, the LCP is terminated.

3.2.4. *Network Analysis Procedure*

In *Figure 4*, an overview of the subsequent steps in the Network Analysis Procedure (NAP) is displayed. The NAP is responsible for the simulation of a proposed line plan, such that it can assess the performance of this line plan and inform the LCP on whether it is moving in the right direction. The above is done four separate stages.

The NAP starts on the left-hand side at ‘*Stage A*’, where the user’s behaviour is simulated by firstly (1) determining the best HSR path option and then (2) comparing this to the level of service of other modes. The HSR path determination is based on a lexicographic travel time and transfer minimisation strategy, as initially proposed by Han and Wilson (1982) and adapted by Fan and Machemehl (2004). This strategy is preferred over frequency share-based multipath assignments, due to the higher information transparency combined with long term trip planning, and flow-concentration techniques, due to the operator interest inclusion in other phases. Knowing the best HSR path, this stage continues its task by assigning the travel demand per mode. This assignment is based on travel time attributes by using the ‘*Random Regret Minimisation*’ technique as developed by Chorus et al. (2008) and applied on long-distance transport by Donners (2016).

Consecutive to this, ‘*Stage B*’ simulates the operator’s response by determining the line frequencies that are required to supply for the demand per line, for which a design load factor of $fac_{HSR}^{lf} = 0{,}8$ was used. Furthermore, this is also the stage where the frequency constraints of *section 3.1.4* are activated to assure feasible solutions. It the following ‘*Stage C*’, the network descriptors (such as average access/egress times or the number of required vehicles are extracted, such that model choices could be interpreted in post-analyses. Furthermore, the indicators are used to determine the performance (objective function value) in the last stage, ‘*Stage D*’. The resulting output is reverted to the LCP.

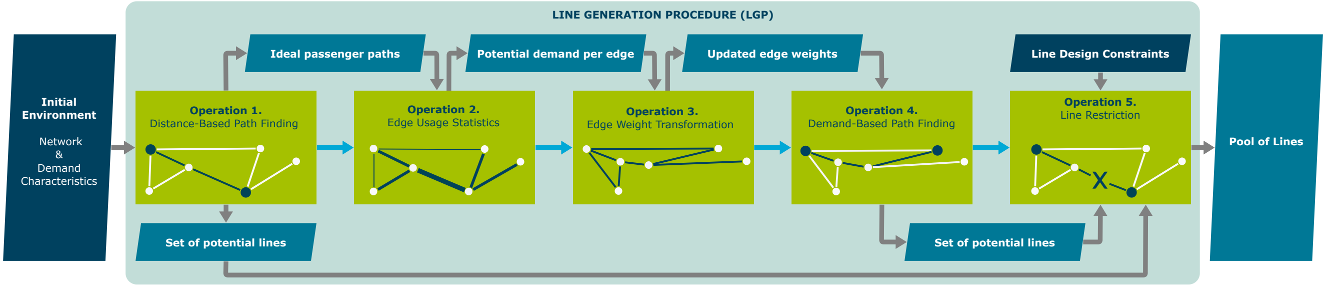

Fig. 2: Flowchart of Line Generation Procedure

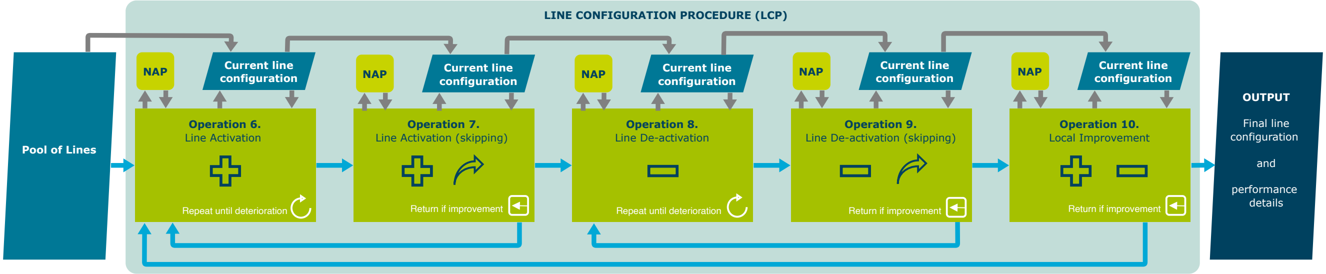

Fig. 3: Flowchart of Line Configuration Procedure

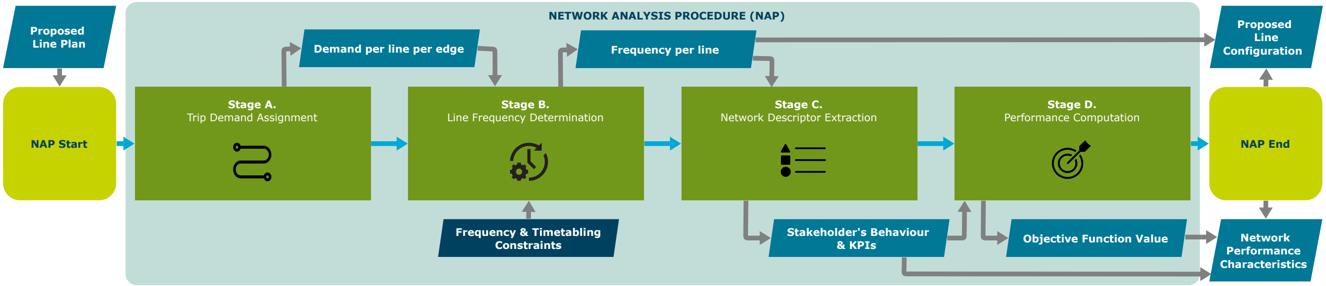

Fig. 4: Flowchart of Network Analysis Procedure

3.3. *Case Study of the European Network*

In search of the potential significance of a European high-speed rail network, the problem was parameterised to realistically describe the characteristics of this continent and currently available technologies. The paragraphs below discuss each of the main network components.

Vertices: The vertices in the graph are described using 124 cities and 385 airports. The former selection is based on the study of Donners (2016), in which the most significant metropolitan areas for a high-level European HSR network are defined using socio-demographic (e.g. population, GDP, research activities) and practical criteria (e.g. availability of rail infrastructure). The latter selection was found by extracting the main airports as reported by participant countries of the annual air-traffic questionnaire by Eurostat (2020). Estimations for access and egress times were location-specific. Within cities, to an HSR station, this time was the function of a city's area and the average time required to reach its centre, assuming an average travel speed of 30 km/h (Donners, 2016). From cities to airports, these average access and egress times were estimated by considering the passenger volume of and travel time to all airports within a 2.5 hours range.

Edges: The model distinguishes three modes of transport: air, road and high-speed rail. The edges in the air-network are again based on the questionnaire of Eurostat (2020), as this reports the actual flights between the modelled airports in 2019. Regarding the road network and considering the difficulty in realistically capturing natural and political barriers (e.g. water bodies, mountains or country borders) by a mathematical function, it was opted to estimate car travel times and distances using the application programming interface (API) of Heidelberg Institute for Geoinformation Technology (2020). This API searches for the fastest route for each OD-pair when considering the currently available road and ferry network. Finally, the high-speed rail infrastructure network is based on the Trans-European Rail network vision of European commission (2013) and the on this elaboration by Donners (2016). The central assumptions in this HSR network follow from the interoperability, the unconstrained capacity and the existence of infrastructure which is not always yet built. The length of each edge was found by converting the road distance, where a 0.91 detour factor is assumed for the HST when compared to the car (Donners, 2016).

Modes: Travelling between the vertices with one of the three modes results in different durations for the five main time elements of a trip, as introduced in *subsection 3.1.3*. The car has the most straightforward profile, as access/egress times, waiting times and transfer times are considered to be irrelevant. This makes that the in-vehicle time follows the actual travel time along the edge, which is supplemented with a rest factor of 10 %. Air travel times were composed of the city-specific access/egress times that differed per destination and a waiting time of 110 minutes (check-in, security, etc.). The in-vehicle times of this mode were estimated based on observed flights, which gave a cruising speed of 850 km/h and fixed take-off/landing and taxi procedures comprising 30 minutes and 50 km each. Finally, high-speed train trips are estimated by city-specific access/egress times, waiting times of 15 minutes and transfer times of 60 minutes (-50 % for a centralised organisation, as explained in *section 4.2*). Following this, the in-vehicle time per edge was composed using an average cruising speed of 275 km/h (Campos and de Rus, 2009), an acceleration constant of 0.3 m/s^2, a deceleration constant of 0.5 m/s^2 Connor (2014) and a dwell time of 5 minutes per stop. Furthermore, the trains are characterised by a capacity of 350 seats each (Campos and de Rus, 2009).

Stakeholders: The objective function represents the interests of three stakeholder groups: the '*user*', '*operator*' and '*society*'. The user's goal is to minimise its costs when travelling through the network. To translate these travel times to a monetary value, the value of time (VoT) is introduced. Following the VoT findings for long-distance transport in The Netherland of Kouwenhoven et al. (2014), but correcting for inflation, wealth differences and uncertainties, this value is estimated at 50 €/h. In addition, the VoT also varies along the stage of a trip. For this, the weights as found by Ramjerdi (2010) are applied. This brings VoT's of 50 €/h for the in-vehicle phase, 67.5 €/h for access and egress times and 75 €/h when waiting or transferring.

The operator's two main expenses are approximated by the averaged seat-km (marginal) values as identified Campos and de Rus (2009), which gives that $c^{oper,marg} = 0{,}130$ €/seat-km and $c^{main.marg} = 0{,}0122$ €/seat-km (which are both reduced by 20 % for the free market governance scenarios, as will be explained in *section 4.2*). Additional costs to be considered follow from the required number of vehicles to operate the network. These higher due to the improvement of a contingency factor of 1.1, a turn-around time of 30 minutes and limitation of operational time (18 hours/day)

Finally, the negative impacts of transportation on its surroundings are expressed in the external costs. Following CE Delft (2019), seven main externalities for long-distance transport are considered: '*accidents*', '*air pollution*', '*climate*', '*noise*', '*congestion*', '*well-to-tank*' and '*habitat damage*'. Considering each of these factors for the three relevant modes gives total values of $c^{ext}_{air} = 4{,}3, c^{ext}_{HSR} = 1{,}3$ and $c^{ext}_{car} = 12{,}1$, all in €-cent/pkm

Constraints: The parameterisation of the constraints (*section 3.1.4*) was focused on a balance betweem realism and freedom for the model. This resulted in minimum line length $ln^{str.min}_{l_k} = 200km$, a minimum number of stops $n^{stops.min} = 3$, a maximum round trip time $t^{rt,max} = 18h$ and a minimum frequency $f^{min} = 1$ for activated lines.

Demand Estimations: Due to the complexity of accurately estimating the demand for long-distance transportation using socio-demographic characteristics, it was opted to use observed travel data of the airline industry in 2019, as collected by Eurostat (2020). However, three main challenges have to be overcome: firstly (1), the observed flows only represent traffic between airport-pairs, rather than city-pairs. Secondly (2), the airports are frequently part of more complicated multi-airport-city systems, which makes that their traffic cannot be 1-on-1 assigned to a specific city. Thirdly (3) it should be noted that air traffic only represents a portion of the total demand and that this portion varies per OD-pair, mainly depending on the level of services (travel time) compared to other modes.

The raw air traffic flows were transformed using a novel methodology that fits the expected travel behaviour between each city-city pair to the relevant airport-airport traffic flows. This was done by (1) determining the city-airport systems, (2) making an inventory of possible flight paths between city-city pairs, (3) estimating the possibility of each flight to be taken and (4) comparing the averaged flight with other modes to compare its competitiveness. Following this, (5) the observed airport-airport demand volume was assigned to city-city pairs based on the likeliness of their route and the competitiveness to other modes. Finally, this air demand between city-pairs was extrapolated using the findings of Donners (2016) on the expected market share for air traffic per distance unit. Together, the operations produced an OD-matrix for long-distance travel demand between all of the 124 cities.

The demand estimation resulted in a total number of $2 \cdot 1{,}07 * 10^6$ trips per day within the network, with demands ranging between a maximum of $(2 \cdot 1{,}03 \cdot 10^4)$ and a minimum of $(2 \cdot 4{,}80 \cdot 10^-1)$ passengers per day per OD-pair. Across the network, flows were observed for 5.174 out of 7.688 possible OD-pairs. To decrease the computational burden of the problem, only the largest OD-pairs - together comprising 90 % of the network's demand - were considered. In this case, this resulted in all ODs having a demand smaller than approximately $2 \cdot 20$ passengers per day to be eliminated. Together, this made that only 985 OD-pairs had to be evaluated.

3.4. *Experimental Set-up*

Having a fully developed HSR-adaption of the TNDSFP and associated solution strategy, combined with a case-specific parameterisation, it became possible to initialise the model for research purposes. This section discusses the experimental set-up of this research. First, *section 3.4.1* presents the implementation characteristics and the performance that the model was able to reach in a small test. Following this, the results were validated on feasibility in *section 3.4.2*, which led to the retrospective introduction of strategic pricing. Finally, *section 3.4.3* sets out the expermiments that were performed to answer the research question.

3.4.1. *Model Implementation and Performance*

The implementation of the model and its solution strategy were written in '*Python 2.7.16*' using the environment of '*Spyder 3.3.6*', which was verified by continuous checks. All tests were performed using single personal computers with an Intel(R) processor, Core(TM) i5-8500, 3.00 GHz and 16 GB RAM memory. To evaluate this computational performance, the algorithm was executed for a smaller problem (Germany: seventeen cities, eighteen possible lines) and compared with an exhaustive search. The exhaustive search required 10.486 seconds to examine all possible line configurations, whereas the heuristic managed to reach this global optimum in 379 seconds, thus reducing the computational time by a factor 28. Further examination showed that using '*line activation*' only (operation 6. and operation 7.), it was possible to reach an objective value performance of 99.4 % in only 101 seconds, hence reducing the computational time by a factor 104.

Performing the simulation for a large scale problem (Europe: 124 vertices, ~2·5000 OD demand flows, ~7000 feasible lines), it was found that the computational burden became too large, with an estimated running of 70 years per simulation. To reduce the size of the problem, three previously mentioned measures were taken. Firstly (1), the number of lines was reduced by assigning 50 key-vertices (37 capitals and 13 cities important by geography or size, see mysectionLGPref); secondly (2), a further reduction was made by the strategic elimination of lines (-50 %, see mysectionLGPref) and thirdly (3), only the top 90 % of the demand was considered (see *section 3.3* on '*demand estimations*'. Together, the measures resulted in a problem of 124 vertices, with approximately 2·1000 demand flows and 350-400 possible lines. The heuristic search required approximately 3-5 days to complete these simulations, depending on the extensiveness of the final network.

3.4.2. *Result Feasibility and Passenger Path Control*

Using standard parameterisation (*section 3.3*),it was seen that simulations were not able to develop into an integrated network, leaving the continent with multiple not-connected sub-networks. Observing relatively high degrees of network completeness and direct passengers within these sub-networks, it was concluded that this standard parameterisation leads to a barrier which prevents the operator from connecting the sub-networks.

The cause for this behaviour was searched into two types of disadvantageous passenger paths: those that make a detour to avoid (1) geographical barriers (oceans/mountains) and those that make an (2) infrastructural detour (both in distance and time) from their shortest paths. Characteristic for these paths is that they provide the user with fewer benefits, whilst imposing higher operator costs, thus decreasing the cost/benefit ratio. To solve this, three possible solutions were proposed: (1) forceful subsidisation, (2) altering transfer characteristics (transfer time and the maximum number of transfers) and (3) strategic pricing (spilling unprofitable passengers).

Testing the potential solutions showed that all options contributed to a better network integration. Comparing the overall impact of the solutions, strategic pricing was considered to be most desirable due to its elegance, as it explicitly impacts the passengers of interest. This led to the inclusion of the infrastructural strategic pricing level constraint of *Equation 16* and the geographical strategic pricing level constraint of *Equation 15*. Analysis on these factors, as will further be discussed by *Table 5* in *section 4.3*, showed the effectivity of intensifying the exclusion of infrastructural detouring passengers to a value of $fac^{SPL,infra} = 1{,}05$. Opposed to this, the relaxation (up until $fac^{SPL,geo} = 1{,}25$) of the geographical detour exclusion constraint gave better results, meaning that the effectivity of this exclusion strategy cannot be confirmed. Additional to this, the same analysis demonstrated the positive impact of limiting the number of transfers to one. Regarding the alteration of transfer time, no pattern of for strategic passenger selection could be identified.

3.4.3. *Experiments*

With all previous steps, it becomes possible to perform experiments that can provide the insights that are necessary to answer the research question, that was concerned with the potential contribution of improved design for line configurations as well as understanding on how these networks look like. The analyses are structured under four experiments, that each consist of one or more strategically chosen scenario simulations. Below, an overview is given:

- **Experiment 1:** Estimation of the current network's characteristics and performance
- **Experiment 2:** Analysis on pricing and governance strategies *(Alterations on objective weights and governance related parameters)*
- **Experiment 3:** Analysis on high-speed rail design variables *(Alterations on vehicle, passenger path and line design variables)*
- **Experiment 4:** Assessment of synthesised scenarios and comparison with initial standard

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4. RESULTS

Results of the experiments as defined in *section 3.4.3* are stated in this chapter, to ultimately answer the research question. First *section 4.1* ('*Experiment I*)' presents the simulation of the initial network, such that later scenarios can be compared. Following this, *section 4.2* discusses the analysis on the impact of pricing and governance strategies ('*Experiment II*'). Continuing, *section 4.3* on '*Experiment III*' assesses the relative importance of the HSR design variables in vehicle characteristics, passenger paths restrictions and line design features. Finally, *section 4.4* ('*Experiment IV.*') constructs two synthesised scenarios based on learned lessons, which allows to determine the potential contribution and design characteristics of improved design for line configurations, when compared to the initial situation.

4.1. *Benchmarking the Initial Performance*

'*Experiment I*' (defined in *section 3.4.3*) concerned the estimation of the network's performance and characteristics for the initial conditions, such that it could be used as a benchmark for further comparisons. These initial conditions were determined to be characterised by the standard case study parameterisation of *section 3.3*, the EU's believe in a competitive railway market (thus '*Free market*' governance structure) and a pricing environment where societal costs are not internalised ($\psi^{user} = 50$, $\psi^{operator} = 50$, $\psi^{society} = 0$). Both of these governance and pricing strategies are further contextualised in *section 4.2*.

The results of the simulated network are stated in the first '*Initial*' column of *Table 6* (descriptive KPIs) and *Table 7* (stakeholder-financial KPIs). An analysis of these number indicates that this scenario has been able to develop into a well functioning HSR system, given its positive cost-benefit ratio of € 24.9 million per day and its considerable HSR-trip substitution of 14.7 %. However, fluctuating behaviours were observed when visually analysing the network. It reached all parts of the network to a certain extent, with 89 of124 cities connected), but still experienced difficulties in connecting sub-networks despite the introduction of strategic pricing (*section 3.4.2*). Something that is confirmed by the low share of transfer passengers ($t_1 = 7{,}5\,\%$, $t_2 = 0{,}5\,\%$). This first simulation is not yet enough to define the typical characteristics of an HSR system, but should rather be seen as a lower boundary for later comparisons. A further analysis of the network's characteristics is stated in *section 4.4.2*.

TABLE 4: EFFECTS OF PRICING GOVERNANCE STRATEGIES

	1. Liberalisation	**2. Total Welfare**	**3. Total Welfare**	**4. Mobility**	**5. Sustainability**	**6. Future Proof**
ψ^{User}	50	33	33	50	25	38
$\psi^{Operator}$	50	33	33	25	25	25
$\psi^{Society}$	0	33	33	25	50	38
	Free market $C^{operator} - 20\,\%$		**Centralised organisation** $t^{transfer} - 50\,\%$			
Number of lines	96	100	100	123	130	143
Connected vertices	93	100	100	105	107	109
Reachable ODs	76	119	100	165	173	169
Centre focused	97	99	100	100	103	102
Total benefits	92	113	100	92	97	97
User Benefits	90	97	100	114	115	117
Operator costs	85	84	100	143	143	143
Societal Benefits	84	101	100	127	134	129
Available seat km	85	105	100	143	143	143
Avg. load factor	97	97	100	95	102	97
Avg. line length	105	108	100	109	99	106
Avg. no. stops / line	100	103	100	108	103	110
Avg. freq. / line	86	92	100	102	107	92
Modal split air	102	100	100	96	94	95
Modal split HSR	85	102	100	125	131	128
Modal split car	105	100	100	92	91	92
Avg. HSR trip dist.	97	101	100	108	110	108
Share direct pax	111	105	100	93	87	96
Share 1-trf pax	48	84	100	129	162	118
Share 2-trf pax	28	40	100	171	155	103
Revenue pax km	82	102	100	136	145	138

Explanation: Normalised development of KPIs for policy alterations, indexed (100) at '3. Total Welfare (CO)' scenario

4.2. *Effects of Pricing and Governance Strategies*

To test the effect of different pricing policies and governance strategies, six diverging scenarios (see top rows of *Table 4*) were simulated in '*Experiment 2*' (see *section 3.4.3*). The two main governance structures are defined as the '*free market*' (sc. 1,2), which benefits from competition and subsequent cost-efficiencies, and the '*centralised organisation*' (sc. 3,4,5,6), that benefits from better network integration with shorter transfer times. Different pricing scenarios were resembled by the adjustment of weights (ψ) in the objective function. These weights ranged from the non-consideration (sc. 1), actual internalisation (sc. 2,3) and active subsidisation/taxation of societal costs (sc. 4,5,6). Combining the governance and pricing strategies gives twelve potential scenarios. However, given the unlikeliness of heavily subsidised private entities or neglected societal costs in centralised systems, a selection was made. The observed relations to the KPIs for altering design variables are given in *Table 4*.

Governance: Isolating the divergent characteristics of governance strategies, as can best be seen in scenarios 2 and 3, indicates a stronger cost-efficiency of a free market (total benefits), whilst offering relatively similar extensiveness (RPK, no. of lines, connected vertices) and performance (user & societal benefits), when compared to the centrally organised network. The benefits of the free market scenario mainly find their origin in the substantial reduction of operator costs. However, it should be noted that the magnitude of this difference follows the arbitrary reduction of 20 % in operator costs, although this nevertheless indicates a relatively substantial increase of efficiency for a small compromise in network performance.

Pricing: Concerning differences in pricing policies, it is seen that the internalisation of external costs induced a strong growth in the extensiveness (ASK, RPK, number of transfer passengers) and the performance (user & societal benefits) of the network. However, mixed results were found for the ratio between costs and benefits (thus total benefits). In the free market scenarios (1,2), the inclusion of societal interests in the design considerations leads the development past a design barrier, hence allowing for a more extensive network. This extended network is then able to take advantage of a better integration KPIs (more transfer passengers, higher load factors), which induces a better cost-benefit ratio. For the centralised scenarios, different behaviour is seen. Enlarging the interests of users or society leads to the inclusion of lines that are not necessarily the most cost-efficient, but that do contribute to the pursued policy goals (sustainability, mobility or social cohesion). The reduction in total benefits is a lot smaller than the increase in user and societal benefits, indicating a positive rate of return, which will be further elaborated in *section 4.4.3*.

4.3. *Importance of HSR Design Variables*

To define the importance of design variables, an analysis was performed on multiple parameter settings in '*Experiment 3*' of *section 3.4.3*. An overview of the observed relations is displayed in *Table 5*. The studied parameters are stated on the vertical axis, whereas the effect on KPIs, as related to goals associated with HSR, are stated on the horizontal axes. The relation values in the table indicate the average expected change for the base value of the KPI when changing the design variable by the defined interval. An exemption applies to those values that reached a peak value (optimum), which are indicated with an asterisk. Here, the KPI changes with the relation value by every interval step from the peak. Below, the vehicle, line and passenger path features are discussed.

Vehicle Characteristics: Altering the characteristics of high-speed trains resulted in the unambiguous patterns of the first to rows in *Table 5*. Increasing the cruising speed allows for a higher level of service, thus contribution to all policy goals. Opposing to this, a higher seating capacity makes it harder for the operator to accurately assign capacity, resulting in a lower performance and a smaller

TABLE 5: MEASURED RELATIONS BETWEEN HSR DESIGN VARIABLES AND KPI CONTRIBUTION TO POLICY GOALS

						Operator (cost-efficiency)				User (mobility)			User (soc. cohesion)			Society (sustainability)		
						Total costs savings	**Operator costs**	**Avg. load factor**	**Share transfer pax**	**User costs savings**	**APK HSR**	**Share direct pax**	**No. connect cities**	**Reachable ODs**	**No. of lines**	**Societal costs savings**	**RPK HSR**	**% HSR**
	Parameter	**Unit**	**Range**	**Interval**	**Base→ Peak⋆ ↓**	$€ 2-2{,}5 \cdot 10^7$	$€ 2-3{,}5 \cdot 10^7$	$60-65\,\%$	$10-20\,\%$	$€ 3-4 \cdot 10^7$	$275-625 \cdot 10^6 km$	$80-90\,\%$	$90-115 (of 124)$	$400-1150 (of 1300)$	$50-90$	$€ 1-1{,}5 \cdot 10^7$	$175-375 \cdot 10^6$ km	$15-30\,\%$
Vehicle	**Cruising speed**	$[km/h]$	225-375	50	*n/a*	1.276	1.145	1.002	1.213	1.238	1.145	0.946	*Var.*	1.070	1.021	1.090	1.148	1.102
	Seating Capacity	$[seats]$	350-600	50	*n/a*	0.994	0.963	0.994	0.947	0.980	0.963	1.013	0.985	0.937	0.950	0.964	0.958	0.966
Passenger Path	**Max. no. of transfers**	$[trf.]$	0 - 2	1	⋆1	0.970⋆	1.087	0.945⋆	*Var.*	0.968⋆	1.087	*Var.*	0.990	1.233	0.939⋆	0.903⋆	0.887⋆	1.089⋆
	Avg. transfer time	$[min]$	15 - 60	15	⋆30	0.979	0.917	0.997	0.722	0.945	0.917	1.070	0.952⋆	0.915	1.017	0.931	0.913	0.934
	Geo. detour excl.	$[-]$	1.05-1.25	0.05	*n/a*	1.106	1.107	1.008	*Var.*	1.110	1.107	*Var.*	*Var.*	1.162	*Var.*	1.097	1.117	1.114
	Infra. detour excl.	$[-]$	1.05-1.25	0.05	*n/a*	0.974	1.030	1.003	1.066	*Var.*	1.030	0.983	*Var.*	1.059	1.016	1.022	1.033	1.022
Line Design	**Min. no. of stops**	$[stops]$	2 - 6	1	⋆3	0.924⋆	*Var.*	0.955⋆	0.886	0.962⋆	*Var.*	1.029	*Var.*	*Var.*	0.925⋆	0.976⋆	*Var.*	0.975⋆
	Usage detour factor	$[-]$	0 - 1	0.125	⋆0,125	0.987	0.977⋆	0.996	1.017	0.986⋆	0.964⋆	0.996	*Var.*	0.983	0.980	0.983⋆	0.980⋆	0.985⋆
	Geo. detour constraint	$[-]$	1.25-1.75	0.25	*n/a*	1.009	1.017	1.008	0.844	1.015	1.018	1.040	1.048	1.048	1.150	1.013	1.025	1.017
	infra. detour constraint	$[-]$	1.25-1.75	0.25	⋆1,50	0.984⋆	0.986⋆	1.001	0.977	0.985⋆	0.986⋆	1.006	0.976⋆	0.989⋆	1.050	0.985⋆	0.987⋆	0.988⋆

- Explanation: Base value is expected to change with the relation factor when increased by the interval of the parameter
- Special case - peak⋆: Base value reaches top at peak and changes with same relation⋆ factor in both directions
- Special case - var.: no clear pattern could be identified.

network. Both effects for vehicle speed and capacity an be expected to be tempered in further and more detailed design stages, as faster vehicles increase for example acquisition costs, whilst the inclusion of heterogeneous vehicles or economy of scale advantages might favour larger vehicles.

Line design: The lower rows of *Table 5* present the adjustments in the lines that compose '*Pool of Lines*' (*section 3.2.2*), from which the model was allowed to select lines. The most important observation regards the usage detour. Here it is seen that the inclusion of slightly demand-based lines in the LGP ($fac^{dt,dm} = 0{,}125$) is beneficial to most user and societal goals, although it also comes at the cost of operator efficiency. Further examination highlights the performance peak when constraining the minimum number of stops to three (two terminal stations and one intermediate) per line, though it should be mentioned that 2-stop lines might still be beneficial when added to the pool of lines, as they currently mostly replace 3-stop lines following the character of the line reduction of *section 2*.

The alteration of the infrastructural line detour constraint (*Equation 9*), an optimum at the a value of $fac^{dt,infra} = 1{,}50$ was found. Here, a lower factor would mainly exclude beneficial routes (given the reduced network development) and higher factor would result in a lower operator efficiency (given the larger number of lines between a smaller number of vertices). Finally, the geographical line detour constraint (*Equation 10*) showed to be nonrestrictive when set at $fac^{dt,geo} = 1{,}50$. Intensifying to $fac^{dt,geo} = 1{,}25$ resulted in a deterioration of both the descriptive KPI performance, as well as the cost-efficiency, thus indicating that it is best to disregard this constraint.

Passenger path features: In *section 3.4.2*, the necessity of passenger path control was demonstrated by the development of non-connected '*sub-islands*' in unrestricted simulations. The same section also provided a context to the findings of *Table 5*.

4.4. Potential Impacts of Improved Design

The final experiment, '*Experiment 4*' as defined in *section 3.4.3*, uses the lessons from previous experiments to determine the typical design characteristics and potential impact of improved HSR line configurations. First, *section 4.4.1* defines these improvements to be made. Following this, *section 4.4.2* analyses the resulting networks on their lay-out to find how a typical strong-performing network looks like, after which the *section 4.4.3* concludes by examine and compare performance that the networks are able to provide to each stakeholder.

4.4.1. Proposed Synthesised Network Settings

To assess the potential contribution of a well-designed HSR system in the European context, two synthesised scenarios were defined and tested. These scenarios find their base in the standard parameterisation of *section 3.3* - as this tried to describe reality - but are adjusted for the lessons learned from the previous analyses, which are comprised in the following adjustments: First of all, both scenarios were limited to a maximum of one transfer per path, whilst the geographical detour path constraint of *Equation 10* was released. Furthermore, it was chosen to set the geographical strategic pricing level to the tested upper limit ($fac^{SPL,geo} = 1{,}25$) and the infrastructural strategic pricing level to the tested lower limit ($fac^{SPL,infra} = 1{,}05$)

The first scenario, '*Economical*', described a low-effort solution that aims for a high cost-efficiency. This holds a '*free market*' governance structure (-20% operator costs) with an equal distribution of objective function weights, thus $\psi = 33{,}3$ for all stakeholders. moreover, this scenarios is characterised by a shortest path-based lines only ($fac^{dt,dm} = 0{,}00$). The second scenario, '*Extensive*', works from a '*centralised*' governance structure (-50% transfer time), which is actively subsiding for user and societal benefits ($\psi^{user} = 37{,}5$, $\psi^{operator} = 25{,}0$, $\psi^{society} = 37{,}5$). Here, the pool of lines is supplemented with demand based-routes ($fac^{dt,dm} = 0{,}125$). The results of the simulated network are stated

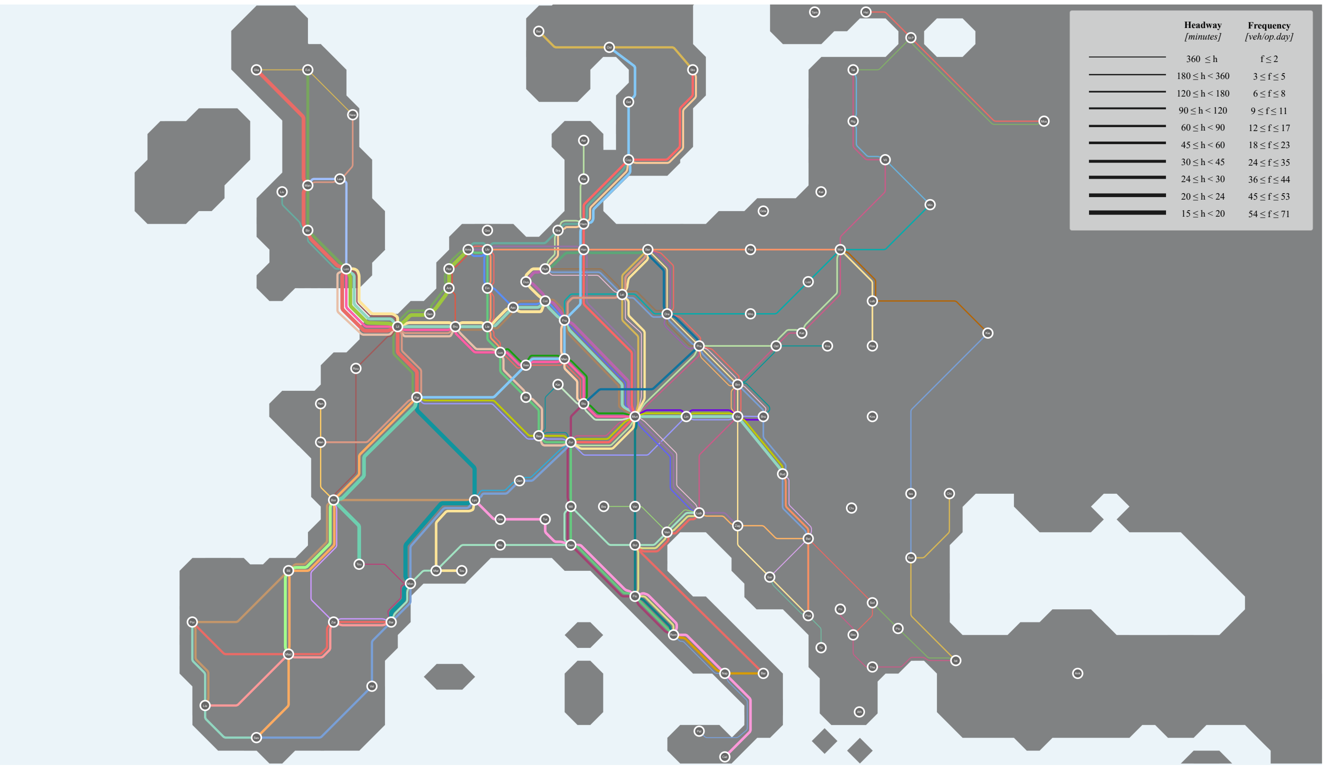

Fig. 5: Transit map of the extensive HSR network

in the second '*Economical*' and third '*Extensive*' column of *Table 6* (descriptive KPIs) and *Table 7* (stakeholder-financial KPIs). These values are used as a basis for further analyses.

4.4.2. *Design Characteristics of Resulting Networks*

The simulation of the initial (*section 4.1*) and improved (*section 4.4.1*) networks led to the observation of multiple recurring patterns in their network design. All scenarios resulted in functional high-level networks with similar shapes, although deviating in more characteristic details. A visualisation of the resulting line configuration for the extensive scenario is presented in *Figure 5*, where colours are used to distinguishes for lines and where widths indicate their associated frequencies. The map provides insights in the dimensions of the network, as well as in the focal points, which are comparable for each of scenarios. Most notable is that the majority of lines that are visiting multiple countries, which indicates the importance of interoperability and cross-border cooperation, as these are justified by the transport demand patterns. Furthermore, it can be seen that most connected cities serve a certain degree of transfer passengers, although the network also focuses its lines towards specific hubs, of which Munich is the strongest example. Below, the design aspects over the lines and the networks they make are further discussed.

Network design: All three simulations have a development of lines throughout the continent, but also show a similar decisions on the exclusion of cities or regions that don't justify connections because of their demand or geographical characteristics, as can for example be seen in in *Figure 5*. Visually analysing the networks resulted in tree main aspects. Firstly (1), it is seen that network density increases towards the geographical centre of the map, in this case Germany. Especially Munich was consistently assigned with a hub function, followed by the other predominant German cities and more peripheral focal points like London, Lille, Bordeaux, Bologna, Copenhagen, Zurich, Warsaw, Budapest and Bucharest. This indicates that hubs are not only the largest cities, but also those strategically located. Secondly (2), it was observed that the network extensiveness and density are slightly skewed to the west, given the lower demand in Eastern Europe. Thirdly (3), it was seen that frequently unvisited cities are those with a lower demand which are not located between at least two higher demand cities (e.g. Rouen, Toulon, Groningen & Gdansk). This explains that these cities do not provide enough aggregated demand to justify a separate line.

Line design: In the observed networks, four recurring line types were distinguished: First (1), all networks accommodate 5-20 (depending on the extensiveness) relatively long lines (length >1000km; number of stops >6) that can frequently sustain hourly services (~18 veh/dir/day), the so-called '*main arteries*'. These lines are selected during the early phase of development and follow routes with relatively high and stable demands along the visited vertices, such that they benefit from so-called '*roof tile effects*'. Following this, the majority of lines have a shorter profile (length <1000km), which can be further subdivided into three categories. The second (2) type of line strategically connects to the main arteries, such that new cities are linked to the network. A decision which is justified by the aggregated demand related to these newly introduced cities. The third (3) line category concerns lines that produce enough demand by themselves, which means that they are found in both low- and high-density areas. Finally, a fourth (4) category is described as additional lines, which primarily follow a one or a few legs of a main artery, to allow for the more specific assignment of seating capacity. An overview of line characteristics is found in the middle rows of *Table 6*.

TABLE 6: SYNTHESIS NETWORK CHARACTERISTICS

	Unit	Initial	Economical	Extensive
Number of lines	[-]	54	83	91
Connected vertices	[-]	89	110	116
Reachable ODs	[-]	396	944	1148
Min. line length	[km]	272	200	200
Avg. line length	[km]	738	834	831
Max. line length	[km]	1747	2039	1950
Min. no. stops/line	[$seats$]	3	3	3
Avg. no. stops/line	[$seats$]	4.00	4.6	4.7
Max. no. stops/line	[$seats$]	11	12	12
Min. freq./line	[veh/day]	1	1	1
Avg. freq./line	[veh/day]	9.2	9.1	11.0
Max freq./line	[veh/day]	37	47	65
Available seat km	[$10^6 km$]	277	499	633
Revenue pax km	[$10^6 km$]	168	300	378
Avg. load factor	[%]	60.5	60.0	59.7
Modal split air	[%]	62.1	56.5	53.5
Modal split HSR	[%]	14.7	25.0	29.9
Modal split car	[%]	23.2	18.5	16.7
Avg. HSR trip dist.	[km]	488	558.3	589.9
Share direct pax	[%]	92.0	87.5	77.8
Share 1-trf pax	[%]	7.5	12.5	22.2
Share 2-trf pax	[%]	0.5	*n/a*	*n/a*

4.4.3. *Potential Contribution of Improved Networks*

To find out how - and to what extend - the improved scenarios can potentially contribute to the policy goals of mobility and sustainability, they are compared with each other and the Initial scenario of the first experiment. This is done by first assessing the resemblances and differences on the multi-aspect performance by the descriptive KPIs, after which the financial-benefit implications for the three main stakeholders are examined.

Geographically dependent performance: The vertex and edge characteristics, resulting from the line configuration of the extensive scenario, are presented in *Figure 6*. In this map, the daily vehicle loads per edge, magnitudes of HSR traffic per city and modal split changes are provided. Striking observations are (1) the increased edge loads towards geographical bottlenecks (Iberian Peninsula, Great Britain, Scandinavia); (2) the relatively high HSR market share for intermediate cities (Bordeaux, Edinburgh, Glasgow, Bari and Lyon), which can be explained by the more locally-oriented demand patterns whilst being large enough to attract multiple lines; and (3) the smallest vertices, which have flows that are considerably smaller than the capacity of one train (Lublin, Tirana, Pristina). The fact that these smaller cities are being connected can be partially explained by roof tile effects in line occupation, but should also be sought in the model's limitations of limited pool size (where the line would ideally be one leg shorter, but which is not available) and the neglection of the smallest demand flows. It is seen that these practices are similar across the scenarios, relative to their extensiveness.

Variations of network extensiveness: Differences in the three networks were identified by extracting and assessing the descriptive KPIs, as presented in *Table 6*. The lower rows of this table show unambiguous results for a further network development along the scenarios. This is primarily confirmed by the increased revenue passengers kilometres (RPK; +26 %) and available seat kilometres (ASK; +27 %) when comparing the '*Economical*' to '*Extensive*' strategies; effects that are even bigger when comparing the '*Initial*' to '*Extensive*' scenarios, with a growth of +125 % for the RPK and +129 % in ASK. The higher connectivity values (number of lines, connected vertices and reachable OD's), as well as the increased

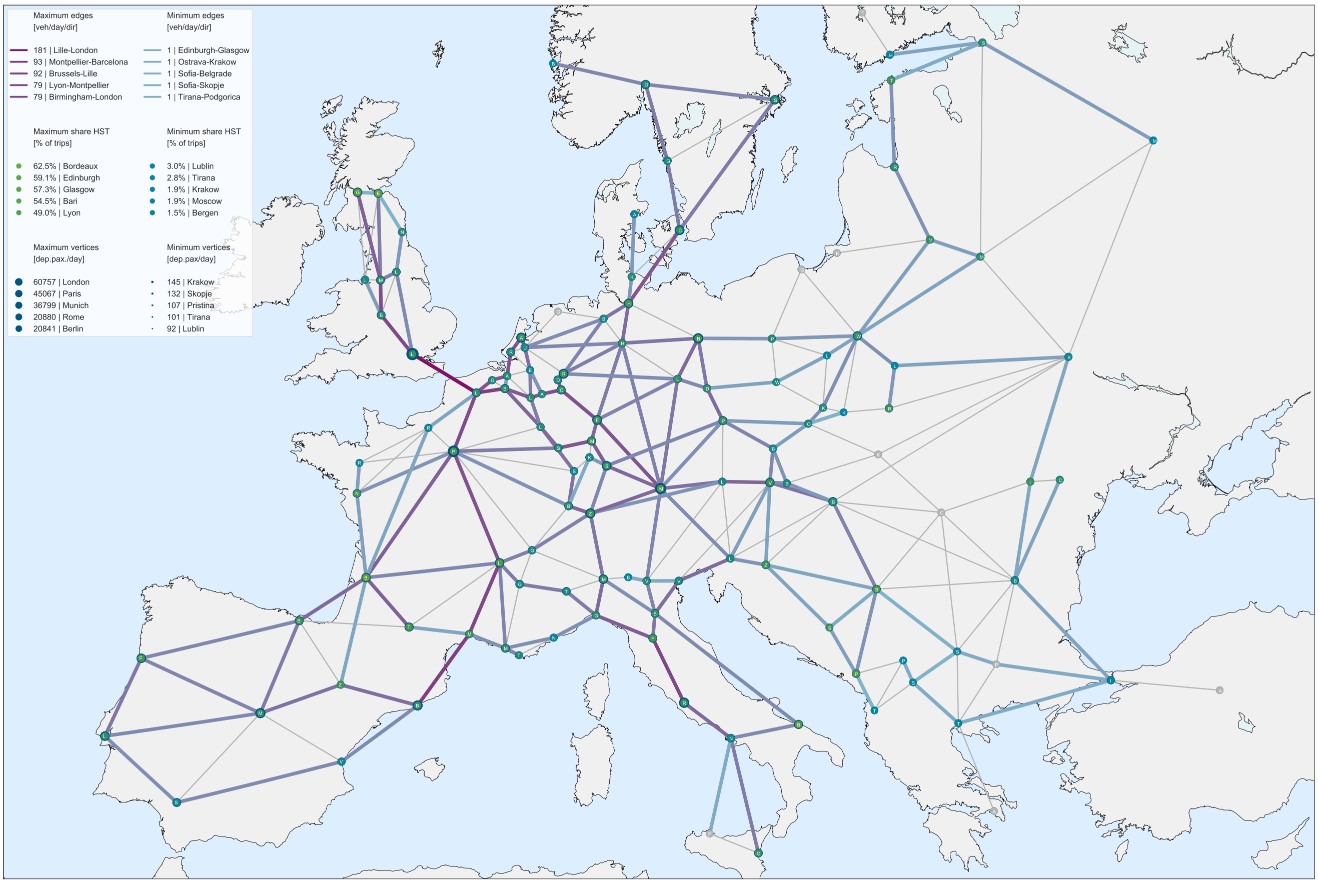

Fig. 6: Network characteristics of the extensive HSR network

share of transfer passengers, indicate that the above growth comes from a more wide-spread and integrated network. More transfer passengers would logically have positive results on the train occupation. However, a slight decrease of the average network load factor (ANLF) is observed ('*Economical*': -0.8 %; '*Extensive*': -1.3 %). This behaviour explains that the model has accepted less profitable routes (thus less competitive with other modes or fewer justification of train capacity) when internalising external costs, as it prioritises the benefits of users and society over the operator's interests.

Differences in induced modal shifts: Considering the competition with other modes, the simulations showed an HSR trip substitution potential of 14.7 % ('*Initial*'), 25.0 % ('*Economical*') and 29.9 % ('*Extensive*') respectively. The market share per distance distribution of this substitution is plotted in *Figure 7*, which shows that the HSR is especially competitive between 400-600 km. A comparison of the '*Economical*' and '*Extensive*' scenario shows that the latter is relatively strong on longer distances (600-1000 km), thus more competitive with air travel. Something which is confirmed by the increased average HSR trip distance (+5.7 %) in *Table 6*. This behaviour can be explained by the better network integration and coverage which allows for ease of travel on longer trips, but should also be sought in the underlying costs aspects. Therefore, a further analysis on these costs is done in the paragraph below.

Cost aspects and stakeholder benefits: To assess the previously mentioned costs aspects, the total expenses and benefits were separated for each stakeholder, further divided in subcomponents and presented in *Table 7*. From the user's perspective, benefits are primarily found for time savings in waiting (fewer air travel) and in-vehicle (fewer road travel) duration. Both factors strongly outweigh the newly introduced transfer times and increased access/egress times. This balance is again shifted towards longer HSR trips when applying the extensive scenario, as the costs associated with waiting times increase the most.

Concerning the societal (external) costs, the most substantial benefits of substitution towards HSR are found within the fields of accidents, congestion and climate. Especially the first two of these have a strong relation to the modal shift from the car, as high costs on these factors are characteristic of road traffic. This is confirmed when categorising the societal benefits per mode, which in a reduction of external costs that was mainly induced by substitution from car traffic (72 %) as opposed to air traffic (28 %). Together, the above indicates that, when aiming for larger societal benefits, most is to be won in the competition with automobile traffic. This also leads to the finding that most societal benefits are won in externalities of car traffic, which are not only environmentally related. *Table 7* shows that for a developed HSR network, only 31 % of societal benefits can be explained by environmental factors of air pollution, climate, habitat damage, noise. It leads to the conclusion that HSR can have even wider impact on society than what is most frequently argumented.

Finally, the benefits of user and societal interests come at the expenses of the operator, who is usually able to pass these costs through by the pricing of tickets. Aiming for policy goals (mobility, social cohesion or sustainability) rather then cost-efficiency, the '*Extensive*' scenario provides a less-beneficial cost-benefit ratio to the '*Economical*', mainly due to a sharp increase of operator costs, though still better than the '*Initial*'. This reduction compared to the '*Economical*' scenario is primarily explained by the lower load factor and the inclusion of less profitable lines.

Comparing the overall costs of the two improved scenarios, it is seen that the increase of user and societal benefits reaches 10.7 million euros per day. At the same time, this comes with a deterioration

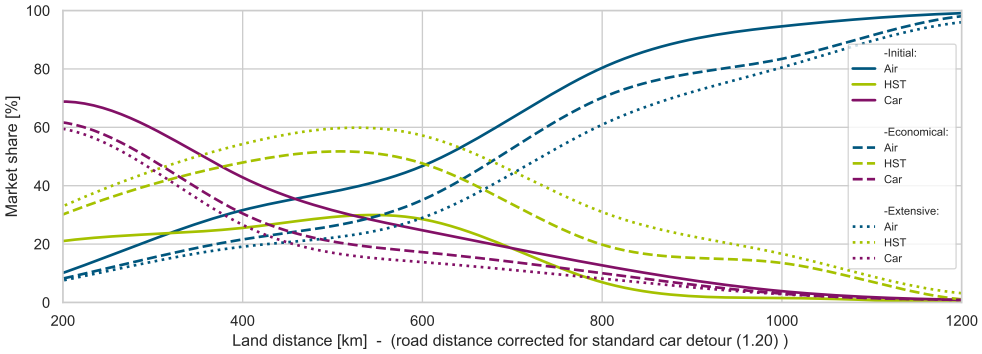

Fig. 7: Modal split per distance

of 5.9 million euros per day on the cost-benefit ratio. Combining these two values gives a rate of return reaching 1.8 when opting for active subsidisation with the defined weights and a centrally organised network. This effect can be expected to be even more substantial when considering secondary benefits of these policy goals. Concluding on that, it means that it should be a political decision whether the performance advantages outweigh the increased subsidisation costs and efforts for centralising and taxing.

TABLE 7: COST COMPONENTS OF SYNTHESISED SIMULATIONS

		Initial	Economical	Extensive
			All in [10^6 € per day]	
User	**Access & Egress**	3.0	4.0	5.1
	Waiting	-19.4	-28.7	-36.1
	In-vehicle	-16.5	-28.0	-30.0
	Transfers	1.9	4.7	5.4
	Sub-total	**-31.0**	**-48.0**	**-55.5**
Operator	**Operational**	14.7	25.8	41.0
	Maintenance	1.1	2.7	4.0
	Sub-total	**15.8**	**28.4**	**45.0**
Society	**Accidents**	-3.2	-5.1	-6.2
	Air pollution	-0.7	-1.2	-1.5
	Climate	-2.5	-4.4	-5.5
	Noise	-0.3	-0.5	-0.5
	Congestion	-3.1	-5.0	-6.0
	Well-to-tank	-0.5	-1.0	-1.2
	Habitat damage	0.6	1.0	1.5
	Sub-total	**-9.7**	**-16.2**	**-19.4**
Total costs (societal costs-benefit)		**-24.9**	**-35.8**	**-29.9**

5. CONCLUSION

This study formulated a customised version of and solution strategy for the '*Transit Network Design and Frequency Setting Problem*' (TNDFSP) in a long-distance transport environment for high-speed rail. This, to find the extent that the user, operator and societal performance of a European high-speed rail network be improved by centrally designed line configurations as well as pricing policies, and to find out such a network would look like.

Performing the above, this research contributed to the current state of knowledge in the field of HSR network design, by the exploring the interface of the research fields comprising HSR broad, general transit planning and strategic network planning research. Together, this ultimately led to the development of an HSR-adapted TNDFSP model, which was demonstrated to be useful for more specific design questions. With this, new ways were opened for further research and thus further understanding of HSR network design.

This study found, in *section 4.2*, that the internalisation of actual external costs results in an improvement of the network performance and policy goals of enhanced mobility, social cohesion and sustainability. Performing this in a free market governance structure results in the best cost-benefit ratio, which is in line with the EU's believe in a competitive railway market. However, centrally designing and organising the HSR network - in combination with actively subsidising and taxing for the user and societal interests - significantly increases the network performances and contribution to the previously stated policy goals. This latter decision comes with a reduced cost-benefit ratio - thus requiring governmental investments - but also allowed for a growth of user and societal benefits approximating 1.8 times this investment, resulting in a positive rate of return as demonstrated for the European case in *section 4.4.3*.

Regarding the features of lines, it was seen in *section 4.4.2* that typical improved network designs comprise a certain number of longer (1000km-2000km) and high frequency (>18 veh/h) lines, socalled '*main arteries*', often connecting multiple countries within the continent. The presence of such lines illustrates the importance of cross-border cooperation and rail interoperability. Furthermore, it was seen that not all cities nor countries were connected, as these are not justified from a network point of perspective. Both arguments plead for overarching design view, as history has shown that a lack of knowledge on HSR design and the national and company interests resulted in a patchwork of poorly connected sub-networks.

Following this, strategic pricing - thus the exclusion of unprofitable passengers by limiting the number of transfers and spilling certain detouring passengers - turned out to be indispensable for the development of a functioning HSR network, as demonstrated in *section 3.4.2* and numerically analysed in *section 4.3*. Such a pricing system requires a coordinated approach and therefore again benefits from improved cooperation.

Concluding, the above arguments describe a situation which - in contrast to the EU's believe in a free market and the current practice - favour a centrally organised network and the internalisation of external costs, as substantial opportunities were identified for the policy goals of mobility and sustainability. However, these advantages come with a governmental monetary investment, an increased effort for the interoperability of infrastructure and a decreased sovereignty of member states with the willingness to subordinate national interests. All in all, the decision for different governance and pricing strategies could be argued in multiple perspectives. However, the findings of this study shed a new light on the current practice and provide political discussion with additional arguments on how to design the most successful European HSR system.

Valuable further knowledge could be gained by future research that generically explores the vertical axis of transit planning, thus including - for example - the construction of infrastructure on one side, or the introduction of heterogeneous vehicles, the adaption of operational strategies or the inclusion of multi-modal trips on the other side. Additionally, knowledge in the field of this specific study could be enhanced by more diverse case studies, a higher detail level within the case or the introduction of innovative technologies.

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B

Demand Estimation Methodology

To provide the model with an overall long-distance transport demand that is based on revealed air transport demand and that respects the above-mentioned difficulties, the methodology of *Figure 4.13* is proposed. In this, the raw air traffic flows are transformed by fitting the expected travel behaviour between each city-city pair to the relevant airport-airport traffic flows. A brief rundown of elements of this methodology was already given in *section 4.6*. Below, a repetition of this run is discussed, after which all of the operations are discussed more thoroughly.

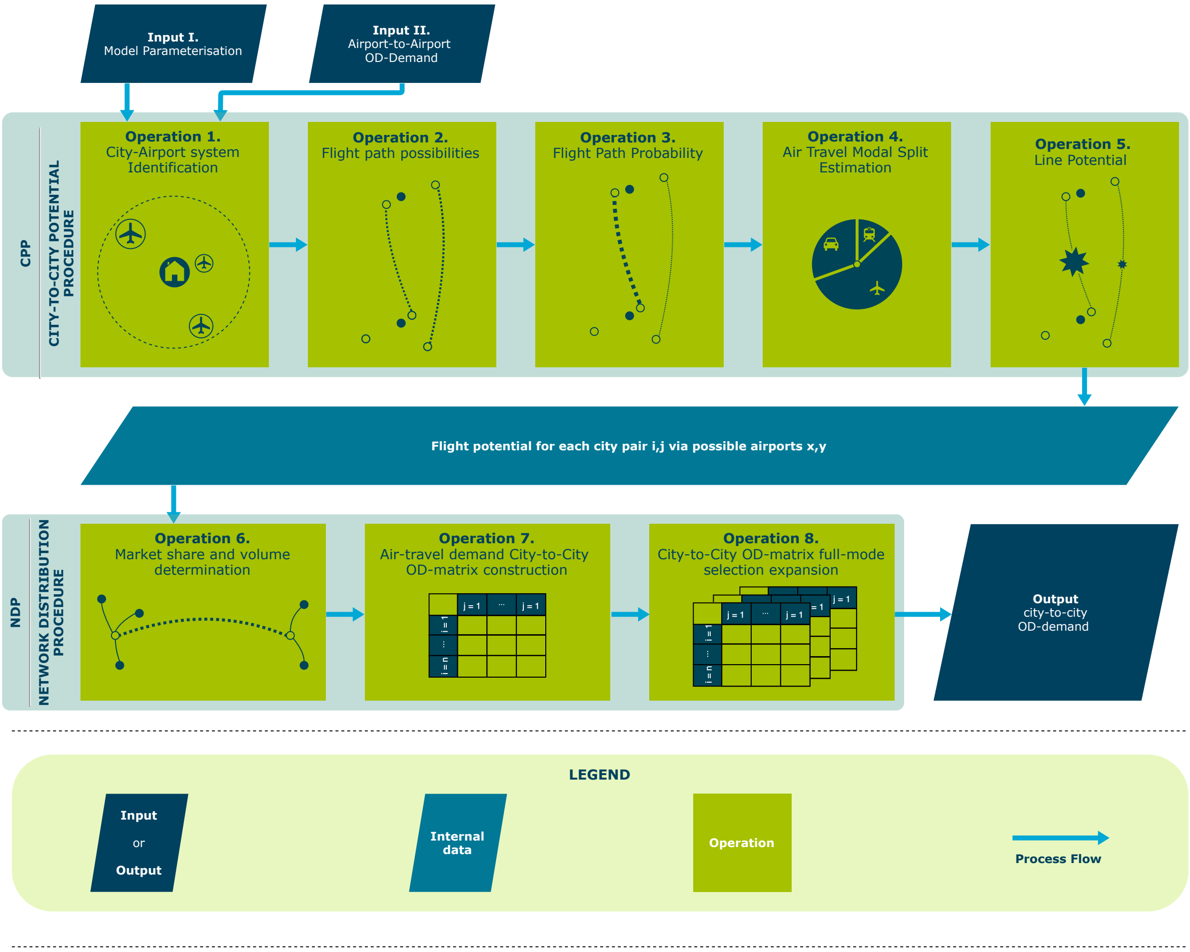

Figure B.1: Proposed demand estimation methodology

B.1. High-Level Methodology Walkthrough

The methodology starts at the upper left-hand corner in ‘*Operation 1.*’, where the city-airport systems are determined assuming a 2.5 hour catchment area. This is then followed by ‘*Operation 2.*’ where an inventory of possible flight paths between city-city pairs is made, considering both city-airport systems. Using a utility maximisation theory (based on access/egress times, border crossings and displaced vehicle time) estimations for the possibility of each flight to be taken are made for each city-city pair in '*Operation 3.*'. Subsequently, the average flight for such city-city pairs is compared with other modes (using the random regret theory as defined by Chorus et al. (2008) and applied to HSR by Donners (2016)) to determine its competitiveness and estimate a modal split. Following this, '*Operation 5.*' assigns a so-called '*potential*' to each flight leg, as can be expected from the travel times between the cities.

The methodology continues at '*Operation 6.*', where the determined traffic flow potentials are combined, such that it becomes possible to explain the percentage of traffic on a certain flight leg which is induced by the demand of a given city-city pair. Scaling this value to the observed travel flows on a flight leg as stated by Eurostat (2020a), an exact number of passengers using that flight whilst travelling between two cities can be estimated in '*Operation 7.*'. This results in an OD-matrix of air passengers between certain cities. Finally in '*Operation 8.*', this air demand between city-city pairs was extrapolated to an overall traffic demand using the findings of Donners (2016) on the expected market share for air traffic per distance unit. Together, the operations resulted in an OD-matrix for long-distance travel demand between all of the 124 cities.

B.2. Input Preparation: Air travel Demand Extraction

The goal of this preparatory step is to construct an Airport-to-Airport OD-matrix based on the questionnaire results regarding '*passengers carried*' as published by Eurostat (2020a). These questionnaire results are not fully complete, as some data of 2019 (Serbia and Sweden) has not been published yet or is not reported in the required level of detail (Slovakia).

Extraction of traffic flows:
The first issue was resolved by using 2018 data for these countries, whereas the second problem was evaded by excluding Slovakia from the data input. This is not expected to result in major discrepancies, as the missing data can be filled in by reported passenger counts from other countries towards Slovakia. This however does not work for countries that are in the model but did not report themselves (Russia, Belarus, Ukraine, Moldova).

OD-Matrix construction and adjustments:
Combining all questionnaires results, an OD-matrix between the 384 European airports is constructed. This matrix however, has three matters that have to be resolved: (1) some airport pairs are only reported from one side, meaning that $airport_x$ to $airport_y$ contains a value, whereas the other way around is empty. Following this (2), it is also seen that some airport pairs are both reported, but with slightly different values. Finally (3), the values in this matrix are '*number of passengers carried*', which includes both arriving and departing passengers.

One of the main assumptions in this thesis is a symmetrical demand, as was also stated in *subsection 3.1.2* on modelling simplifications. With this in mind, a procedure to symmetrise the air-travel OD-Matrix is performed. This procedure, as stated in *Equation B.1* takes the maximum value of passengers carried ($PAX^{carried}$) reported between two airports and divides it by two in order to split arriving and departing passengers.

$$DM_{x,y}^{air} = DM_{y,x}^{air} = \left(\frac{max\left(PAX_{x,y}^{carried}, PAx_{y,x}^{carried}\right)}{2} \right) \tag{B.1}$$

Resulting matrix:
The resulting matrix gives a numerical image of air-traffic flows within Europe. In this matrix, it can be found that the smallest observable flow consists of 5.171 passengers per annum between the Swedish airports of Stockholm-Bromma (ESSB) and Jönköping (ESGJ). Contrasting to this, the

largest passenger flow is found between the Spanish airports of Madrid (LEMD) and Barcelona (LEBL) with a yearly total of 1.286.446 passengers per direction.

B.3. City-to-City Potential Procedure

The first five operations of the proposed methodology concern the search towards a so-called '*city-to-city potential*', which is relative number that indicates the size of traffic between different cities and that allows for a comparison of different city trips. Obtaining this will ultimately allow to explain certain traffic on certain flight legs.

Operation 1: City-Airport-System Identification

In this operation, the access and egress times as determined in operation 2. (see *subsection 4.1*) are used to define which airports are considered as feasible options for air travellers originating from or destined to a certain city. Generally, most studies estimate the maximum access/egress time between 2.5 and 3.5 hours, depending on the distance of the planned flight trip. For this research it is chosen to assume a maximum perimeter of 2,5 hours, as the modelled flights only reach the area of Europe. The airports within this reach are considered feasible when considering a flight to any place, which make that together they make the city-airport system for a specific city. In *Figure B.2*, these systems have been visualised for London and Rotterdam.

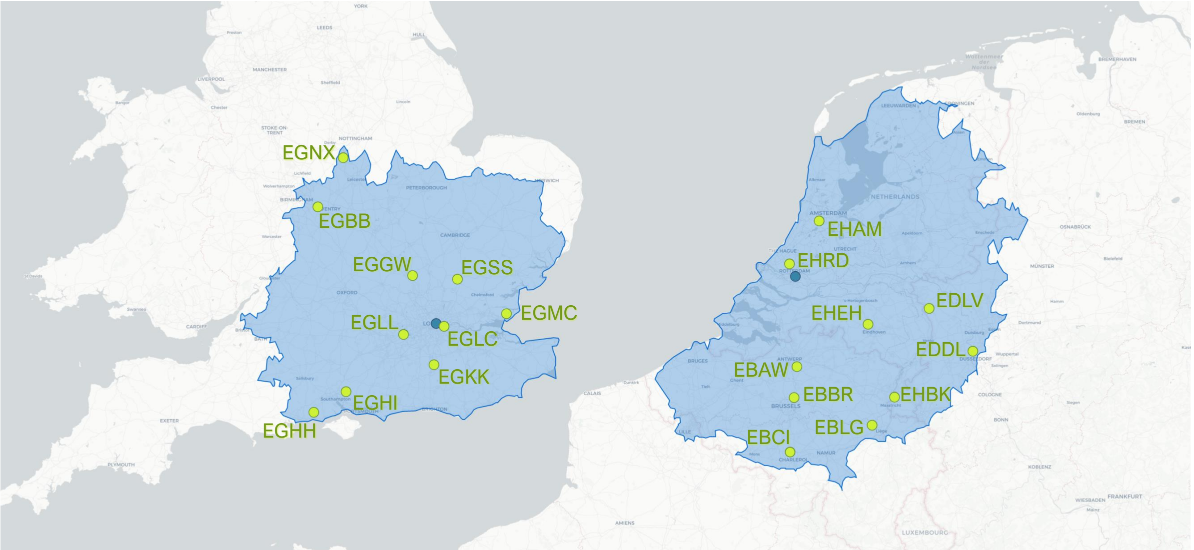

Figure B.2: City-Airport systems for London and Rotterdam (perimeter = 2.5 hours) (author's elaboration)

Table B.1: Access / Egress times London airport system by car in hours (extracted from Heidelberg Institute for Geoinformation Technology (2020))

	EGBB	EGHH	EGGW	EGKK	EGLC	EGLL	EGSS	EGNX	EGHI	EGMC
city-airport duration [h]	2:11	2:01	1:01	1:13	0:28	0:35	1:05	2:12	1:37	1:12

Table B.2: Access / Egress times Rotterdam airport system by car in hours (extracted from Heidelberg Institute for Geoinformation Technology (2020))

	EBAW	EBBR	EBCI	EBLG	EDDL	EDLV	EHAM	EHEH	EHBK	EHRD
city-airport duration [h]	1:21	1:37	2:14	2:22	2:28	2:02	0:45	1:25	2:16	0:09

Operation 2: Flight Paths Possibilities Assessment

After defining the city-airport systems for each of the cities, it is possible to evaluate which air connections are considered plausible when planning a flight trip. In *Table B.3*, this example is given for the previously mentioned city couple of London - Rotterdam.

Table B.3: Example flight path possibilities and duration between London and Rotterdam (author's elaboration, flight time estimations of *section 4.3*)

	EGBB	**EGHH**	**EGGW**	**EGKK**	**EGLC**	**EGLL**	**EGSS**	**EGNX**	**EGHI**	**EGMC**
EBAW	-	-	-	-	-	-	-	-	-	-
EBBR	1:26	-	-	-	-	1:19	-	-	-	-
EBCI	-	-	-	-	-	-	-	-	-	-
EBLG	-	-	-	-	-	-	-	-	-	-
EDDL	1:35	-	-	1:27	1:26	1:28	-	-	1,551	-
EDLV	-	-	-	-	-	-	1:22	-	-	-
EHAM	1:24	-	1:18	1:19	1:17	1:19	1:15	1:22	1:25	1:13
EHEH	-	-	-	-	-	-	1:18	-	-	-
EHBK	-	-	-	-	-	-	-	-	-	-
EHRD	-	-	-	-	1:15	-	-	-	-	-

Operation 3: Flight Path Probabilities Determination

Knowing the available flight paths and their associated travel times, the next step is to determine which of these flight legs are most likely to be used. This knowledge is acquired in multiple steps:

Aggregated and weighted travel time:
Using the four components of a standardised (non-transfer) flight trip, it becomes possible to construct an aggregated travel time for each of the possible paths. This aggregated and weighted travel time sums the different time components after scaling them to their relative value of time (VoT), which was previously discussed in *section 4.4* and for which the outcomes are briefly revisited in *Table B.4*.

Table B.4: Value of time for long distance travellers per trip component (based on Kouwenhoven et al. (2014) and **?** (**?**)) - (revisit of *Table 4.8*)

	access	**waiting**	**in-vehicle**	**transfer**	**egress**
Weight [-]	1.36	1.50	1.00	1.50	1.36
VoT [€/h]	67.5	75	50	75	67.5

Using these values in the formula of *Equation B.2* provides the aggregated and weighted travel time. The result of this operation for the previously used example of the Rotterdam-London city-pair is stated in the third column ('tt_w') of table *Table B.5*.

$$t_{i,x,y,j}^{tot,air,wgh} = \left(\xi^{acs} \cdot t_{x,i}^{acs}\right) + \left(\xi^{wai} \cdot t^{wai}\right) + \left(\xi^{inv} \cdot t_{x,y}^{inv}\right) + \left(\xi^{egr} \cdot t_{y,j}^{egr}\right) \tag{B.2}$$

Air path choice modelling:
The comparison and probability calculation of the different flights paths is done using a multinomial logit model that is based on the maximisation of the utility. From literature, it was found that for the choice modelling of airlines passengers, the access and egress times, the frequency and whether a border had to be crossed were the more important choice attributes (**?**, **?**; De Luca, 2009; Zijlstra, 2020). However, they were not previously combined and used for the determination of a flight path probability in this specific network manner.

It was therefore chosen for this study to formulate a utility function and to fit the choice attribute weights to the observed travel flows. The main formulation for this model is presented in *Equation*

B.3. Here, $U^{fp}_{i,x,y,j}$ represents the utility for choosing the flight path alternative that uses ap_x and ap_y when travelling between v_i and v_j. Following this, α^1 is the weight for the attribute access/egress time, α^2 is the weight for the attribute border barrier and α^3 is the weight for displaced schedule time.

$$U^{ffp}_{i,x,y,j} = \alpha_1 \cdot \left(t^{acs}_{i,x}\right) + \alpha_2 \cdot \left(t^{acs}_{i,x} \cdot BB_{i,x}\right) + \alpha_1 \cdot \left(t^{egr}_{y,j}\right) + \alpha_2 \cdot \left(t^{egr}_{y,j} \cdot BB_{y,j}\right) + \alpha_3 \cdot \left(t^{DST}_{x,y}\right) \quad \text{(B.3)}$$

where:

$t^{acc}_{i,x}$ = Access time between v_i and ap_x
$t^{egr}_{y,j}$ = Egress time between ap_y and v_j and
$B^{bor}_{i,x}$ = Border barrier between v_i and ap_x ; (0 if same country, else 1)
$B^{bor}_{y,j}$ = Border barrier between ap_y and v_j ; (0 if same country, else 1)
$DST_{x,y}$ = Displaced schedule time for route between ap_x and ap_y ; ($1/4$ of headway $h_{x,y}$)

The weights (α^1, α^2 and α^3) of this utility function define the relative importance between the choice attributes. These exact values are not known because of the new application and new utility function formulation of this methodology. To find the accurate values, it was chosen to fit the formula to the observed passenger flows. This was done by measuring the squared error of the formula estimation compared to these observed flows.

To test a range of values that cover the whole solution space, each of the three alphas was assigned with a value between 0 and 1, with an interval of $\delta = 0.1$. Combining all these values resulted in $11 \cdot 11 \cdot 11 = 1331$ possible configurations. Analysing these outcomes, for which every iteration took approximately 20 minutes, it was seen that the error value R ranged between $R^{min} = 5.0 \cdot 10^{11} minutes^2$ and $R^{max} = 4.7 \cdot 10^{12} minutes^2$ for the whole network. Averaging the 20 best solutions, it was estimated that:

$$\alpha_1 = -0.40 \quad \alpha_2 = -0.04 \quad \alpha_3 = -0.56$$

Resulting probability:

Applying the steps of this operation results in a probability of choosing a specific flight path. The result of this operation for the previously used example of the Rotterdam-London city-pair is stated in the fourth column (Prob.) of *Table B.5*. Here, it can be seen that especially the access/egress times play an important role. Explanatory for this is the trip between EHRD (Rotterdam-The Hague Airport) and EGLC (London City Airport), which is relatively important despite its lower number of seats offered.

Operation 4: Air Travel Modal Split estimation

Not every city-pair using a specific flight leg is equally dependent on air travel. This effect can be led back to two origins. The first (1) is the relative position of the airports compared to the cities. Travelling along an egress/access path which is opposite to the greater circle path means that a certain path is travelled double, making the route slower. This effect has already been covered in the previous operation on flight probability.

Accounting for natural barriers:

The most important factors (2) that have not yet be addressed are the obstacles that are found using land travel. An example for this, related to the Rotterdam-London case, is the relative large detour that comes with having to use the canal tunnel near Calais (France) in order to bridge the north sea. This detour varies per city pair, as for example people travelling between London-Rotterdam and Brussels-London experience a relative effect of this barrier, or even no barrier when travelling between Rotterdam-Frankfurt.

Average flight per city-city pair:

To compensate for this effect, the potential is corrected by an estimate of the modal split share of air travel in this city pair. This value is acquired by defining an average flight, after which the average flight is compared to performance of other modes on this city-pair. The average flight between v_i and v_j is collected by summing the result of all flights paths between $AP_i^{v2.5}$ and $AP_j^{v2.5}$ and their associated choice probability, as can be seen in Equation B.4

$$t_{i,j}^{tot,air,wgh,avg} = \sum_{x}\sum_{y}\left(t_{i,x,y,j}^{tot,air,wgh} * P_{i,x,y,j}^{ffp}\right) \quad ; \quad \forall \quad x,y \quad \in \quad AP_i^{v2.5}, AP_j^{v2.5} \tag{B.4}$$

Relative regret and probability:

This average flight is then compared to the performance of other available modes (car and conventional public transport) using the '*Random Regret Theory*' as introduced in *subsection 3.3.4*. Below, these functions are briefly revisited in *Equation 3.34 - revisited* and *Equation 3.35 - revisited*.

$$R_m^{est} = \sum_{n\neq m}\sum_{TT} ln(1 + e^{\gamma_{TT}*(\chi_{nTT}-\chi_{mTT})}) - ln(2) \quad ; \quad \forall \quad m \in M \tag{3.34 - revisited}$$

$$P_{i,j;m}^{est} = \frac{e^{-R_m^{est}}}{\sum_{TT} e^{-R_n^{est}}} \quad ; \quad \forall \quad m \in M \tag{3.35 - revisited}$$

Air travel modal split estimation:

Having defined the relative importance of all modes on the city pair v_i and v_j, the modal split of air travel is set to be the probability of choosing this mode, as described in *Equation B.5*.

$$MS_{i,j}^{air,air} = P_{i,j;air}^{est} \tag{B.5}$$

Operation 5: Line Potential Determination

The previous operations led to a state in which it is known what percentage of travellers between certain city-city pairs will take the plane and how they will spread over the available flights.Following this, it is also known how much passengers travel between certain airport-airport pairs. To connect these two knowledge factors one more link has to be made, which estimates the relative size of city-city pairs, such that it can be seen how much of a specific flight leg can be justified by a certain city pair.

Translation from probability into potential:

Finally, after defining the possible paths, their choice probabilities and the chance that passengers take the plane anyway, a potential is assigned to the specific flight legs. This $Potential^{i,x,y,j}$ represents a relative number of passengers that would like to take the flight from ap_x to ap_y when travelling between cities v_i and v_j. This potential is calculated by the function of *Equation B.6*. In this, the left term originates from a basic gravity model to estimate the relative number of travellers between the cities. The second term ($MS_{i,j}^{air,ext}$) indicates the number of passengers that would opt for a flying option, whereas the last term $p_{i,x,y,j}^{ffp}$ indicates the probability of the flight between ap_x and ap_y.

$$Potential_{i,x,y,j} = MS_{i,j}^{air,est} \cdot \frac{\left(V_i^{pop} \cdot V_j^{pop}\right)}{\left(DS_{i,j}^{road}/fc_{car}^{detour}\right)} \cdot P_{i,x,y,j}^{ffp} \tag{B.6}$$

Applying this function to the example of our Rotterdam-London trip, values ranging between $4.51 * 10^8$ and $6,24 * 10^9$ can be observed, as can be seen in the fifth column ('*Potential*') of *Table B.5*. These numbers however, do not give a complete view about the actual number of travellers between these two cities, as they only represent relative values. In further operations, these potentials will be matched to the actual number of observed flying passengers.

AP 1.	AP 2.	tt_w [h]	Prob.	Pot. [-]
EBBR	**EGBB**	6:44	2.0%	8,3 E+08
EBBR	**EGLL**	5:00	5.6%	2,4 E+09
EDDL	**EGBB**	7:45	1.1%	4,5 E+08
EDDL	**EGKK**	6:38	2.1%	8,8 E+08
EDDL	**EGLC**	5:52	3.3%	1,4 E+09
EDDL	**EGLL**	6:02	3.0%	1,3 E+09
EDDL	**EGHI**	7:08	1.6%	6,5 E+08
EDLV	**EGSS**	6:00	3.1%	1,3 E+09
EHAM	**EGBB**	5:50	3.4%	1,4 E+09
EHAM	**EGGW**	4:34	7.3%	3,0 E+09
EHAM	**EGKK**	4:46	6.4%	2,7 E+09
EHAM	**EGLC**	3:59	10.3%	4,3 E+09
EHAM	**EGLL**	4:09	9.3%	3,9 E+09
EHAM	**EGSS**	4:35	7.2%	3,0 E+09
EHAM	**EGNX**	5:48	3.4%	1,4 E+09
EHAM	**EGHI**	5:16	4.8%	2,0 E+09
EHAM	**EGMC**	4:41	6.8%	2,9 E+09
EHEH	**EGSS**	5:19	4.6%	1,9 E+09
EHRD	**EGLC**	3:22	14.9%	6,2 E+09

Table B.5: Example of estimated flight path duration, probabilities and potential

B.4. Network Distribution Procedure

Following the previous operations that worked towards the development of so-called '*potential*' between city-city pairs, the following step is to compare these acquired potentials to the actually observed flights, such that the actual size of the demand can be estimated. This procedure, the '*Network Distribution Procedure*' works towards a fully expanded OD-matrix that concerns the transport demand for all modes. This is done in three operations.

Operation 6: Market Share and Volume Determination

Now that an image of which routes passengers would like to take is available, they are going to be compared to the passengers that are actually transported. This is done by evaluating each of the flight legs separately.

Total potential per flight leg:

First of all, the airport-city system (*not to be confused with the city-airport system*)is defined, which means that all cities within 2.5 hours of the airport are considered to be feasible feeder cities. This zone, which is very similar to the city-airport system, but then from the airport perspective has a similar character as the map of *Figure B.2*. following this, a set of city-city pairs that use a specific flight leg is constructed. The model assumes that all the traffic on this line has to explained by the city-city pairs in this list, which means that the potential of a specific line $Potential_{x,y}^{line,sum}$ is given by the summation of all separate potentials.

Market share determination:

Knowing the total potential for a flight leg, the number of passengers that are transported are shared over all city-pairs that wish to use the leg. The market share function, as stated in *Equation B.7* describes this relation. Here it can be seen that the potential of one specific path is divided over the total potential that runs over a specific flight leg

$$Marketshare_{i,x,y,j} = \frac{Potential^{i,x,y,j}}{\sum_{i\in V_x^{2.5}}\sum_{j\in V_y^{2.5}}\left(potential^{i,x,y,j}\right)} \tag{B.7}$$

Operation 7: City-to-City Air Travel Demand OD-Matrix Construction

With the market share determination, it was found what percentage of passengers on a specific flight leg can be justified by a specific city-city pair. With this knowledge, it is possible to assign the percentage of the observed demand on the flight legs to the city pairs, a statement that is expressed in *Equation B.8*. Doing this results in an city-city OD-matrix that represents the demand for air transport within the network.

$$DM_{i,j}^{air} = \sum_{x}\sum_{y}\left(marketsharei,x,y,j * N_{x,y}^{pax}\right) \qquad \forall \qquad x,y \in AP \tag{B.8}$$

Operation 8: City-to-City Full Transport Demand Construction

Air transport demand only represents a part of the total demand between cities. To translate the air travel demand to an overall demand, an extrapolation has to made. For this, it has to be considered that the airplane has a different competitiveness to other modes based on the distance between the two cities of interest. The market share per distance for different long-distance modes was described in Donners (2016), of which the visualisation is given in *Figure B.3*. Fitting a polynomial function trough the market share points, it was found that that airplane market share per distance was best described by the formula of *Equation B.9*, having an $R**2$ value of 0.997.

$$Modalsplit_{ds}^{air} = ((1.49 \cdot 10^{-12} \cdot ds^{4}) - (4.73 \cdot 10^{-9} \cdot ds^{3}) + (4.60 \cdot 10^{-6} \cdot ds^{2}) - (5.03E \cdot 10^{-4} \cdot ds)) \quad \text{(B.9)}$$

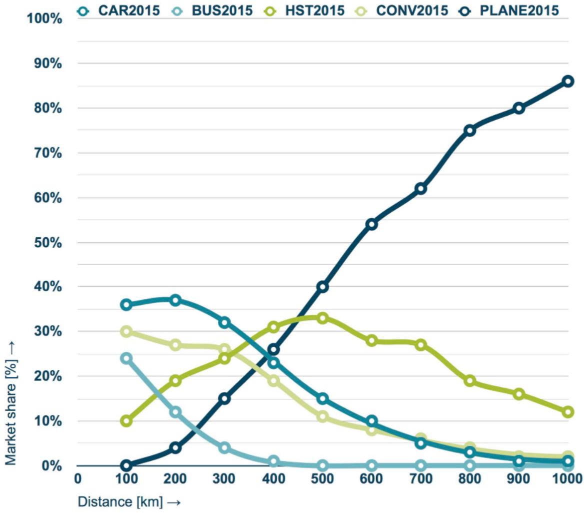

Figure B.3: Modal split per distance for long distance travel, as determined by Donners (2016) - *revisit of Figure 5.3*

Being able to estimate the market share for air traffic on a specific city pair, it also becomes possible to estimate the complete demand between these city pairs. This was done using *Equation B.10*. However, given the low share of air passengers on distances smaller than 200 km, they are not included in this calculation, as this introduce a large chance of inaccuracies.

$$DM_{i,j}^{tot} = \frac{DM_{i,j}^{air}}{Modalsplit_{i,j}^{air}} \quad \text{(B.10)}$$

C

Detailed Results of the Analysis on Governance and Pricing Strategies

The second experiment, as defined in *section 3.4*, concerned the analyses of pricing and governance strategies. This, to find the effects that such strategies have on the resulting network and performance and to learn how they can be used in a contribution to certain policy goals. The final outcomes of this analysis were previously discussed in *section 6.2* of *chapter 6* on '*Results*'. However, to reach final outcomes, a more thorough analysis on separate aspects was made. In this appendix, these findings are presented in a step-wise manner:

- *section C.1* - '*Influence of Strategies on Network Characteristics*' discusses the general characteristics of the developed networks for different strategies, thus concerning the lay-out, focal points and completeness
- *section C.2* - '*Development of Costs Components*' Differing networks show differing impacts the costs and benefits that are experienced by each of the stakeholders. This section tries to find patterns induced by certain strategies
- *section C.3* - '*Operator's Behaviour Under Different Circumstances*' analyses the observed patterns in network characteristics and stakeholder benefits from an operator's perspective, in search of explanatory factors
- *section C.4* - '*User's Behaviour Under Different Circumstances*' similarly searches for explanatory factors, but now by analysing the behaviour of passengers within the network
- *section C.5* - '*Connection of the Isolated Findings*' combines all the previous results and findings evaluate the possibility for a more overarching view

The experiment on governance and pricing strategies was based on six different scenarios, as revisited in *Figure C.1*. Summarising this, a division was made between a '*free Market*' and '*Central Organisation*' governance strategy, in which the first was modelled by a a 20% reduction on operator costs and the second by a 50% reduction on transfer time. Following scenario deviations were made by the pricing policies, which were simulated for different weights for the user, operator and society stakeholders as represented in the objective function of *Equation 3.9*. To allow for comparison, it is chosen to use the '*centralised market - Total Welfare*' settings as the base scenario.

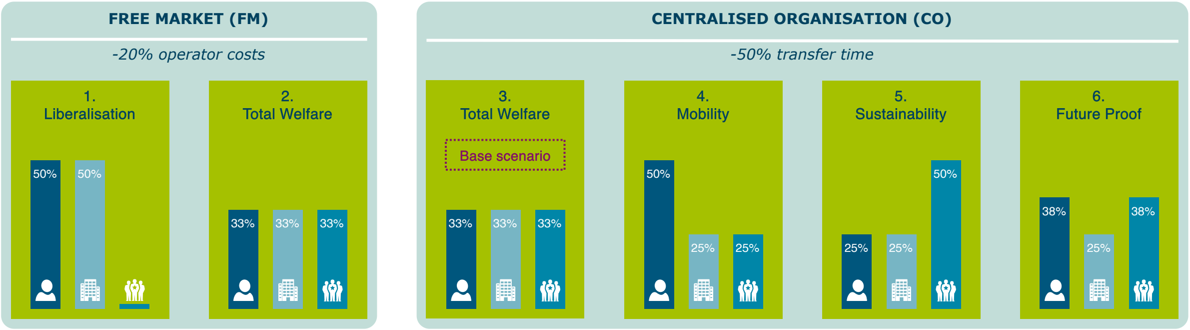

Figure C.1: Overview of modelled policy scenarios - *revisit of Figure 3.24*

C.1. Influence of Strategies on Network Characteristics

In search of finding characteristic line configuration properties, a first analysis is performed on the general lay-out of the developed scenario networks. In the first part of this analysis, each of the scenarios is separately assessed as based on the lay-out, completeness, vertex properties and edge properties.

General network lay-out

The general network lay-outs of this HSR network are best understood when visualising the networks on the map. This has been done for the Total Welfare (CO) scenario in *Figure C.2*. The figure shows which edges of the network are used by the line configuration using a light purple tint. This tint gets darker if an edge is has a relatively higher frequency of trains on it. With this, it gives an indication of the focus points within the network. Furthermore, The blue border around the vertices indicates the absolute HSR demand of vertex in passengers per day, whereas the green tint of a vertex indicates the modal split that is reached. Detailed maps of all scenarios can be consulted in. For ease of comparison, simplified maps are given in *Figures C.3*, *C.4*, *C.5*, *C.6*, *C.7* and *C.8*.

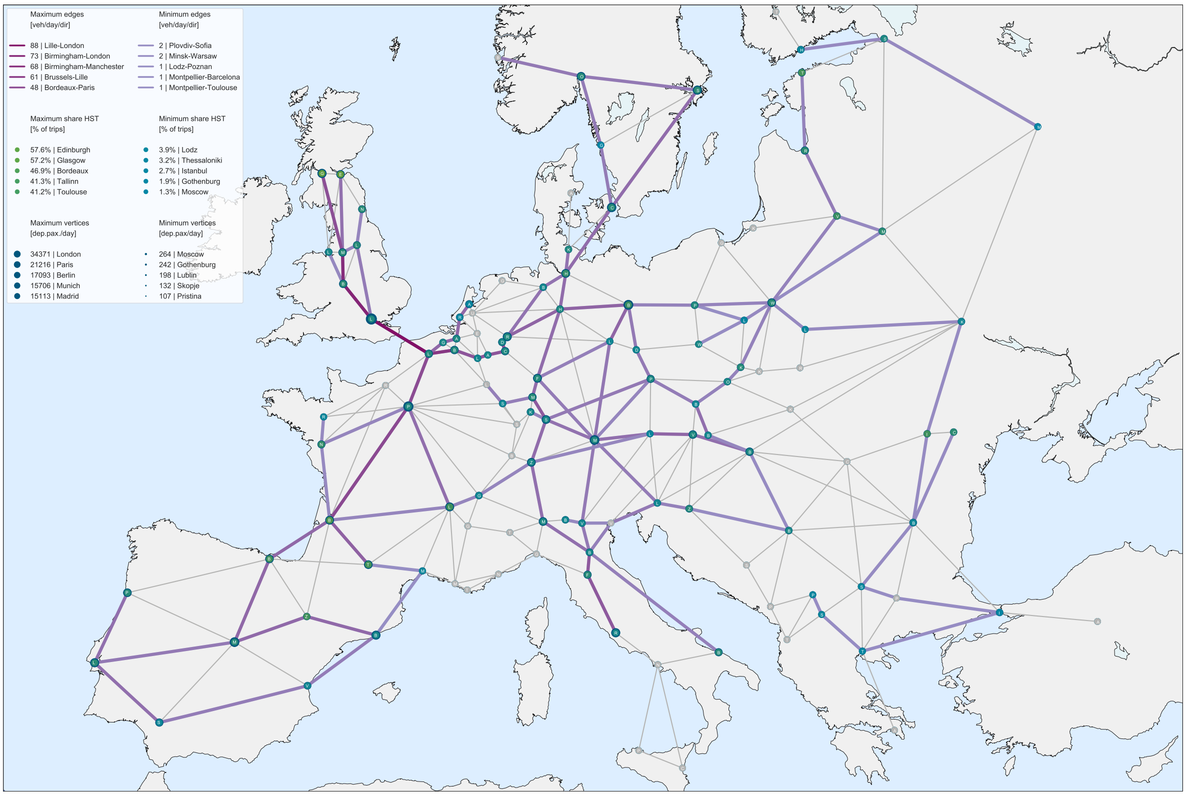

Figure C.2: Map of vertex and edge characteristics for the base scenario (Total Welfare (CO))

Network uniformity and network focal points:

At first sight, it can be seen that all scenarios are capable of designing lines throughout the map, In which all parts of the continent are served to some extent. The density is slightly skewed towards the west of Europe, as it can be seen that especially the south-eastern side of the network is rather incomplete.

Following this, the network density increases towards the geographical centre of the map, in this case Germany. It is seen that especially Munich seems to be a pivot point for all scenarios, as it is constantly connected in almost every direction. Shifting to the more subsidised scenarios (4,5,6), the size of this high-density centre increases, with which also Berlin, Hamburg, Hanover, Frankfurt and

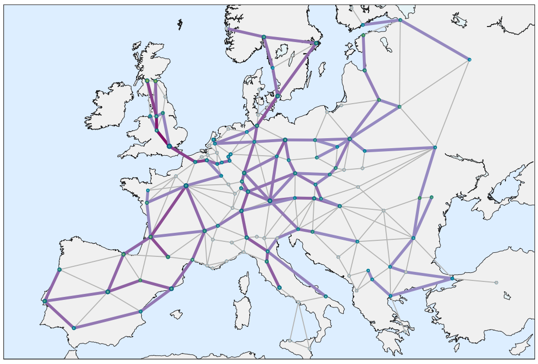

Figure C.3: Developed network for scenario: free market - Liberalisation

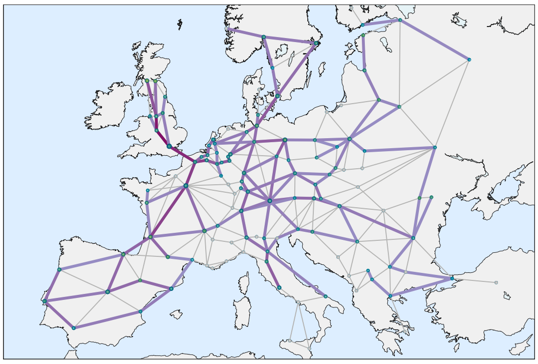

Figure C.4: Developed network for scenario: free market - Total Welfare

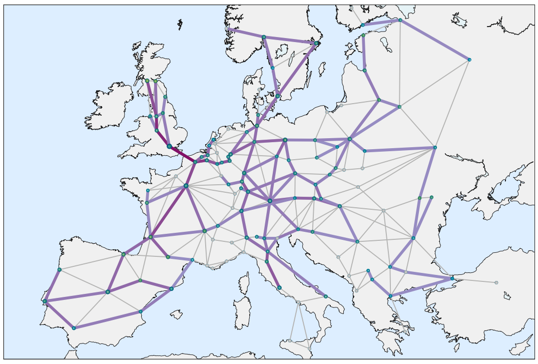

Figure C.5: Developed network for scenario: Centralised Organisation - Total Welfare

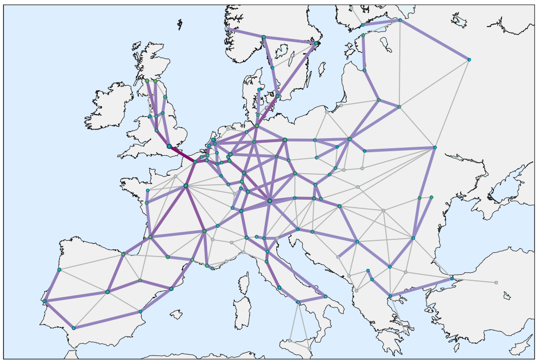

Figure C.6: Developed network for scenario: Centralised Organisation - Mobility

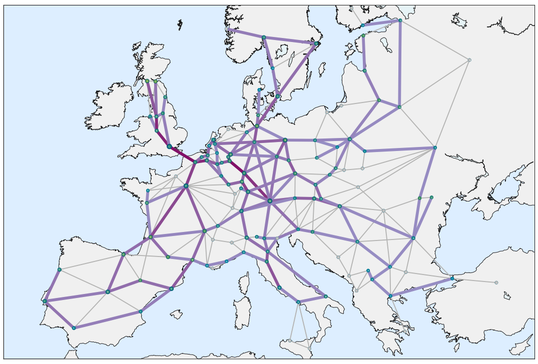

Figure C.7: Developed network for scenario: Centralised Organisation - Sustainability

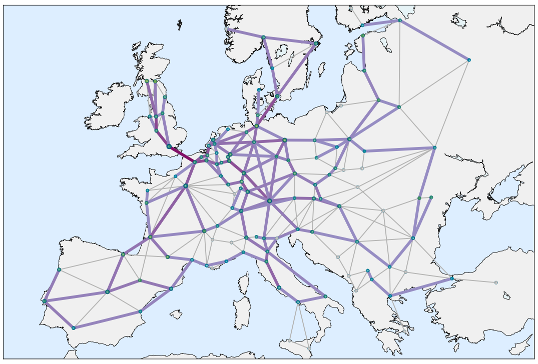

Figure C.8: Developed network for scenario: Centralised Organisation - Future Proof

Cologne/Ruhrgebiet are becoming stronger hubs.

Moving away from the geographical centre, it is seen that that the different scenarios frequently use the the same peripheral focal points. In the less extensive networks, priority is given to cities like London, Lille, Bordeaux, Bologna Zurich, Copenhagen and Warsaw. In the further developed networks, it seen that the network importance of cities like Bucharest, Budapest, Ljubljana, Montpelier, Lyon, Paris, Brussels and Utrecht grows.

Connection of separate island networks:
Despite the introduction of strategic pricing, as was introduced in the '*Method Validation*' of *chapter 5* it is observed that the model still experiences a certain degree of difficulties in connecting different sub-networks (also defined as separate island networks, as explained in *subsection 5.2.2*). This behaviour is especially strong for the the free market scenarios (1 and 2). Explanatory, the first of these (Liberalisation (FM)), is not even able to properly connect the English, French and German networks. This manner of conduct seems to repeat its self for other scenarios, although it seen that the internalisation of external costs and/or the increased importance for user benefits increase the general performance. This suggests that an improved model would require a mix of policies and passenger constraints in order to reach a stronger performance.

Degree of network completeness
The edges that are used, as visualised in *Figures C.3*, *C.4*, *C.5*, *C.6*, *C.7* and *C.8*, only give a limited view on the completeness of the network. This, because is also dependent on the lines that use these edges and the vertices that are connected by these lines. To gain more insights in the degree of completeness, each of these factors is addressed in the paragraphs below.

Number of lines:
The core fundamental of the heuristic as designed for this specific problem, is to start with an empty line set and to sequentially expand the network by including new lines. Altering this with short-term step forecasting, line deactivation and line substitution, it works towards a full line set. The result of this process for the base scenario (Total Welfare (CO)), is displayed in *Figure C.9*. In this graph, the total number of lines per iteration is indicated by the light-blue line. After its procedures, this scenario ends with a total number of 54 lines, creating the network map as was presented *Figure C.2*.

A comparison of the total number of lines for the other scenarios is presented in the third column of *Table C.1*. Here it can seen that the number of lines per network ranges between 54 and 80, and that the first three scenarios are all on the lower side of this scope. Increasing the weights of the user and/or external benefits results in an increase of the number of lines, as showed by the three latter scenarios. This KPI gives a quick indication on the size of the network, although it should combined with other factors to see its complete contribution.

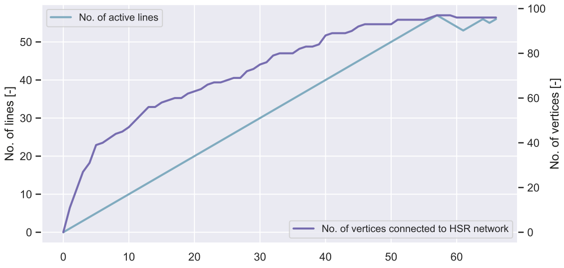

Figure C.9: Iteration development for the number of lines (base scenario)

Scenario		No. lines	V connect.
Open Market	Liberalisation	54	89
	Total Welfare	56	96
Centralised market	Total Welfare	56	96
	Mobility	69	101
	Sustainability	73	103
	Future Proof	80	105

Table C.1: Number of Lines for the developed policy scenarios

Number of connected vertices:
One of the extra factors that is taken into account, is the number of vertices that are connected by the previously discussed lines. Referring to the same graph as previously (*Figure C.9*, but now focusing on the purple line, it can be seen that the Total Welfare (CO) scenario ends up connecting 96 out of the 124 cities. This graph follows a logarithmic path. Something that can be explained by the fact that early lines still have the chance to connect many unvisited cities.

Comparing the total number of vertices connected for the other scenarios, as stated in the fourth column of *Table C.1*, a pattern similar to that of the previous KPI is observed. Increasing the importance of user and/or external factors leads to a network that includes more cities. However, the difference between the two extreme scenarios (1. Liberalisation and 6. Future Proof) is relatively seen larger for the number of lines than the number of cities connected.

Number of reachable ODs:
the last KPI regarding the network completeness concerns the OD-flows that are enabled by the set of lines, which is measured in the number of reachable origin-destinations. For the total welfare scenario, this development is plotted in the graph of *Figure C.10*. The chart shows a step-wise logarithmic pattern, which is most clear between the 15th and 50th iteration. In this range, it is seen that the network slowly expands and accepts new passenger paths. However, at 50th iteration, a sudden increase of indirect paths can be observed. This peak indicates that two networks are being connected, creating a lot of new feasible paths. It is striking to see that this behaviour is less typical for the subsidised scenarios (4,5,6), which show a more gradual increase. this means that these scenarios are less reserved in accepting lower quality paths from the beginning on, which means that the chance of ending up in such an island division is smaller. The numerical results of these simulations are displayed in *Table C.2*.

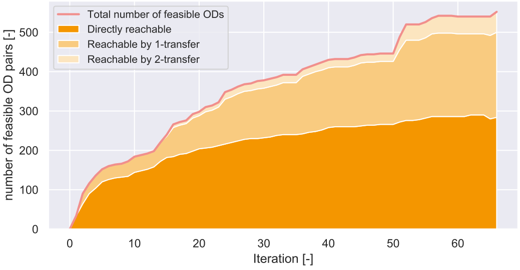

Figure C.10: Iteration development for the number of reachable OD's (base scenario)

Scenario		**ODs reachable by path**			
		Total	**Direct**	**1-trf.**	**2-trf.**
Open Market	**Liberalisation**	396	68,1%	25,5%	6,4%
	Total Welfare	622	54.5%	38.6%	6.9%
Centralised market	**Total Welfare**	552	50.7%	39.4%	9.9%
	Mobility	860	39.6%	48.5%	11.9%
	Sustainability	904	44.3%	42.8%	12.9%
	Future Proof	880	49.2%	42.2%	8.5%

Table C.2: Reachable OD's for the developed policy scenarios

C.2. Development of Costs Components

The objective function considers three main stakeholders: the User, Operator and Society (external). The costs made by these parties are multiplied with their weights, creating a three separate contributions to the objective function value. The weight has a direct impact on this contribution. However, giving parties different weights does not mean that their actual costs are changed in the same manner. An example of this is given for the 5. Increased Sustainability (CO) scenario, where the societal benefits are enlarged by a factor 2. For this scenario, the objective function value development is given in *Figure C.11*, the development of the actual costs is given in *Figure C.12*.

On the left hand side graph (*Figure C.11*), it can be seen that the objective function value (purple) steadily decreases during the modelling process, only steps the improve the system (objective value)

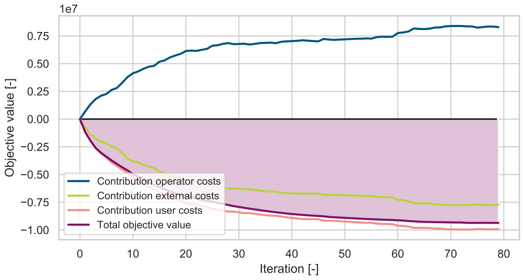

Figure C.11: Iteration development for the objective function value (5. Increased Sustainability)

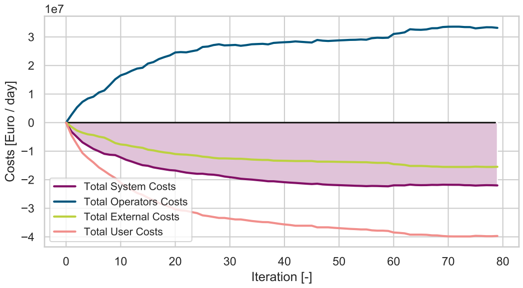

Figure C.12: Iteration development for the main cost components (5. Increased Sustainability)

are accepted. However, in reality, the actual costs are not subject to the chosen weights, which is visualised by the decreased external cost in the right hand side figure (*Figure C.12*). It means that, by reviewing the actual costs, some choices are made that not necessarily justified by their costs, but rather by their contribution to the policy goals. The most exemplary illustration for this is found iteration 60 on. At this point, the model accepts a strong increase of operator costs, which causes the total costs to develop in a negative direction. However, the objective function development shows that this reaction is cancelled by the increased weight for external costs.

Comparing the separate cost components allows to determine why the system makes certain decisions and what effects the policy have on different stakeholder's behaviours. In the subsections below, each of the separate costs components will be elaborated on.

Main costs components

In *Figure C.13*, the development of the cost for the 3. Total Welfare (CO) scenario is projected. The graph shows that, at the end of the simulation, the total cost end a value of $-22.8*10^6$ euro per day. This means that the sum of the user and societal benefits outweigh the cost that are related of operating this system. In other words: the introduction of an HSR system is able to provide for an effective advantage. The third column (Total) of *Table C.3*, indicates that this finding is true for all scenarios. It does however also show that the direct monetary advantage alters per scenario, as the total value ranges between $-20.9*10^6$ and $-25.8*10^6$ euro per day.

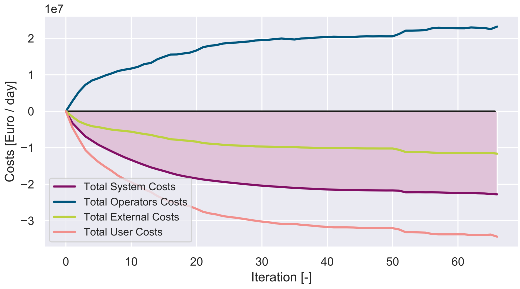

Figure C.13: Iteration development for the main costs components (base scenario)

Scenario		**Cost Component [million € / day]**			
		Total	**User**	**Operator**	**Societal**
Open Market	**Liberalisation**	-21.0	-31.0	19.7	-9.7
	Total Welfare	-25.8	-33.5	19.5	-11.7
Centralised market	**Total Welfare**	-22.8	-34.4	23.2	-11.6
	Mobility	-20.9	-39.4	33.2	-14.7
	Sustainability	-22.0	-39.7	33.2	-15.5
	Future Proof	-22.2	-40.4	33.2	-15.0

Table C.3: Main costs components for the developed scenario networks

The total costs value cannot be directly interpreted as a measure of total network performance, but should rather be seen as measure of relative efficiency. To explain this, it is necessary to evaluate how this total cost is composed. The detailed information on the three main costs components is presented in the fourth, fifth, and sixth columns of *Table C.3*. Here it can be seen that the size of the network is not in a directly correlated with the total costs. This is strongly the scenario 1 Liberalisation (FM) and scenario 4 Mobility. Having a difference of 0.1 million euro per day, their total costs are similar. However, the significantly larger separate costs components of the mobility scenario indicate a larger network for the same netto result. Similar to this, but from the opposed perspective, it seen that the scenarios 2 Total Welfare (FM) and 3 Total Welfare (CO) provide almost the same benefits for users and society, but at a great difference of operator costs. From this, it can be stated that the free market scenario is undoubtedly more efficient.

Combining the number the numbers, it can be concluded that the 2 Total Welfare (FM) is the most efficient scenario, providing the best societal cost/benefit ratio. Following this, it can be seen that the three subsidised scenarios (4. Mobility (CO), 5. Sustainability (CO) and 6. Future Proof (CO)) provide the most extensive networks. In these settings, they are able to increase the user benefits ($\pm 20\%$) and external benefits ($\pm 30\%$). Considering specifically scenario 6 Future Proof (CO), as is most efficient given its total cost, it can be said that these advantages come at daily price of 3.6 million euros. However, the experienced benefits for users ($6.9*10^6 euro/day$) and society ($3.3*10^6 euro/day$) might be able to justify this investment when politically desired

User costs components
The user costs are constructed from the five factors involved with the travel time composition: Access time, waiting time, in-vehicle time, transfer time and egress time. The development of these cost elements for scenario 3 (Total Welfare (CO)) is depicted in *Figure C.14*, in which to total user costs are indicated with the purple line. This figure shows the relative difference in cost compared to a transportation system without an HSR system.

It can been seen that the majority of user benefits are gained from shortened in-vehicle times (purple), which might be considered counter-intuitive with the relatively low value of time (VoT, see *section 4.4*) of this segment. This explained by two factors. First of all (1) the fact the in-vehicle time represents a relative large part of the total travel time, meaning that any percentage time saving results in a large absolute number. The second explanatory factor (2) concerns the apparent competitiveness with other modes.

The second positively contributing factor is the waiting time, for which users spend less in the new system. This factor is negatively influenced by people who substitute from car to HST (as they now have to wait at the station), but positively influenced by passengers shifting from air transport since their waiting time is strongly decreased. In *subsection C.4*, it was determined that the HST receives approximately the same number of trips originating from air and car passengers. This together explains the strong decrease in total user waiting time.

The introduction of a high-speed train network does not only bring positive developments for the user. The fact that former road travellers now have to reach a high-speed train station means that they experience an increase of access & egress times, which does not outweigh the shorter access & egress time that former air passengers gain. In line with this, it is seen that also the time needed for transfers increases. This could be expected from the model, as it was assumed that air passengers only fly direct routes within the continent.

Operator costs components
The operator costs development (as provided in *Figure C.15*) shows a rather stable and straightforward behaviour. The growth of the separate cost components is in line with the the development of the APK/RPK (*Figure C.18*) and addition or elimination of the number of lines (*Figure C.9*). This can be explained by the responsive strategy of the operator. This starts with the linear relation of the between both cost components (operational & maintenance) and the number of seat-km (APK), which is related to the total demand (RPK). Following this, the RPK in its turn is linked to the lines available. This means that the total operator costs will always be close to the ratio between the operational and maintenance costs, as was stated in the parameterisation of the European case study of *chapter 4*.

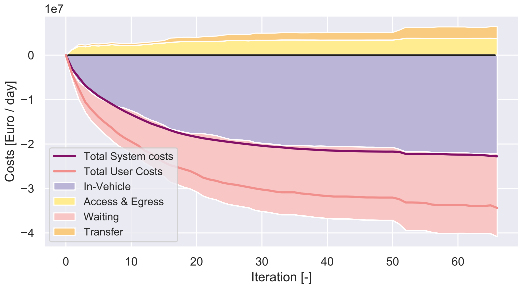

Figure C.14: Iteration development for the user costs components (base scenario)

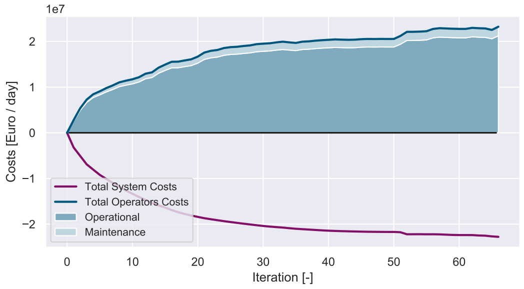

Figure C.15: Iteration development for the operator costs components (base scenario)

Societal costs components

As was shown in the discussion on main cost components, the introduction of an HSR system is able to provide benefits in the field of external costs. These summed mode-specific costs are the lowest for high-speed trains when compared tot the other two modes and comprises the factors as stated in *Table 4.10* of *section 4.3* on the mode specifications of the case study. The development of the societal cost components per mode is visualised in *Figure C.16*.

This graph shows that the introduction of HSR (bright green) only brings a minimal growth of externalities, which is cancelled out by the positive effects of reduced air and road demand. The most eye-catching factor in this graph is the strong positive effect of reduced car traffic compared to air traffic. This is explained by two factors: The first (1) is the rather comparable substitution from air and road modes to high-speed rail in the number of trips (see *section C.4*), which combined with the (2) higher external costs per kilometre of the car makes this a strong component. The effect on the external costs, as induced by this higher km-cost for the car, could potentially be flattened by the shorter distances that are generally travelled in this mode or enlarged by larger demand between closer cities. These factors can however not be extracted from this figure and the model's scope limitations.

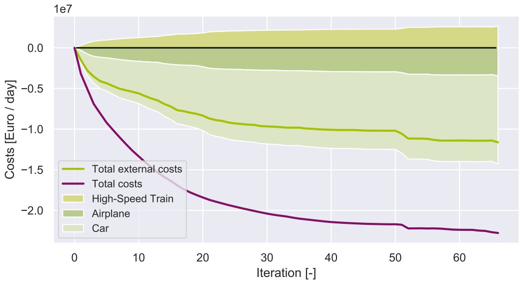

Figure C.16: Iteration development for the main societal components (base scenario)

	Liberalisation (FM)		**Total Welfare (CO)**		**Sustainability (CO)**	
Accidents	3.19	32.86	3.84	33.02	4.95	32.02
Air Pollution	0.72	7.40	0.87	7.48	1.18	7.61
Climate	2.49	25.67	3.02	26.02	4.32	27.95
Noise	0.27	2.74	0.30	2.55	0.39	2.52
Congestion	3.10	31.97	3.74	32.20	4.85	31.34
Well-to-Tank	0.52	5.37	0.61	5.24	0.90	5.80
Habitat Damage	-0.58	-6.01	-0.76	-6.52	-1.12	-7.25
Total	9.71	100	11.62	100	15.47	100

Table C.4: Societal costs components for the developed policy scenarios

Breakdown of external costs components:

The external costs per mode only represents the sum of the seven sub-components that are considered for the external costs. In *Table C.4*, the total costs per mode are divided and summed for the costs per external component. This is done for three specific scenarios: Liberalisation (FM) since has the lowest contribution for external costs, Total Welfare (CO) for it is the base scenario and Sustainability (CO) as it reached the highest reduction in external costs.

The left hand side column of each scenario indicates the true reduction for each of the sub-components. This data shows that for all of the scenarios, the greatest impacts can be seen in the fields of '*accidents*', '*climate*' and '*congestion*'. The only deteriorating factor is the '*habitat damage*', which mainly follows from the required infrastructure, which is relatively small for air transport but large for high-speed rail. In the right hand side columns, the values are normalised. This shows that the proportional differences are very similar for each of the scenarios.

C.3. Operator's Behaviour Under Different Circumstances

Based on the total transport demand and the competition with other modes, the operator decides which lines it uses in its network. In *section C.1*, it was already determined that the scenarios as modelled had a set of lines with a size between 54-80 lines, that were able to connect between 89-105 vertices and that could link 396-904 origin-destination pairs. In different environments and with pursuing diverging policy goals, the strategy and resulting set of lines varies.

In *Figure C.17*, an overview of the set of lines resulting from scenario 3 Total Welfare (CO) is stated. Each stop is indicated with a dark-blue dot and the first three letters of the corresponding city. These cities are connected by green lines which represent the edge between the cities. The travel distance between the stops is indicated by the light-blue colour beneath the edge. The loading factor of the trains of that line travelling a specific edge are stated in green above the line. The colour of the edge corresponds to this number, as a brighter tint of green represents a higher load factor. The last information of this graph is seen on the left hand side of each line. Here, the frequency is stated in dark-blue, whereas the summed line distance is given in a light blue tint.

In this section on the operator's behaviour, the set of lines is discussed and compared for each of the policy scenarios. This is first done from operational efficiency perspective, which is then followed by a focus on the lines physical properties of the lines themselves.

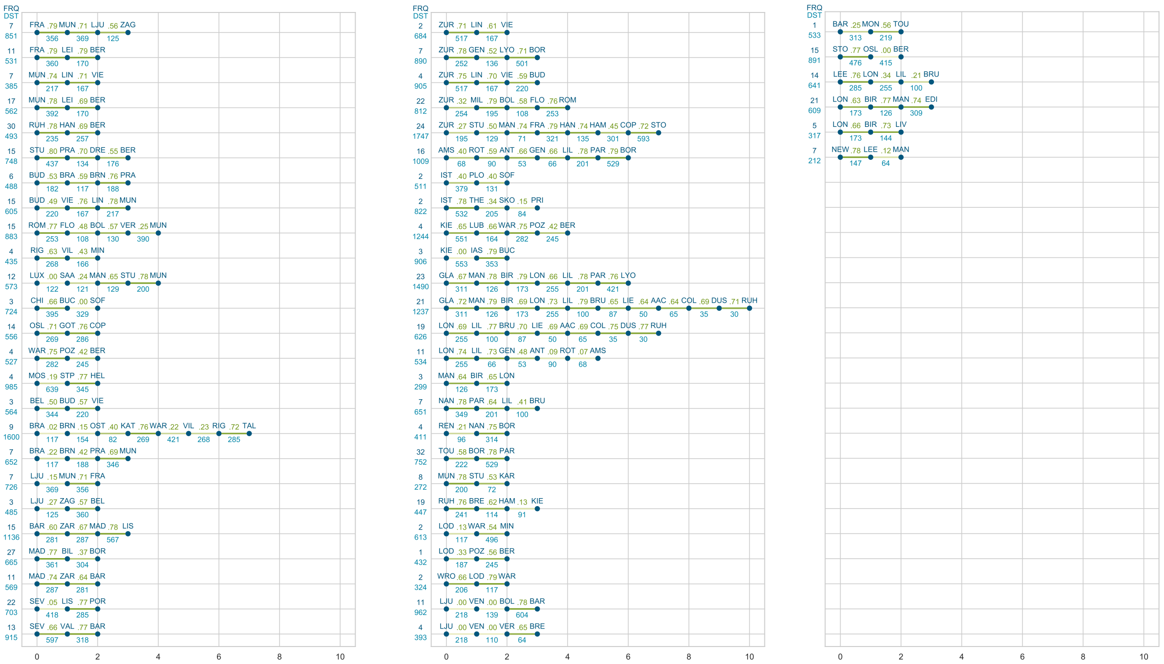

Figure C.17: Developed line plan with distance and occupation per line leg (base scenario)

Operator Efficiency

The efficiency of the operator is primarily measured by the load factor, which is the number that expresses the balance between the seat kilometres that are offered (ASK) and the seat kilometres that are used by the passengers (RPK). This can be done from both a line specific perspective (LF), as well as from a network perspective (ANLF).

Line specific Loading factors:
The overview of lines, as depicted in *Figure C.17*, gives insights in the occupation of lines along the route. First of all, it is seen that almost every line has at least one segment that approaches the design loading factor of 0.8. However, there also many segments that do not come close to this value. This behaviour can be explained by both operator's decisions that still sees profit due to further network effects, but also by shortcomings of the model.

Regarding the operator's decisions, most weaker segments are part of line because of they are either part of through-going paths, or the serve to connect another city to the network. An illustration of the first reason can be found halfway the middle chart of *Figure C.17*, where the line with the most stops travels between Glasgow and Ruhrgebiet. This line has high occupations on the ends and centre, whilst having slightly lower occupation rates in between. However, using a so-called '*rooftile effect*', it is able to fill the lower demand stretches to a decent number. For the second reason (connecting a city to the network), a glance has to be given again to the upper side of the middle chart (*Figure C.17*). The line between Zurich and Rome (fourth line) has a high frequency of 22 vehicles per day, despite having a very low occupation (0.32) on the first stretch between Zurich and Rome. This is explained by this line enabling passengers from or to Rome to connect to the rest of the network by transfers in Bologna or Zurich, which makes that its indirect contribution might be larger.

Analysing the chart, it is also seen that some stretches are nearly empty, which is due to modelling limitations. First of all, the limited pool of lines makes that some routes are less efficient, though still the only way to make a connection. besides this, the demand resolution makes that smaller OD-flows are not always taken into account, which is especially hurt full for lower demand cities. Thirdly, the model is not able to adjust the lines by for example cutting a last segment of, which line of reasoning as the last argument, where it is stated that the model is also not able to perform operational tricks, such as short turning, deadheading or station skipping.

Average network loading factors:
The average network loading factor is determined by dividing the available seat kilometres (ASK) over the (RPK) over the whole network. The development of these values for the scenario '*3 Total Welfare (CO)*' are plotted in the graph of *Figure C.18*. In addition to this, the light-green dashed line demonstrates the maximum design load factor, thus the theoretical optimal value. From the figure, it can be read that the ANLF fluctuates during the first iterations. At this moment, the model starts with the long lines that are most profitable, which explain the slightly higher ANLF at this point. After several iterations, the ANLF converges towards a relative steady value of 62.4

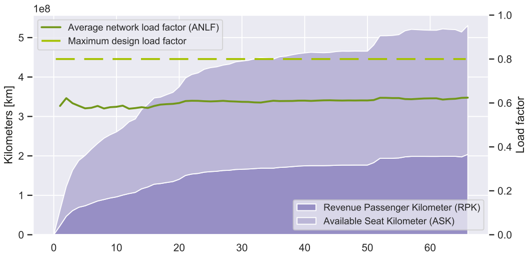

Figure C.18: Iteration development for the operator's RPK and ANLF (base scenario)

Scenario		ASK [million km]	ANLF [-]
Open Market	**Liberalisation**	277.3	60.49
	Total Welfare	342.3	60.69
Centralised market	**Total Welfare**	326.6	62.42
	Mobility	466.5	59.28
	Sustainability	466.6	63.38
	Future Proof	466.8	60.36

Table C.5: Operator's RPK and ANLF for the developed policy scenarios

Comparing this value with other scenarios, as was done in Table C.5, a clear pattern can be seen. The free market scenarios have a lower ANLF than the base scenario. This finding is contradictory to the standpoint that a company is more efficient than a governmental organisation. In this case, the difference can be explained by two rationales: The first (1) reasoning comes from the reduced operator costs in the free market (-20%, as simulated by the scenarios), which makes that routes can still be profitable with lower train occupations. The second (2) argument follows the reduced number of transfer passengers in free market scenario, as examined in section C.4. This means that it is harder to fill line segments that could be shared, or accept feeder lines that rely on a further network structure.

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The scenarios that work from a centralised market perspective show varying, but also explainable, numbers. At first, it can be seen that the networks reach almost the identical ASK's, meaning that the operator's efforts are very comparable. Analysing the ANLF's gives that the '*4. Mobility (CO)*' scenario stays at a relative low level of 59.28. This is in line with expectations, as the mobility is stimulated by allowing passengers to travel routes that are not necessarily most profitable. The opposite is seen for the sustainability scenario, which has a high ANLF of 63.38. Being more conservative with making unnecessary seat-kilometres and focusing on passenger-streams, it also not against expectations to see this. Finally, the '*6. Future Proof (CO)*' scenario seems to find a balance between the to others, although being slightly skewed to the mobility scenario.

Line characteristics

To evaluate how the chosen line set differs per scenario, an overview of the main line characteristics is presented in this subsection. For this, the line lengths, line stops and line frequencies are considered.

Line lengths:

Figure C.19 provides a bar plot of line lengths with an intermediate bin size of 200 km for the '*3. Total Welfare (CO)*' scenario. The figure shows that lines throughout the length spectrum are selected, though the centre of gravity is found within lines ranging between 400-800 kilometres. Having a shortest line of 212 kilometres suggests that the selection is indeed strongly bounded by the minimum line length constraint of Equation 3.19 as stated in subsection 3.2.5 of the '*Problem Formulation*'. Something that is confirmed when analysing the minimum line length of other scenarios in Table C.6, where it is seen that lines do exactly tangent this constraint. This suggest that - from a network perspective - shorter lines could be beneficial to the model. However, the minimum line length constraint was designed to prevent nesting with national networks. It means that the connectivity with these national networks has to be researched.

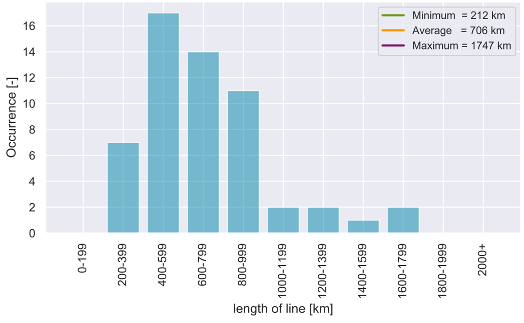

Figure C.19: Distribution of line lengths (base scenario)

Scenario		**Line length [km]**		
		Minimum	**Average**	**Maximum**
Open Market	**Liberalisation**	272	738	1747
	Total Welfare	212	761	1747
Centralised market	**Total Welfare**	212	706	1747
	Mobility	200	766	2088
	Sustainability	200	701	1792
	Future Proof	200	748	1959

Table C.6: Line length characteristics for the developed policy scenarios

Regarding the average line length, it is seen that all scenarios stay within a 700-800 kilometres scope. For the policy, it goes that enhancing mobility results in slightly longer lines and enhancing sustainability results in slightly shorter lines. This, is similarly to the findings of subsection C.3 explained by the balance between services for users and reservations for inefficient use. In line with the average lines lengths, it is seen that longest line is found in the mobility scenario with a covered distance of 2088 km, travelling from Helsinki via St. Petersburg, Minks, Warschau and Poznan to Berlin.

Line stops:

The graph that indicates the number of stops per line for the '*3. Total Welfare*' scenario, see *Figure C.20*, leans heavily towards the lower side of the scope.The majority of lines visit three stops (both terminal station and one midway station), which are supplemented with a smaller selection of lines that stop more often. This makes that the average value does not reach higher tan 4.0 stops per line. Comparing this for other scenarios, as has been done in *Table C.7* gives a similar result. All scenarios have routes that are bounded between three and eleven stops, with averages between 4.0 and 4.4 stops per line. For the subsidised centralised market scenarios, it is seen that especially the scenarios which emphasise user benefits have more stops per line. However, scenario '*1. Liberalisation*' does not show this behaviour.

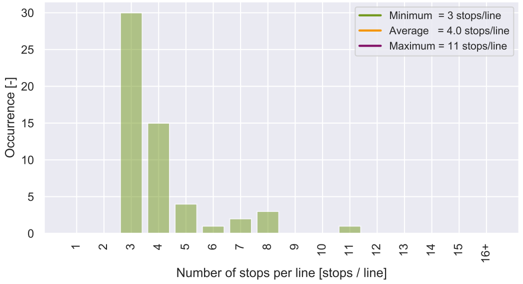

Figure C.20: Distribution of the number of stops per line (base scenario)

Scenario		Stops per line [-] Min.	Avg.	Max.	Average stop distance
Open Market	**Liberalisation**	3	4.0	11	185
	Total Welfare	3	4.1	11	185
Centralised market	**Total Welfare**	3	4.0	11	177
	Mobility	3	4.3	11	178
	Sustainability	3	4.1	11	171
	Future Proof	3	4.4	11	170

Table C.7: Line stop characteristics for the developed policy scenarios

Combining the knowledge on the line lengths and line stops, it is possible to determine average stop distances. These values are stated in the last column of *Table C.7*. It can be seen that the values range between 170-185 kilometres per line segment and that they get shorter in scenarios that increase the weight for external costs.

Line frequencies:

Not being able to change the seating capacity of a train, the frequency is the operator's main instrument to set the volume and importance of different lines. An overview of the frequencies used in the '*3. Total Welfare (CO)*' is provided in *Figure C.21*. Diverging from the previous line characteristics (lengths and stops), it is seen that value spreads itself across the spectrum a lot better, especially for the bar plots of other scenarios. The high peaks in this specific scenario do not seem to show a pattern but, should rather be explained by coincidences, given the varying peaks that are observed for the other scenarios.

Focusing on the quantitative data, of which an overview is stated in *Table C.8*, it is seen that all models have at least one line with a frequency of one train per day. Other than that, the averages vary between 9.2 and 11.4 trains per day. It seems that the centralised market scenarios use higher average frequencies, although this not true for the '*6. future proof*' scenario. The same is seen for the maximum frequency, that most of tops at values between 30 and 40. The only outlier in this is found again in the '*6. future proof*' scenario, with a maximum frequency of 26.

The line overview of *Figure C.17* gives insights in the types of frequencies per line. It shows that short lines show larger variations within their frequencies, that are found all over the spectrum as given in *Figure C.21*. From the other perspective, it is seen that most of the longer lines (1000+ kilometer) have relatively high frequencies between 10-20 vehicles per day.

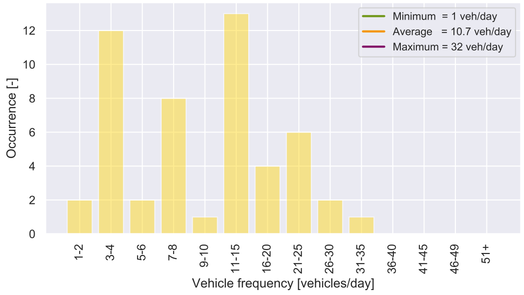

Figure C.21: Distribution of the vehicle frequency per line (base scenario)

Scenario		Line frequency [veh / day]		
		Minimum	Average	Maximum
Open Market	Liberalisation	1	9.2	37
	Total Welfare	1	9.8	38
Centralised market	Total Welfare	1	10.7	32
	Mobility	1	10.9	42
	Sustainability	1	11.4	41
	Future Proof	1	9.8	26

Table C.8: Line frequency characteristics for the developed policy scenarios

C.4. User's Behaviour Under Different Circumstances

The user adapts its travel preferences based on the transportation possibilities that are offered. This can be seen from two levels: One overarching view, that trades utilities of the three modes and one more specific view that looks into the differences for HST travel. In the subsections below, These two views will be addressed based on the modal split and HST transfer data.

HSR Transfer behaviour

Making transfers in the high-speed rail system allows passengers to reach destinations that are not directly connected to their origin city. These transfers are not only dependent on the travellers preference, but also on the strategy of the operator and its wish to accept transferring passengers. It could be beneficial to take these passengers because of the increased flows and transportation demand, but the also come at a lower cost/benefit ratio, as was discussed in *subsection 5.2.2*.

In *Figure C.22*, the development of transferring passengers are plotted for the '*3. Total Welfare (CO)*' scenario. It can be seen that throughout the simulation, the majority of passengers travel a direct path, a smaller part makes one transfer and a minimal part changes their lines twice. As the network becomes more extensive, more people tend to make a transfer. Furthermore, the graph shows a few peaks in the development, indicating that two separate sub-networks or significant lines are connected. In the end, this scenario ends up with a 82.7% (direct), 15.45% (1-transfer), 1.88% (0-transfer) division of passengers.

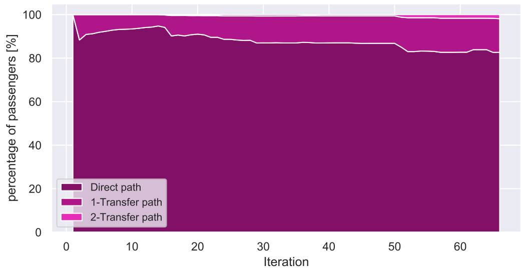

Figure C.22: Iteration development for the share of transfer passengers (base scenario)

Scenario		Path type used by passengers [%]		
		d0	d1	d2
Open Market	Liberalisation	91.99	7.49	0.52
	Total Welfare	86.34	12.91	0.75
Centralised market	Total Welfare	82.66	15.46	1.88
	Mobility	76.87	19.92	3.22
	Sustainability	71.98	25.10	2.92
	Future Proof	79.81	18.26	1.93

Table C.9: Transfer behaviour for the developed policy scenarios

The accumulated table of *Table C.9* displays rather strong differences between the scenarios regarding the transfers. It is clear that the free market scenarios have an emphasis towards direct passengers, given their lower degree of d_1 and d_2. This originates from two main sources: Firstly (1), the increased transfer time makes that it is less attractive to make a transfer from a passenger perspective. Secondly (2), the focus of these scenarios towards operator and user interests (especially for '*1. Liberalisation (FM)*') make that they are more efficient and thus more selective in the types of passengers they accept. Direct passengers being more profitable, it logically follows that these are over represented in these scenarios.

From the other scenarios, it is seen that the inclusion of external costs results in higher fractions of transferring passengers. Especially scenario '*5. Sustainability*' shows a an elevated score for this. The same is seen for scenarios that emphasis the weights of the user, though to smaller extend.

Network modal splits

Introducing a new mode in the system means that passengers are offered new and sometimes better performing alternatives. This makes that they substitute from their original mode to the new mode. In this subsection, this substitution is discussed from perspective in the number of trips as well as the distance of the trips.

Modal split per trip:

The development of the model split (in trips) during the simulation of the '*3. Total Welfare (CO)*' is depicted in *Figure C.23*. The graph shows a steady and converging behaviour towards a total market share of 17.30 % for the high speed train. One of the most eye-catching findings is that the absolute number of trips that are substituted from car and air are very similar. However, relatively seen, this impact is a lot bigger for road transport, as this represents a smaller part of the original traffic. It means that high-speed train is especially competitive to the car. Combining this with the knowledge on external costs (*subsection C.2*), it can be concluded that the impact on externalities (but also user benefits) could be maximised when specifically designing for car-rail substitution, rather than air-rail. Comparing this result to other simulation, a similar view is seen. However, as the inclusion of user and external benefits increases, it is seen that the modal split rises to a maximum of 22.72 % for the '*5. Sustainability*' scenario.

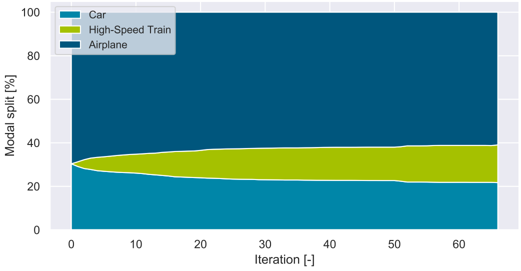

Figure C.23: Iteration development for the modal split per trip (base scenario)

Scenario		Modal split per trip [%]		
		Airplane	HST	Car
Open Market	Liberalisation	62.14	14.68	23.18
	Total Welfare	60.58	17.52	21.90
Centralised market	Total Welfare	60.69	17.30	22.01
	Mobility	58.07	21.68	20.25
	Sustainability	57.26	22.72	20.02
	Future Proof	57.74	22.06	20.20

Table C.10: Modal split per trip for the developed policy scenarios

Modal split per distance:

Given the previous finding that, based on the number of trips, HSR is more competitive to car than it is to air, it becomes interesting to see how the modes perform on different distances. A visualisation for the '*3. Total Welfare (CO)*' scenario of this is plotted in *Figure C.24*. It shows the market share of each mode for different land-distances, which are the road distances corrected for the standard detour experienced in a car. In this scenario, the three modes intercept near 450 kilometre. From that moment on, the HSR shows comparable results to the car for distances larger than 400 kilometre.

Comparing this to the other scenarios, it can be seen that on average, the HSR traveller travels a distance of 488-555 km. This value especially rises for the subsidised scenarios, which can be explained by a more extensive scenario and more opportunities to travel further. This is also

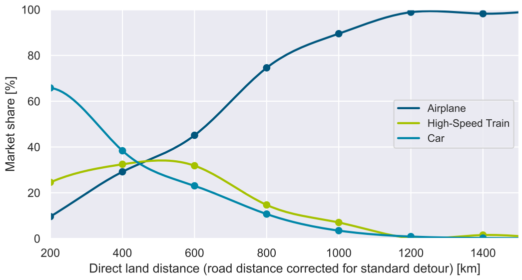

Figure C.24: Iteration development for the modal split per distance (base scenario)

Scenario		Distance [km]		
		Avg. trip HSR	**Intercept Car-HSR**	**Intercept Air-HSR**
Open Market	**Liberalisation**	488	250	500
	Total Welfare	506	450	450
Centralised market	**Total Welfare**	503	450	450
	Mobility	544	650	400
	Sustainability	555	650	350
	Future Proof	545	650	400

Table C.11: Modal split per distance for the developed policy scenarios

confirmed by the modal split per distance development, where it is seen that the more extensive networks especially become more competitive to air travel.

C.5. Connection of the Isolated Findings

The findings of the above discussed sections provide insights in isolated impacts on key performance indicators. However, to allow for a global view that is able to compare the overall impacts of pricing and governance strategies, the separate outputs were combined in *Table C.12*. This table - which was previously discussed in *section 6.2* - presents the effects in normalised values, that are indexed on the base scenario ('*3. Total Welfare (CM))*'. A more thorough analysis of the the aspects that are represented by this table has previously been discussed in the main matter of this thesis, more specifically in *section 6.2*.

Table C.12: Effects of pricing governance strategies - *(revisit of Table 6.2)*

	1. Liberalisation	**2. Total Welfare**	**3. Total Welfare**	**4. Mobility**	**5. Sustainability**	**6. Future Proof**
ψ^{User}	50.0	33.3	33.3	50.0	25.0	37.5
$\psi^{Operator}$	50.0	33.3	33.3	25.0	25.0	25.0
$\psi^{Society}$	0.0	33.3	33.3	25.0	50.0	37.5
	Free market $c^{operator}$ -20%		**Centralised organisation** $t^{transfer}$ -50%			
Number of lines	96	100	100	123	130	143
Connected vertices	93	100	100	105	107	109
Reachable ODs	76	119	100	165	173	169
Centre focused	97	99	100	100	103	102
Total benefits	92	113	100	92	97	97
User Benefits	90	97	100	114	115	117
Operator costs	85	84	100	143	143	143
Societal Benefits	84	101	100	127	134	129
Available seat km	85	105	100	143	143	143
Avg. load factor	97	97	100	95	102	97
Avg. line length	105	108	100	109	99	106
Avg. no. stops / line	100	103	100	108	103	110
Avg. freq. / line	86	92	100	102	107	92
Modal split air	102	100	100	96	94	95
Modal split HSR	85	102	100	125	131	128
Modal split car	105	100	100	92	91	92
Avg. HSR trip dist.	97	101	100	108	110	108
Share direct pax	111	105	100	93	87	96
Share 1-trf pax	48	84	100	129	162	118
Share 2-trf pax	28	40	100	171	155	103
Revenue pax km	82	102	100	136	145	138

D

Detailed Results of the Analysis on High-Speed Rail Design Variables

The third experiment, as defined in *subsection 3.4* on the experimental set-up, concerned the analysis of high-speed rail design variables. This, to find the relative importance of these variables such that they can strategically be used to improve the overall network performance or contribution to desired policy goals. The final outcomes of this experiment have already been discussed in *subsection 6.3* of *chapter 6* on '*Results*'. These encompassing results were however based on a deeper analysis of the separate aspects, which will be discussed in this appendix. An overview of the studied aspects is revisited in *Figure D.1*

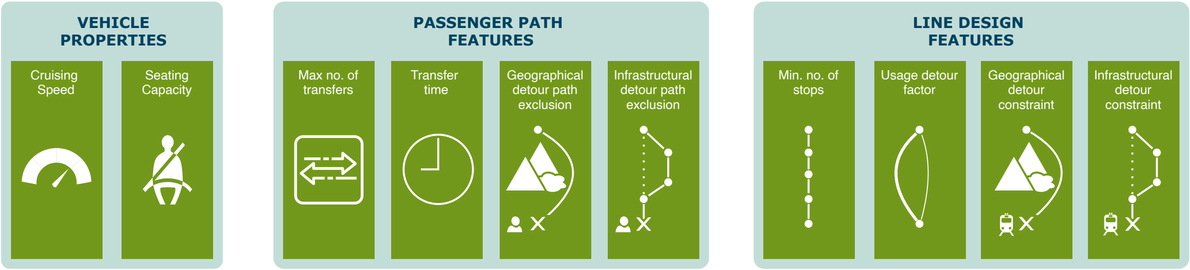

Figure D.1: Overview of modelled HSR design variables - *(revisit of Figure 3.25)*

The overview restates the three-stage division that was used to structure this analysis. The first category is discussed in *section D.1*, which concerns the properties of vehicles that are used on the network. Following this, *section D.2* examines the characteristics of and limitations on the paths that are made by passengers travelling through the network. Subsequently, the third category - focused on the lines that make the '*Pool of Lines*' - are discussed in *section D.3*. To conclude, *section D.4* combines the acquired knowledge into an overall overview, which was used as a base for the analysis of *subsection 6.3*.

D.1. Vehicle Properties

The review of Campos & de Rus (2009) - on 166 high-speed rail projects across the world - found that an variety of trains are used in practice. As was also discussed in *subsection 4.3* on the parameterisation of the European case study, the vehicle properties provided to the model were based on the averaged numbers as found by this author. However, given the variety of trains that are used, it was decided to perform a further analysis on two main vehicle properties: the cruising speed and the seating capacity.

Cruising speed

The maximum vehicle speeds for high-speed trains in Europe - as collected by Campos & de Rus (2009) - ranged between a minimum of 230 km/h, a maximum of 330 km/h and an average of 296 km/h. Considering that - acceleration and deceleration excluded - a train will not always be able to cruise on its maximum speed, it was chosen to model with a cruising speed of 275 km/h. For the analysis on this design variable, three alternative cruising speeds are proposed. This gives the following scenarios: (A) 225 km/h ; (B - base) 275 km/h ; (C) 325 km/h ; (D) 375 km/h. These first values range between the observed speeds by Campos & de Rus (2009) and simulate the more idealised scenario with cruising speeds reaching up to 375 km/h.

Evaluating *Figure D.2*, a positive relationship between the vehicle cruising speed and the three main costs components can be observed. This behaviour indicates that both the benefits from the user and external perspectives, as well as the costs from the operator's side increase, which means that the network grows in its overall size. This is confirmed by the data in *Figure D.3*, where a growth in the revenue passenger kilometers (RPK), feasible OD's is seen.

However, the above described growth does not contribute to all of the stakeholders in the same amount. It is seen that the especially the users benefit from an increase in speeds, whereas the winnings regarding external costs are slightly lagging. This behaviour can again be explained by further information in *Figure D.3*, as it seen here that both RPK and the HSR modal split (in number of trips) strongly grow.

Additionally, the fact that the number of trips does not grow as fast as the RPK, suggest that passengers travel longer distances by high-speed train, indicating that the substitution to HSR mainly originates from air passengers. Combining this with earlier finding (see *section C.2* that car substitution brings more societal benefits than air substitution, explains the behaviour as described.

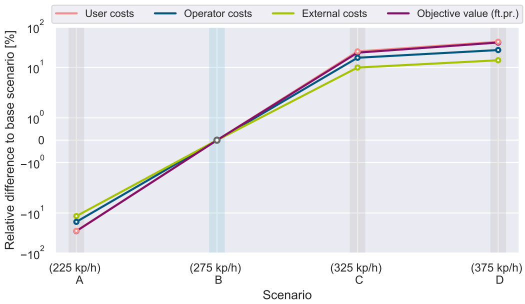

Figure D.2: Monetary stakeholder KPI shifts for cruising speed

Figure D.3: Descriptive network KPI shifts for cruising speed

Seating capacity

In the same work of Campos & de Rus (2009), a range of vehicle seating capacities were found. Based on a minimal observed value of 329 seats, an average value of 439 seats and a maximum capacity of 627 seats per train, the following scenarios are proposed: (A - base) 350 seats; (B) 450 seats ; (C) 600 seats. The base scenario was estimated on the low side of this spectrum, to prevent the model from being limited too much by rounding issues.

Figure D.4 shows a negative correlation for the three costs components and the objective function when increasing the seating capacity of the trains. The clearest example of the underlying behaviour is seen for Scenario B, in which the seating capacity is 450. At this setting, user and societal costs are already displaying a deterioration of the network performance. However, the operator costs are still the same. This finding suggests that the network offers fewer options for passengers, but that the operator still has to make the same expenses.

This suggestion is confirmed by *Figure D.5*. From the passenger's perspective, it is seen that the number of feasible OD's decrease, just like the RPK and number of connected cities. From the operators perspective however, it is seen that fewer lines have to be operated. This could potentially be beneficial for the operator, were it not that this operator has to deal with a relative strong decrease in average network load factor (ANLF) due to to fewer transfer passengers. It makes that in the end, the model performs less when increasing the seating capacity of the vehicles, although it should be mentioned that in using heterogeneous vehicles and operational strategies like merging short turning will likely be able to reduce these problems, whilst benefiting from economies of scale.

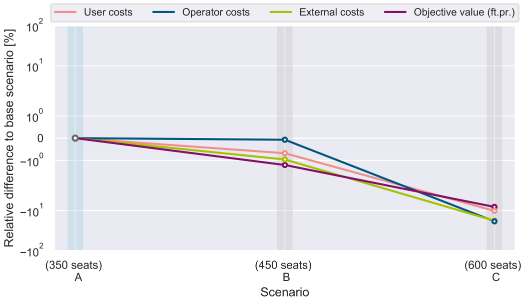

Figure D.4: Monetary stakeholder KPI shifts for seating capacity

Figure D.5: Descriptive network KPI shifts for seating capacity

D.2. Passenger Path Features

The analysis on the passenger path features has a strong link with the '*Method Validation*' of *chapter 5*. Here, it was found that without restrictions on the passengers ability to travel through the network, no feasible network could be made. To solve this, retroactive constraints were added to the '*Problem Definition*' of *chapter 3*. In this section, an analysis is performed on the relevant passenger path features that can be controlled, such that it allows for an improvement of network performance and policy contributions.

Maximum number of transfers

In general, transfers between lines allow passengers to travel further and more diverse paths within the network, whilst using a smaller number of lines. This can be beneficial for as long as the passenger benefits outweigh the operators costs. However, having to make transfers adds up to the dis-utility experienced by passengers, making that the relative overall benefits of using HSR become smaller. Seeking the sweet spot for this, an analysis on the number of allowable transfers was made. In this case, three possible scenarios are sketched: (A) max. 0 transfers ; (B) max. 1 transfer ; (C - base) max. 2 transfers.

Referring to the peak of the objective function value in *Figure D.6*, it quickly becomes visible that system reaches its best performance when allowing for maximum of one transfer. In this situation, the operator has to make fewer costs for transporting unprofitable passengers, whilst users and society experience more benefits. From this point on, it is deduced as to why the other setting perform less.

Comparing Scenario A to B, it is seen that especially large compromises are made by the user and societal benefits when not allowing for transfers. This can be explained by the greatly reduced number of feasible ODs, RPK and active lines.*Figure D.6*. On the other hand, when allowing for a transfer, it turns out that the operator is able to strongly increase its load factors and thus active lines.

Seeing the advantage of allowing for one transfer, it becomes even more interesting to find out why introducing a second transfer deteriorates the overall performance. For this, one of the more explanatory factors is the '*Direct Pax* (d_0)' line, which makes a counter intuitive movement in a 2-transfer model. The increase in the share of direct passengers in combination with the lower load factor and the slightly lower RPK indicates that the model rejects the option of connecting certain parts of the network, which would allow for 2-transfer passengers. This behaviour indicates that the second transfers indeed reaches past the sweet spot between increased travel options offered by the ability to transfer and the reduced profit margin due to the high operator costs involved.

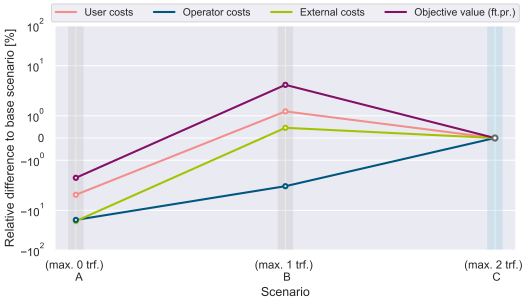

Figure D.6: Monetary stakeholder KPI shifts for the maximum number of transfers

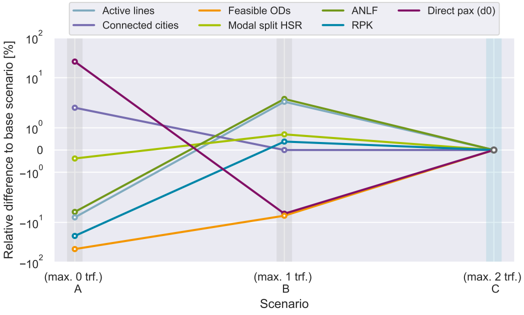

Figure D.7: Descriptive network KPI shifts for the maximum number of transfers

Transfer time

The average transfer time within the network is not a purely given factor, but can be subject to change due to different design, network, policy and strategic decisions. The exact composition of this average transfer time is not influenced by networks that are built in this model, but it is good to know what implications are brought to the system when applying different transfer times. For that reason, transfer times are further analysed in this section based on three scenarios: (A) 15 minutes ; (B - base) 30 minutes ; (C) 60 minutes. Where the last two have also been used to simulate the centralised organisation (B) and free market (C) governance strategies.

Examining *Figure D.8* on the shifts in costs and objective values when changing the transfer time, a clear negative correlation is found. This trend indicates that shortened transfer times directly improve the system. This response is slightly stronger for the operator costs, which suggests that this stakeholder benefits the most from this decision.

The slightly stronger response of the operator goes hand-in-hand with the marginally weaker response of the user. This follows from the previously mentioned theory (*section D.2*) that transfer passengers experience limited benefits from HSR because of the extra time required for transferring, whereas the costs of the operator remain the same. Fending these passengers by longer transfer time should therefore be relatively more beneficial to the operator, than disadvantageous to the user.

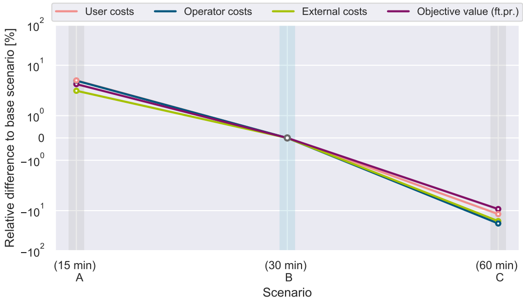

Figure D.8: Monetary stakeholder KPI shifts for the average transfer time

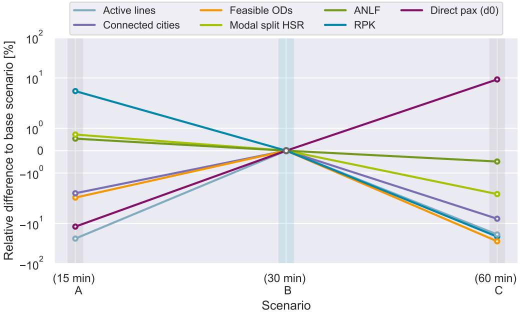

Figure D.9: Descriptive network KPI shifts for the average transfer time

Geographical detouring passenger exclusion

The '*Method Validation*' of *chapter 5* demonstrated the importance of excluding undesirable passengers and indicated the global effect of detouring passengers. These detouring passenger paths were classified in two field, those following a geographical detour around natural barriers and those following an infrastructural detour. To find the exact influence of the first group and to learn how they can be managed, a further analysis on this design aspect was made in this section. More precisely, the factor $fac^{SPL,geo}$ of *Equation 3.30* was varied over different settings. this gave the following scenarios: $fac^{SPL,geo}$ = (A) 1.05 ; (B - base) 1.10 ; (C) 1.15 ; (D) 1.25.

$$p(i,j) = \begin{cases} feasible, & \text{if } ln^{str}_{p(i,j)} \leq fac^{SPL,geo} \cdot ds^{gc}_{i,j} \\ infeasible, & \text{otherwise} \end{cases} \tag{3.30 - revisited}$$

Figure D.10 and *Figure D.11* show that, in contrast to what was previously thought, passengers travelling between geographically obstructed areas do not necessarily have to be excluded from the system. Relaxing this constraint allows for more people to use the system (see RPK), increased modal splits for HSR, higher ANLFs and more feasible ODs.

These positive effects however, do not grow completely linear to the increased $fac^{SPL,geo}$. It is seen that especially scenario C, where $fac^{SPL,geo} = 1.15$, shows a relatively large growth of the user benefits compared to those of society and to the costs experienced by the operator. This effect becomes smaller when reaching $fac^{SPL,geo} = 1.25$

This finding becomes especially interesting when modelling with lower weights for user costs, such as the increased sustainability or the total welfare scenario. In this case, a pivot point where the benefits do not outweigh the costs might be expected.

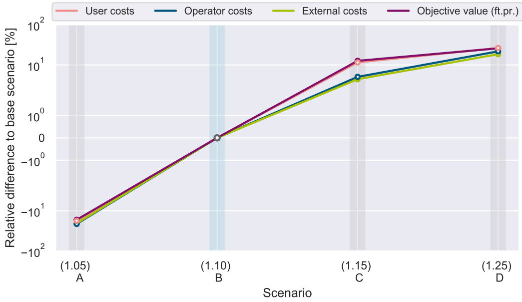

Figure D.10: Monetary stakeholder KPI shifts for strategic pricing level for geographical path detours

Figure D.11: Descriptive network KPI shifts for strategic pricing level for geographical path detours

Infrastructurally detouring passenger exclusion

Similarly to the previous paragraph, this analysis builds upon the findings of the '*Method Validation*' of *chapter 5* which found the importance of controlling detouring passengers. However, for this case, the focus shifts towards the exclusion of passengers following an infrastructural detour, both in time and distance. The tested scenarios were based on the alteration of the infrastructural strategic pricing level $fac^{SPL,infra}$, as used in *Equation 3.29*, and defined as: $fac^{SPL,infra}$ = (A) 1.05 ; (B - base) 1.10 ; (C) 1.15 ; (D) 1.25.

$$p(i,j) = \begin{cases} feasible, & \text{if } t^{inv\&trf}_{p(i,j)} \leq fac^{SPL,infra} \cdot t^{inv,min}_{p^d(i,j)} \\ infeasible, & \text{otherwise} \end{cases} \tag{3.29 - revisited}$$

Analysing the effects of altering the strategic pricing level for infrastructural path detours, as visualised in *Figure D.12* and *Figure D.13*, results in interesting outcomes. The originally chosen factor $fac^{SPL,infra} = 1.10$ finds itself close to a pivot point, where a balance between the users benefits of being able to travel the path they wish and the operators hindrance that is experienced due to moving passengers along relatively inefficient lines, comes close. Slightly reducing the $fac^{SPL,infra}$ to 1.05, and thus excluding even more infrastructural path detours, it is seen that the operators cost reduction strongly outweighs the reduced user benefits. This results an increased performance, as indicated by a growth of the objective function value.

In contrast to previous increases of the objective function value, which frequently resulted from an enlarged network, it is seen that this is not the case for this analysis (see *Figure D.13*). Excluding more detour paths reduces the RPK and number of lines, whilst increasing the ratio of direct passengers and ANLF. This indicates an increase in operator efficiency. However, it does also decrease number of connected cities and feasible ODs, which makes that a smaller contribution can be made on social cohesion. Furthermore, it turns out that a small improvement of the HSR modal split does not weigh out the reduced RPK, making that this move does also not contribute to improved external effects of HSR transport.

On the other side of the graph in *Figure D.13*, a similar but reversed image can be found. It means that it is not possible to give an optimal value for this factor, but that its ideal rate depends on the overall goals of the system, such as extensive policy goals or cost-efficiency.

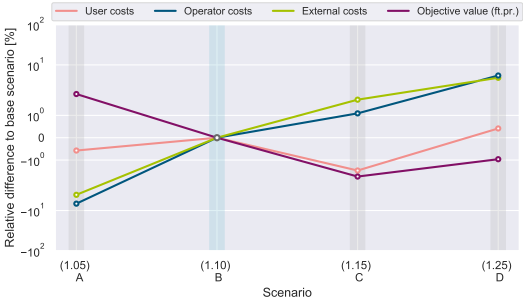

Figure D.12: Monetary stakeholder KPI shifts for strategic pricing level for infrastructural path detours

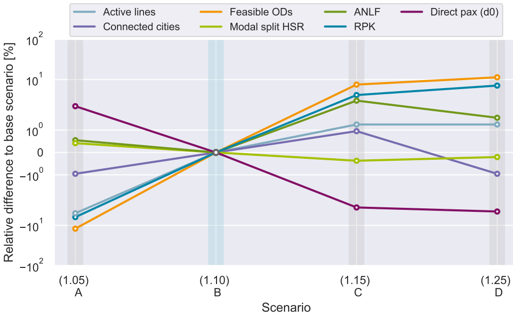

Figure D.13: Descriptive network KPI shifts for strategic pricing level for infrastructural path detours

D.3. Line Design Features

The line design features have a strong connection to the '*Line Generation Procedure*' (LGP) of the proposed heuristic (*subsection 3.3.2* and the '*line design constraints*' of *subsection 3.2.5*. The '*Pool of Lines*', which results from the previous two components, has a substantial impact on the performance of the heuristic. This, because the size strongly impacts the required computation time but also allows for a high-quality solution. To find the right balance in this, a further analysis was made on four aspects that concern the design of lines: (1) the minimum number of stops per line , (2) line design usage factor, (3) allowable geographical line detour and (4) allowable infrastructural line detour.

Minimum number of stops per line

In *subsection 3.2.5* constraint specification, it was chosen to set a constraint (*Equation 3.20*) for the minimum number of stops per line at three (thus two terminal stations and one intermediate station), to prevent the HSR network from nesting with the conventional train and to force the system think as a network. In order to test the legitimacy of this decision, an analysis on the ideal number of stops was performed in this section. For testing, the following scenarios were defined: (A) 2 stops ; (B - base) 3 stops ; (C) 4 stops ; (D) 5 stops ; (E) 6 stops.

The objective function values for all of the relevant scenarios, as indicated by the purple in *Figure D.14*, confirm that the minimum number of three stops allows the system to perform best. This effect is especially strong when increasing the number stops, as it is seen that the performance rapidly deteriorates. The differences on the left-hand side (2-stops) cannot be explained by the argumented nesting effects, as these networks are not modelled for this problem. However, it is possible to find explanatory factors as to why the results are as they are.

For this, a closer look has to be given at the factors that are modelled in *Figure D.15*. For the two-stop scenario, an increase of the ANLF and decrease of RPK and direct passengers is seen. This indicates that the system in general consists of shorter lines, which force the passenger to transfer more often. This leads to more efficient train use, as they are filled to higher degree and the frequency can be set more precisely for that line, but it also decreases the service that is offered to the passengers. This costs aspects are confirmed on the left hand graph (*Figure D.14*), where it is also seen that the operators benefits are not able to outweigh the loss of user and external benefits.

Allowing for more stops, slightly different patterns occur, although they are based on the same principles. For the four-stop scenario (C), it is observed that all factors - except the direct passenger percentage - decrease. This suggests that the model makes lines which are longer than ideal, which is also seen by the lower ANLF. Following this, the lower RPK and connectivity KPIs explain that the model ends with a lower degree of integration. In the final two scenarios, it is seen that this behaviour is taken to such extreme levels, that the connectivity degrees increase, with more feasible OD's an higher RPKs. However, for figure *Figure D.14*, that this comes at very high operator prices, especially when compared to the benefits that passengers experience.

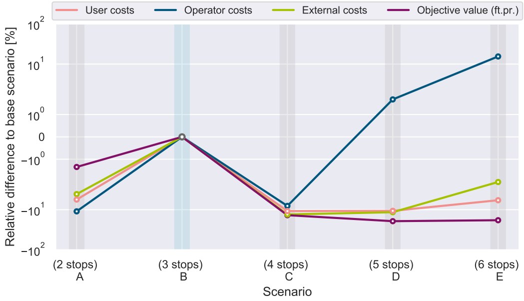

Figure D.14: Monetary stakeholder KPI shifts for the minimum number of stops per line

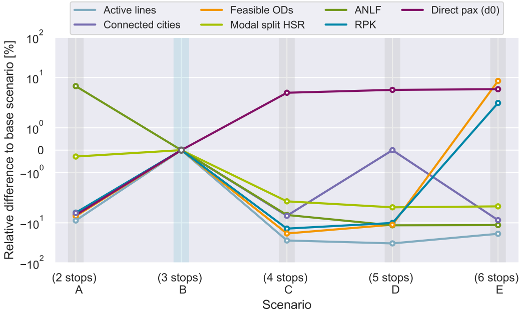

Figure D.15: Descriptive network KPI shifts for the minimum number of stops per line

Demand based lines by usage factor

The line design usage factor (fac^{usage}) - part of demand-based line generation (*subsection 3.3.2*) - was introduced with the idea that it could potentially be beneficial for lines to make small detours, such that they travel along higher demand edges. This would allow the lines to pick up more passengers, although it would require some passengers to accept a slightly longer in-vehicle time. To test whether this could be true, an analysis on the line design usage factor was performed. Below, in *Equation 3.33 - revisited*, the definition of the combined edge weight determination is briefly recapped. The base scenario was executed with time-based lines only (thus $fac^{usage} = 0.00$). For testing, a the following range of alternations was used: fac^{usage} = (A - base) 0.00 ; (B) 0.125 ; (C) 0.25 ; (D) 0.50 ; (E) 0.75 ; (F) 1.00.

$$w^{comb}(i,j) = \left(u^{nor.,inv}(i,j) \cdot fac^{usage}\right) + \left(t^{rid,norm.}(i,j) \cdot (1 - fac^{usage})\right) \qquad \text{(3.33 - revisited)}$$

The result of the main costs component graph of *Figure D.16* provides a clear picture. The best objective value is reached when designing lines as close to their shortest paths as possible. A small detour factor - as modelled in scenario B - is able to provide a benefit for users and society, but these benefits are not out-weighted by the additional operator costs. From the right-hand side graph (*Figure D.17*), it is seen the user and societal benefits mainly originate from an increased RPK between a smaller selection of cities. This is indeed beneficial from a mobility and environmental perspective, but it does decrease the potential for social cohesion. The source for the increased operator costs is mainly found in the combination of the increased RPK with the lowered ANLF. Especially the latter factor explains the relative high operator costs compared to the user benefits.

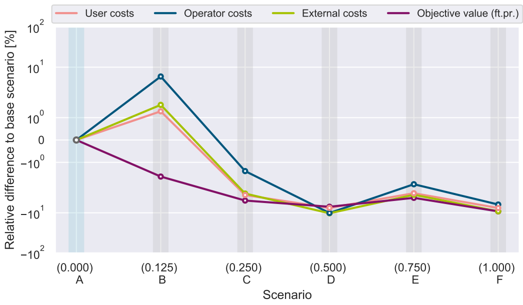

Figure D.16: Monetary stakeholder KPI shifts for the line design usage factor

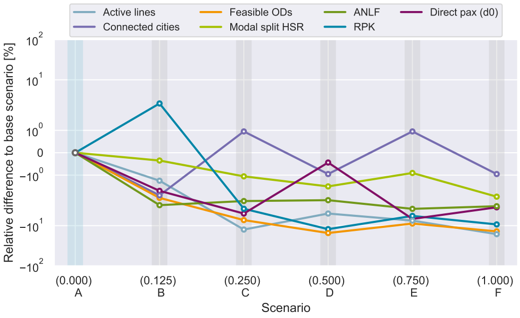

Figure D.17: Descriptive network KPI shifts for the line design usage factor

Line design geographical detour constraint

The line design geographical detour constraint (*Equation 3.24 - revisited*) prevents lines to be selected that are between two terminal vertices and that are separated by a natural obstacle, which make that the line has to make a significant detour. This constraint was introduced to decrease the size of the pool of lines, as it was considered an elegant way of eliminating lines that were less likely to be chosen, since the airplane is likely more competitive due to its direct path character. To evaluate the effect of this decision, an analysis was performed on this factor. The followin scenarios were applied: $fac^{dt,geo}$ = (A) 1.25 ; (B - base) 1.50 ; (C) 1.75.

$$ln^{str}_{l_{k(i,j)}} \leq fac^{dt,geo} \cdot ds^{gc}_{i,j} \tag{3.24 - revisited}$$

Surprisingly,the analysis shows that the setting of the base-scenario (B, 1.50) was non-functional. This can be seen by the comparison with scenario C in *Figure D.18*. In this scenario, the constraint is slightly relaxed, but this gives no effects on any of the KPIs. Analysing the stricter scenario (A) shows that a geographical detour constraint with a factor of 1.25 decreases the performance by approximately 1%. This is explained by relative strong reduction of lines, compared to other KPIs. This suggests that this restraining this factor is especially hurt full when aiming for social cohesion, although effect is not very large.

Line design infrastructural detour constraint

Similar to the previous analysis, this constraint was introduced to reduce the size of the pool of lines, for computational reasons, by eliminating lines that were considered less feasible. The line design infrastructural detour constraint (*Equation 3.23*) eliminates routes between two terminal cities that are poorly connected by infrastructure, such that a relative large detour has to be made compared to the land distance. This means that HSR is likely to be significantly less competitive to the car. For the base scenario, a value of 1.50 was selected. This was tested to both sides by the following scenarios:

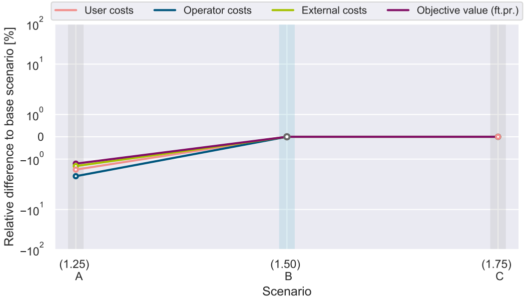

Figure D.18: Monetary stakeholder KPI shifts for the allowable geographical line detour

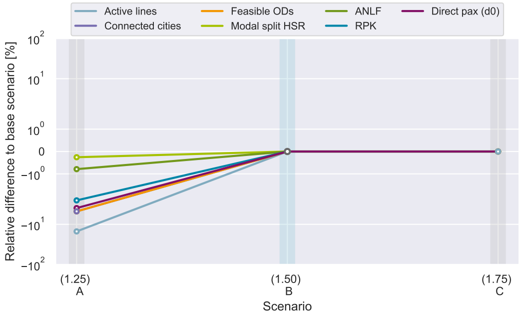

Figure D.19: Descriptive network KPI shifts for allowable geographical line detour

$fac^{dt,infra}$ = (A) 1.25 ; (B - base) 1.50 ; (C) 1.75.

$$ln^{str}_{l_{k(i,j)}} \leq fac^{dt,infra} \cdot p^{d,min}_{i,j} \tag{3.23 - revisited}$$

The costs and objective functions, as plotted in *Figure D.20* show an optimum at the value that was used in the base scenario. Tightening this constraint (A, 1.25) is especially disadvantageous for the user and external interests, as the network becomes less elaborate (fewer lines, connected vertices and OD's). This results in a lower RPK. Maintaining the same average network load factor, but transporting fewer RPKs, the operator books a small advantage, though this is not big enough to compensate. Translating these numbers to reality, it means that this tightened constraint excludes routes that could still be beneficial to the HSR operator, thus that the HST could still be competitive on these routes.

The relaxation of the constraint was tested in scenario C. Here the objective function value decreases again, when compared to the base scenario. In this case, especially the operator experiences a strong cost reduction, although this is not enough to compensate users. Most interesting in this is the joint-effects on the number of lines and the degree of connectivity, as can be seen in *Figure D.21*. It is seen, that more lines are selected, which – contradictory - results in a slightly smaller number of cities and ODs that are connected. It explains that, despite a slightly higher load factor, the operator works relatively inefficient when choosing these routes.

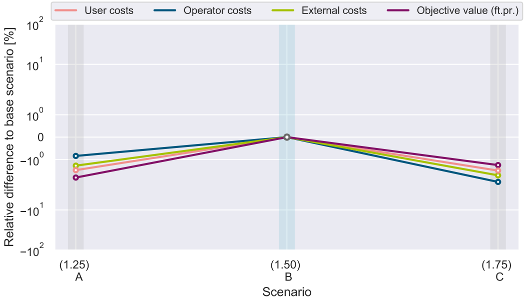

Figure D.20: Monetary stakeholder KPI shifts for the allowable infrastructural line detour

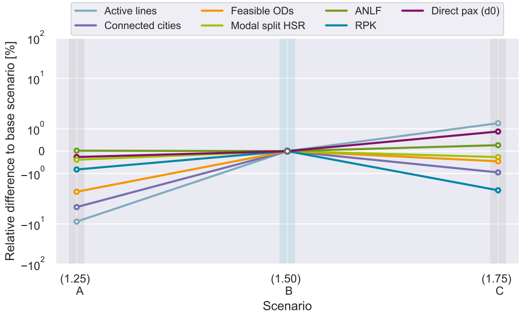

Figure D.21: Descriptive network KPI shifts for the allowable infrastructural line detour

D.4. Overview

The findings of the above discussed sections provide insights in isolated impacts on key performance indicators. However, to allow for a global view that is able to compare the overall impacts of choices in the design variables of high-speed rail, the separate outputs were combined in *Table D.1*. This table - which was previously discussed in *section 6.3* - presents the visualised relations between the design variables and the KPIs in a numerical manner, such that it becomes possible to assess the overall effects when altering one of the variables. A more thorough analysis of the the aspects that are represented by this table has previously been discussed in the main matter of this thesis, more specifically in *section 6.3*.

Table D.1: Estimated relations between HSR design variables and KPI contribution to policy goals - (revisit of *Table 6.3*)

						Operator (cost-efficiency)				User (mobility)			User (social cohesion)			Society (sustainability)		
						Total costs savings	**Operator costs**	**Avg. load factor**	**Share transfer pax**	**User costs savings**	**HSR available seat km**	**Share direct pax**	**No. connect cities**	**Reachable ODs**	**No. of lines**	**Societal costs savings**	**Revenue. pax km HSR**	**Modal split HSR**
	Parameter	**Unit**	**Range**	**Interval**	**Base→ Peak* ↓**	$€\ 2-2.5\cdot 10^7$	$€\ 2-3.5\cdot 10^7$	$60-65\%$	$10-20\%$	$€\ 3-4\cdot 10^7$	$275-625\cdot 10^6 km$	$80-90\%$	$90-115(of 124)$	$400-1150(of 1300)$	$50-90$	$€\ 1-1.5\cdot 10^7$	$175-375\cdot 10^6$ km	$15-30\%$
Vehicle	**Cruising speed**	$[km/h]$	225-375	50	*n/a*	1.276	1.145	1.002	1.213	1.238	1.145	0.946	*Var.*	1.070	1.021	1.090	1.148	1.102
	Seating Capacity	$[seats]$	350-600	50	*n/a*	0.994	0.963	0.994	0.947	0.980	0.963	1.013	0.985	0.937	0.950	0.964	0.958	0.966
Passenger Path	**Max. no. of transfers**	$[trf.]$	0 - 2	1	$\star 1$	0.970*	1.087	0.945*	*Var.*	0.968*	1.087	*Var.*	0.990	1.233	0.939*	0.903*	0.887*	1.089*
	Avg. transfer time	$[min]$	15 - 60	15	$\star 30$	0.979	0.917	0.997	0.722	0.945	0.917	1.070	0.952*	0.915	1.017	0.931	0.913	0.934
	Geo. detour excl.	$[-]$	1.05-1.25	0.05	*n/a*	1.106	1.107	1.008	*Var.*	1.110	1.107	*Var.*	*Var.*	1.162	*Var.*	1.097	1.117	1.114
	Infra. detour excl.	$[-]$	1.05-1.25	0.05	*n/a*	0.974	1.030	1.003	1.066	*Var.*	1.030	0.983	*Var.*	1.059	1.016	1.022	1.033	1.022
Line Design	**Min. no. of stops**	$[stops]$	2 - 6	1	$\star 3$	0.924*	*Var.*	0.955*	0.886	0.962*	*Var.*	1.029	*Var.*	*Var.*	0.925*	0.976*	*Var.*	0.975*
	Usage detour factor	$[-]$	0 - 1	0.125	$\star 0.125$	0.987	0.977*	0.996	1.017	0.986*	0.964*	0.996	*Var.*	0.983	0.980	0.983*	0.980*	0.985*
	Geo. detour constraint	$[-]$	1.25-1.75	0.25	*n/a*	1.009	1.017	1.008	0.844	1.015	1.018	1.040	1.048	1.048	1.150	1.013	1.025	1.017
	infra. detour constraint	$[-]$	1.25-1.75	0.25	$\star 1.50$	0.984*	0.986*	1.001	0.977	0.985*	0.986*	1.006	0.976*	0.989*	1.050	0.985*	0.987*	0.988*

- *Explanation: Base value is expected to change with the relation factor when increased by the interval of the parameter*
- *Special case - peak*: Base value reaches top at peak and changes with same relation* factor in both directions*
- *Special case - var.: no clear pattern could be identified.*

E

Simulation Results of Initial and Synthesis Scenarios

The simulation results start at the next page

E.1. Scenario: Starting (Experiment 1)

C^{tot}	C^{user}	C^{oper}	C^{soc}	N^{line}	V^{con}	OD^{fea}
$€-24.9 \cdot 10^6$	$€-31.0 \cdot 10^6$	$€15.8 \cdot 10^6$	$€-9.7 \cdot 10^6$	54	89	396

APK	RPK	$ANLF$	d^0	d^1	d^2	MS^{HSR}
$277 \cdot 10^6$	$168 \cdot 10^6$ km	60.5	92.0%	7.5%	0.5%	14.7%

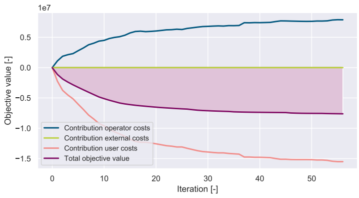

Figure E.1: Objective function

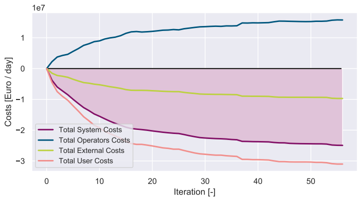

Figure E.2: Main costs components

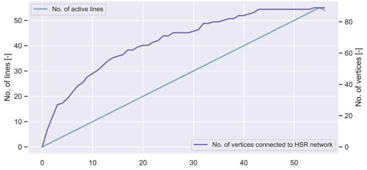

Figure E.3: Network completeness

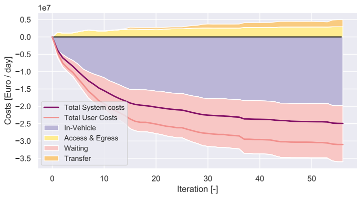

Figure E.4: User costs components

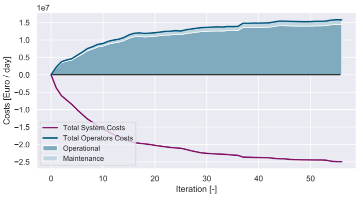

Figure E.5: Operator costs components

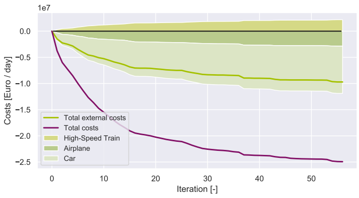

Figure E.6: Societal costs components

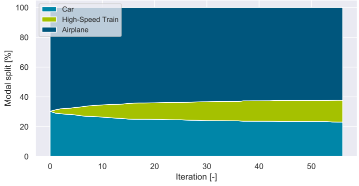

Figure E.7: Modal split for trips

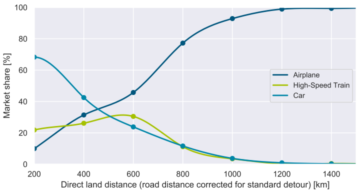

Figure E.8: Modal split per distance

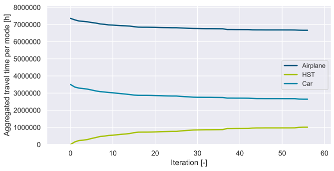

Figure E.9: Aggregated travel times

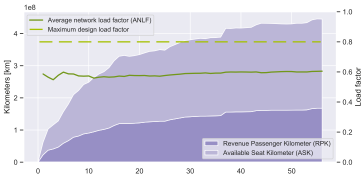

Figure E.10: Operator performance

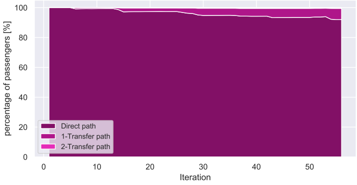

Figure E.11: Trip transfer characteristics

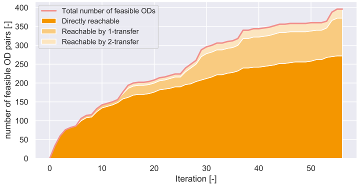

Figure E.12: OD-reachability

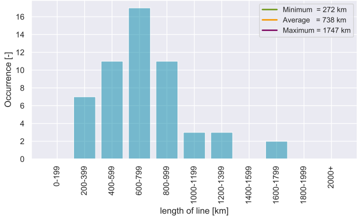

Figure E.13: Line lengths

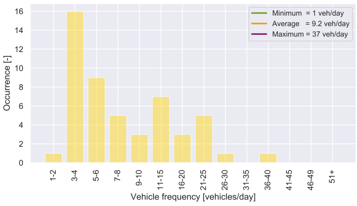

Figure E.14: Line frequencies

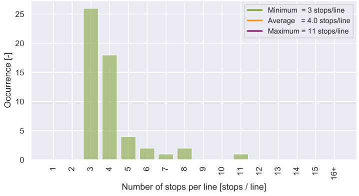

Figure E.15: Line stops

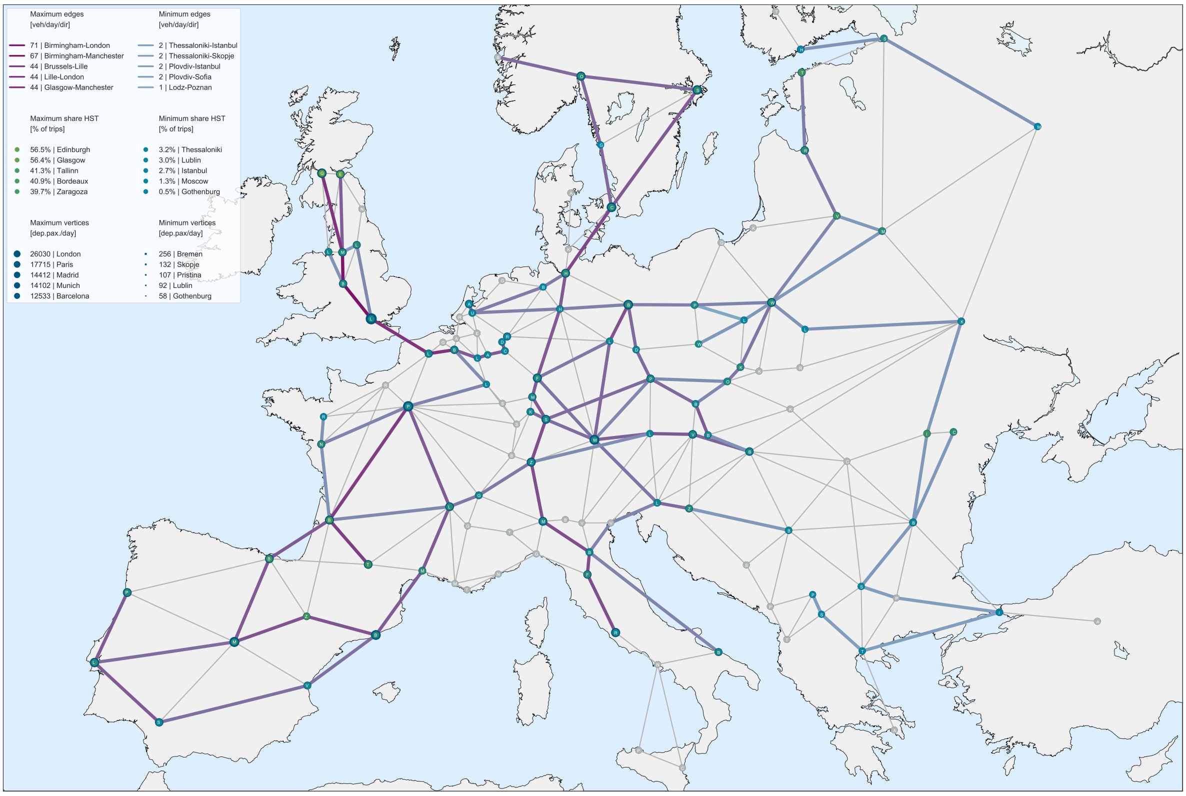

Figure E.16: Vehicle frequency per edge and market share High-Speed Train per city

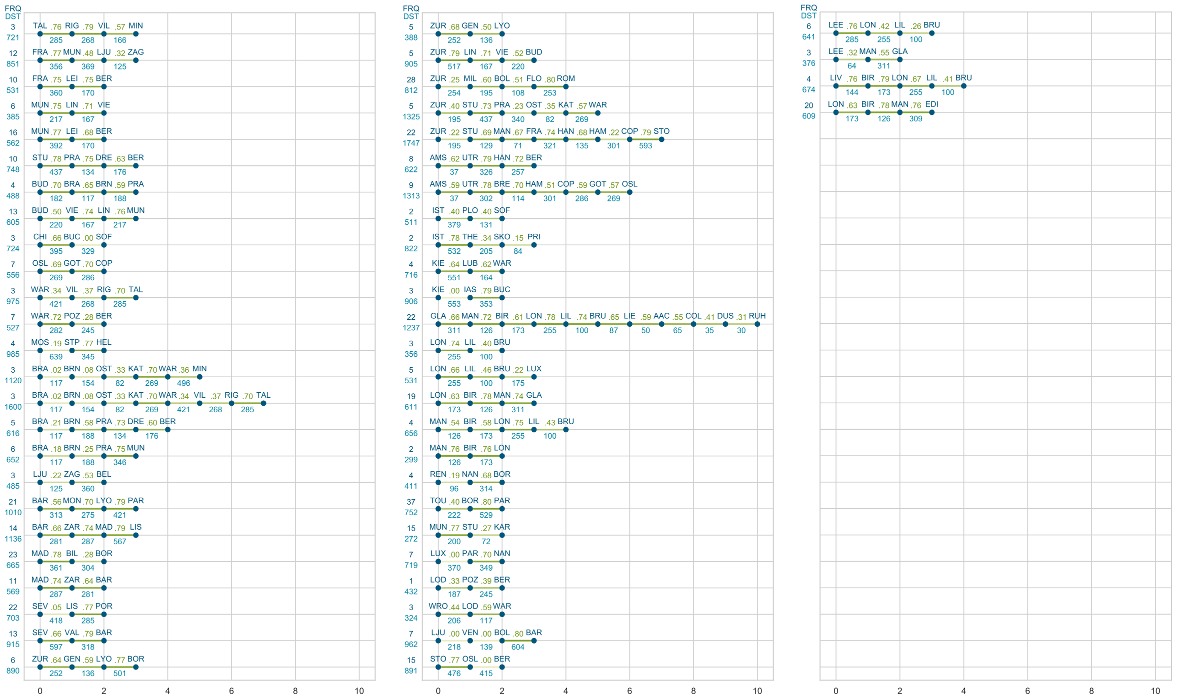

Figure E.17: Set of Lines

E.2. Scenario: Economical (Experiment 4)

C^{tot}	C^{user}	C^{oper}	C^{soc}	N^{line}	V^{con}	OD^{fea}
€$-35.7 \cdot 10^6$	€$-48.0 \cdot 10^6$	€$28.4 \cdot 10^6$	€$-16.4 \cdot 10^6$	83	110	944

APK	RPK	$ANLF$	d^0	d^1	d^2	MS^{HSR}
$300 \cdot 10^6$	$499 \cdot 10^6$ km	59.97	87.5%	12.5%	n/a	25.0%

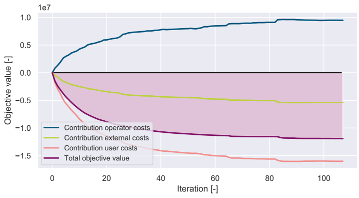

Figure E.18: Objective function

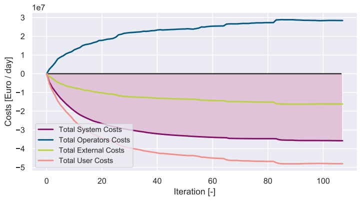

Figure E.19: Main costs components

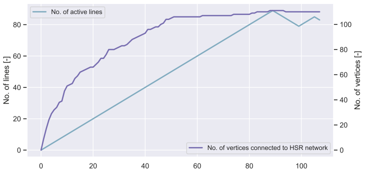

Figure E.20: Network completeness

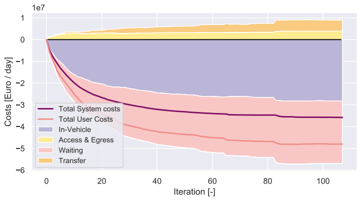

Figure E.21: User costs components

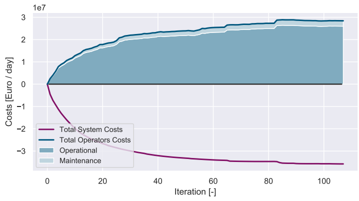

Figure E.22: Operator costs components

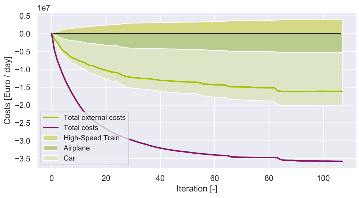

Figure E.23: Societal costs components

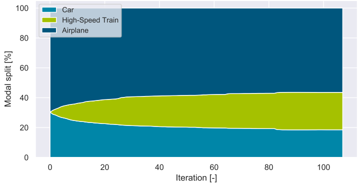

Figure E.24: Modal split for trips

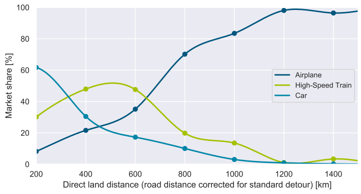

Figure E.25: Modal split per distance

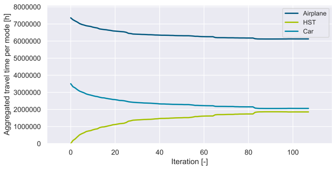

Figure E.26: Aggregated travel times

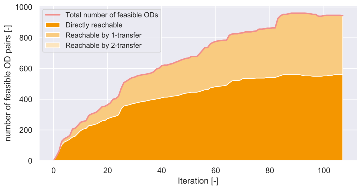

Figure E.27: Operator performance

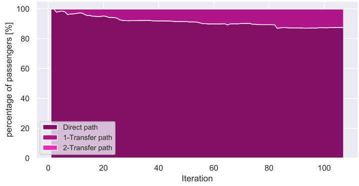

Figure E.28: Trip transfer characteristics

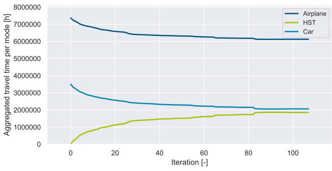

Figure E.29: OD-reachability

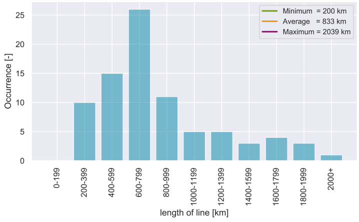

Figure E.30: Line lengths

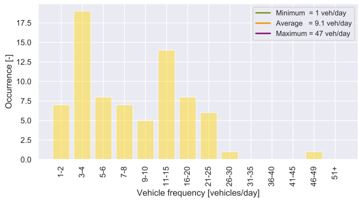

Figure E.31: Line frequencies

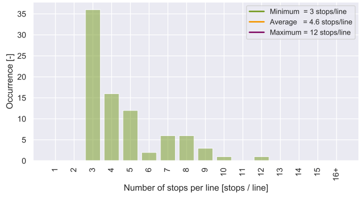

Figure E.32: Line stops

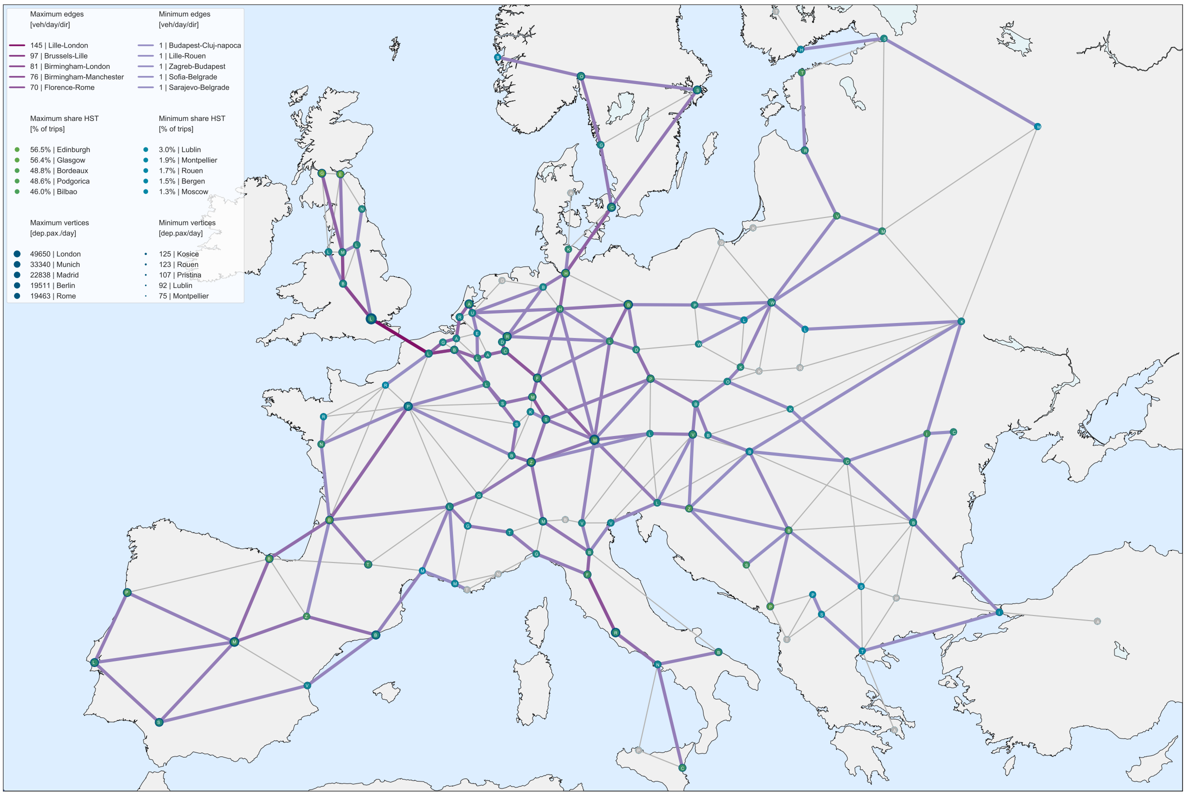

Figure E.33: Vehicle frequency per edge and market share High-Speed Train per city

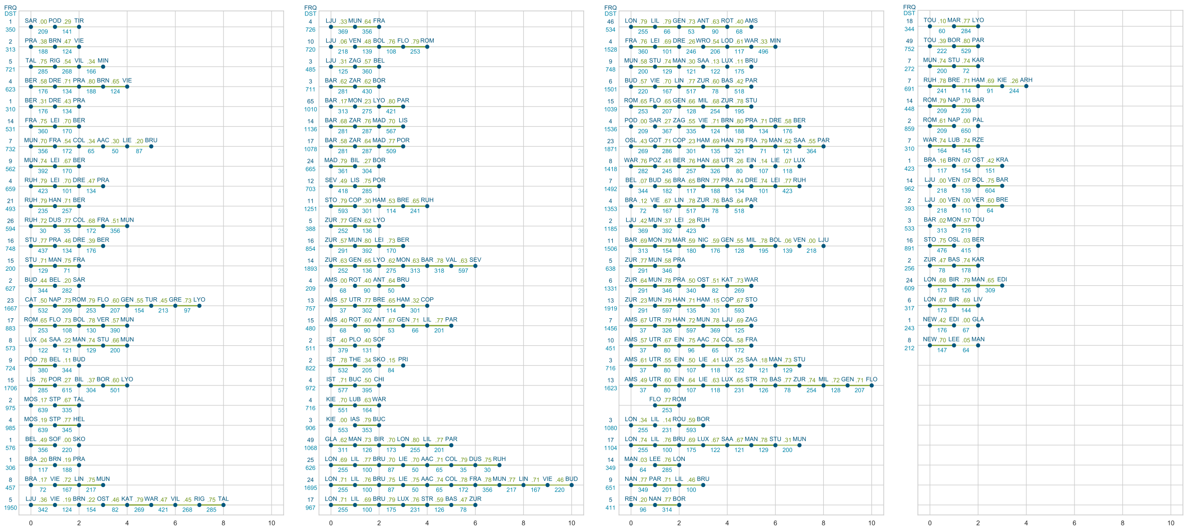

Figure E.34: Set of Lines

E.3. Scenario: Extensive (Experiment 4)

C^{tot}	C^{user}	C^{oper}	C^{soc}	N^{line}	V^{con}	OD^{fea}
€$-29.9 \cdot 10^6$	€$-55.5 \cdot 10^6$	€$45.0 \cdot 10^6$	€$-19.4 \cdot 10^6$	91	116	1148

APK	RPK	$ANLF$	d^0	d^1	d^2	MS^{HSR}
$633 \cdot 10^6$	$378 \cdot 10^6$ km	59.68	77.8%	22.2%	n/a	29.9%

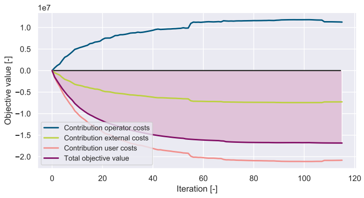

Figure E.35: Objective function

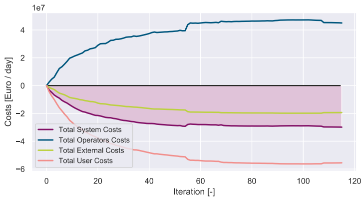

Figure E.36: Main costs components

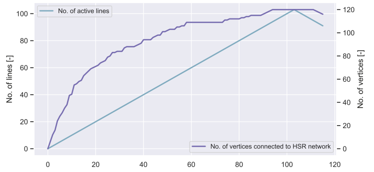

Figure E.37: Network completeness

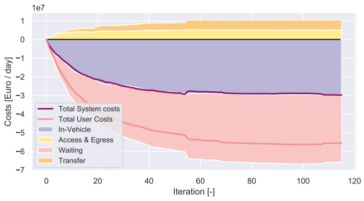

Figure E.38: User costs components

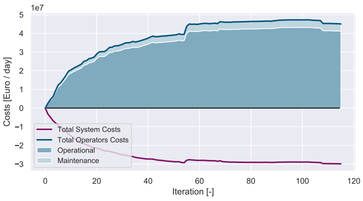

Figure E.39: Operator costs components

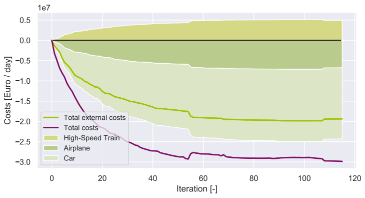

Figure E.40: Societal costs components

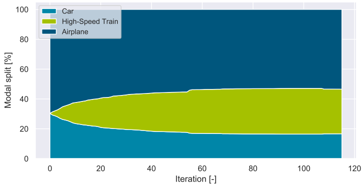

Figure E.41: Modal split for trips

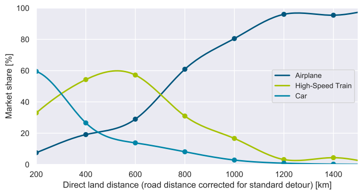

Figure E.42: Modal split per distance

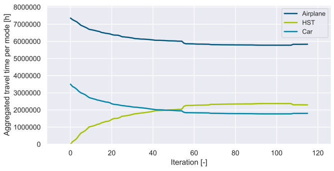

Figure E.43: Aggregated travel times

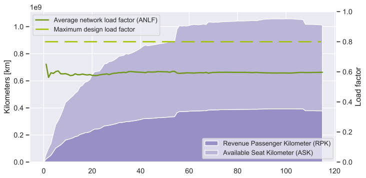

Figure E.44: Operator performance

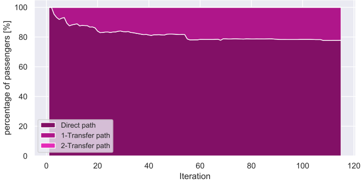

Figure E.45: Trip transfer characteristics

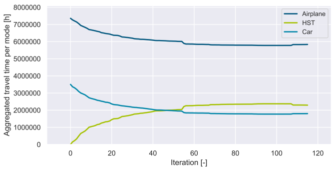

Figure E.46: OD-reachability

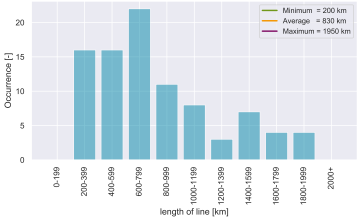

Figure E.47: Line lengths

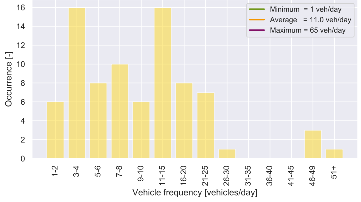

Figure E.48: Line frequencies

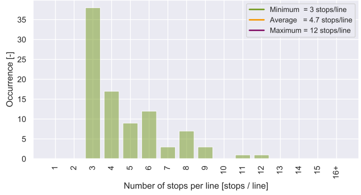

Figure E.49: Line stops

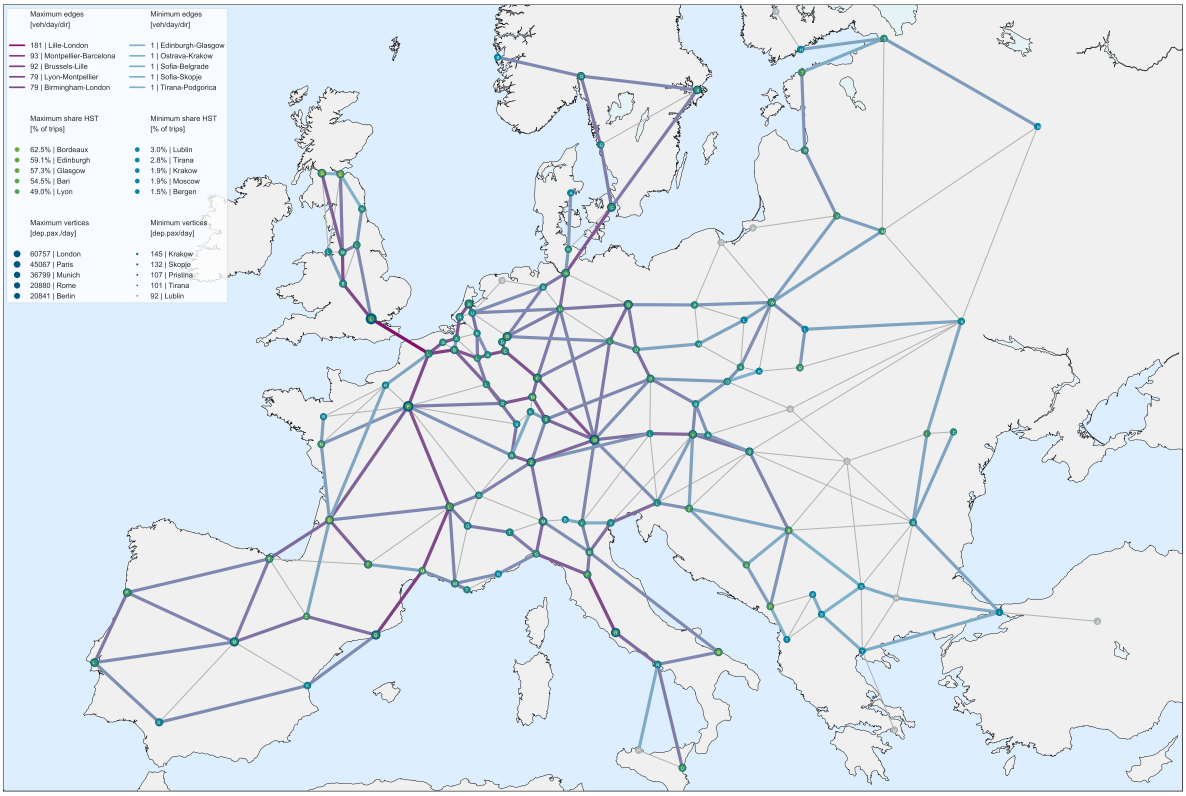

Figure E.50: Vehicle frequency per edge and market share High-Speed Train per city

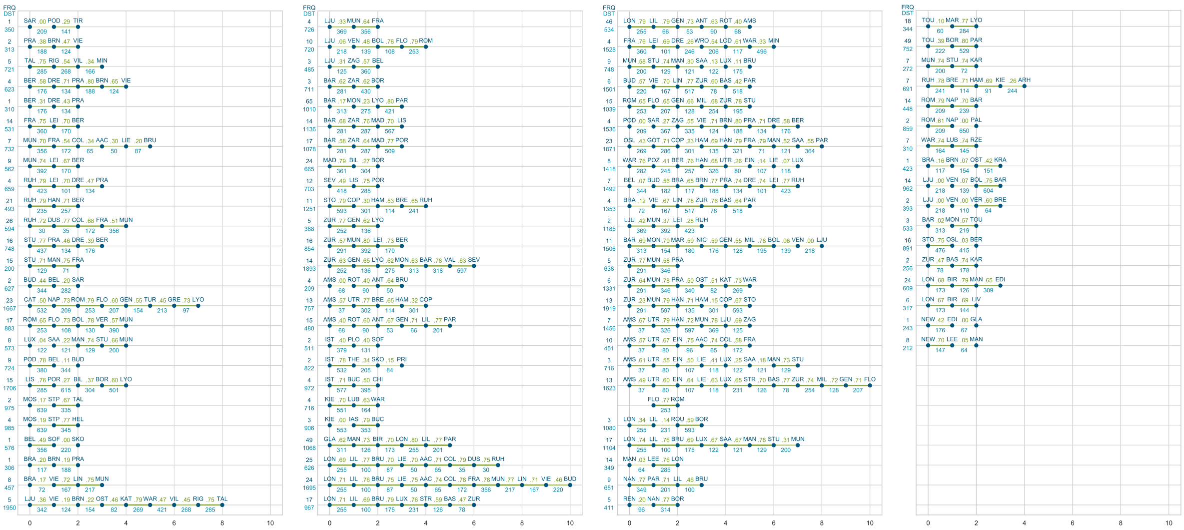

Figure E.51: Set of Lines