Politecnico di Milano

SCHOOL OF INDUSTRIAL AND INFORMATION ENGINEERING

Master of Science – Aeronautical Engineering

Demand estimation and optimal network definition of a hybrid-electric commuting air transport system

Supervisor

Lorenzo TRAINELLI

Co-Supervisor

Alberto ROLANDO

Carlo E. D. RIBOLDI

Candidate

Germán GARCÍA GONZÁLEZ – 10646571

Academic Year 2019 – 2020

Acknowledgements

First and more important, I would like to thank Francesco Salucci for his constant support and guidance throughout these months, despite all of the difficulties. This thesis would not have not been possible without his help.

Special appreciation goes to Pablo and Víctor, for the support, advice, and putting up with my crankiness (in distance mode).

Also, thank you to Gianluca Magni from the help provided and for letting me continue somehow his work. I would like to thank also professors Maurizio Bruglieri and Roberto Maja, for their orientation at the beginning of my work. Also to Martin Lankowski from AMPL Inc. for providing the necessary software licenses without hesitation.

Finally, to my professor and supervisor Lorenzo Trainelli, and the co-supervisors Carlo Riboldi and Alberto Rolando, for the opportunity they gave me allowing me to do a small contribution to their project.

Sommario

In questa tesi si studia la stima della domanda e la definizione di rete ottimale di un innovativo sistema di trasporto in aria pulita rivolto a passeggeri regolari (pendolari). L'Intercity miniliner è un aereo ibrido-elettrico da 19 posti Near Zero Emission (NZE) che può essere utilizzato da un piccolo aeródromo oro secondario anche da piste non asfaltate. In questo modo non necessita di infrastrutture aggiuntive. È un'alternativa ecologica ed efficiente ai viaggi su strada, l'attuale scelta principale per i pendolari a lunga distanza. Lo scenario presentato è il mercato italiano, ma il sistema è preteso di essere Scalato a livello europeo. Il punto di partenza è una matrice origine-destino dei pendolari, ovvero il numero di pendolari che vivono in una città e lavorano in un'altra città. Al fine di determinare per quali rotte il miniliner Intercity è competitivo, il suo tempo di percorrenza viene confrontato con quello su strada per lo stesso viaggio. Successivamente, la richiesta viene introdotta in un modello matematico Integer Linear Programming (ILP) che risolve il Green Vehicle Routing Problem (GVRP), ottenendo così la rete ottimale. Particolare attenzione viene prestata all'influenza sia dei parametri dell'aeromobile (autonomia, velocità di crociera ...) che dei parametri di rete (dimensione della flotta, fattore di carico minimo) sul risultato finale.

Abstract

In this thesis, the demand estimation and optimal network definition of an innovative clean air transport system is studied aimed at regular passengers (commuters). The Intercity miniliner is a NZE 19-seater hybrid-electric aircraft that can be operated from small secondary aerodromes or even unpaved runways. This way, it does not need additional infrastructure. It is an environmentally-friendly and efficient alternative to road travel, the current main choice for long distance commuting. The scenario presented is the Italian market, but the system is pretended to be scaled at a European level. The starting point is an origin-destination matrix of commuters i.e. the number of commuters that live in a town and work in another town. In order to determine for which routes the Intercity miniliner is competitive its travel time is compared to road travel for the same trip. Afterwards, the demand is introduced in a mathematical ILP model that solves the GVRP, thus obtaining the optimal network. Special attention is paid to the influence of both aircraft parameters (range, cruise speed...) and network parameters (fleet size, minimum load factor) on the final result.

Contents

Acknowledgements **iii**

Sommario **v**

Abstract **vii**

Contents **x**

List of Figures **xii**

List of Tables **xiii**

1 Introduction **1**
1.1 Motivation 1
1.2 MAHEPA project 3
1.3 UNIFIER19 project 4
1.4 Microfeeder and Intercity problems 4

2 Potential demand estimation **7**
2.1 Origin-Destination matrix 8
2.2 Aerodrome clustering and selection 9
2.3 Travel time comparison 10

3 Optimal network definition **19**
3.1 Demand time distribution 19
3.2 Mathematical model 21
3.2.1 String model 21
3.2.2 Demand splitting 24
3.3 Optimization 25

4 Results **27**
4.1 Commuter flows 27
4.2 Potential demand estimation 29
4.2.1 Runway, cruise speed and range sensitivity analysis 30
4.2.2 Airport times and time gain sensitivity analysis 36
4.3 Optimal network definition 38
4.3.1 Full day case 41
4.3.2 Capacity relaxation 42
4.3.3 Sensitivity analysis 43

5 Conclusion **47**

A Additional data **49**

Acronyms **53**

Bibliography **56**

List of Figures

Figure 1.1 Extra-urban commuting distribution in Italy according to means of transportation used. 2
Figure 1.2 MAHEPA logo. 3
Figure 1.3 UNIFIER19 logo. 4

Figure 2.1 Italian aerodrome selection after clustering 11
Figure 2.2 Example of the dendogram resulting from a clustering process. From [1]. 12
Figure 2.3 Scheme of the commuting trip phases using the miniliner aircraft as opposed to traditional commuting by car (grey). 13
Figure 2.4 Transition from the original OD matrix to the aggregated aerodrome OD matrix 15

Figure 3.1 Distribution of commuters in Italy according to departure time. 20
Figure 3.2 Distribution of intercity network demand along the day. 21
Figure 3.3 Example of the demand distribution after being splitted. . . . 24

Figure 4.1 Extra-urban commuting distribution in Italy according to means of transportation and condition (student or worker). 28
Figure 4.2 Extra-urban commuting distribution in Italy according to residence region (NUTS 2 level). 29
Figure 4.3 Commuter outflow distribution in Italy according to residence region (NUTS 2 level). 30
Figure 4.4 Employed persons commuting to another region within their country in Europe [2]. 31
Figure 4.5 Miniliner travel time and road time for all the town pairs, including trip constraints. 32
Figure 4.6 Miniliner time advantage with respect to road distance for all the town pairs. 32
Figure 4.7 Potential demand sensitivity analysis against the aircraft design parameters results for minimum runway length of 600 meters. 33
Figure 4.8 Potential demand sensitivity analysis against the aircraft design parameters results for minimum runway length of 800 meters. 34
Figure 4.9 Potential demand sensitivity analysis against the aircraft design parameters results for minimum runway length of 1000 meters. 35
Figure 4.10 Potential commuter sensitivity against minimum runway length requirement and range. 36
Figure 4.11 Active towns and aerodromes for different ranges and cruise speeds (minimum runway length 800m). 37

Figure 4.12 Potential commuters with respect to overall airport time and time gain parameter. 38
Figure 4.13 Town pair selection results for different values of the airport times and gain time parameter. 39
Figure 4.14 Captured demand of the optimized network in the nominal case for different fleet sizes and charging times. 40
Figure 4.15 Optimal Intercity network. Fleet 200 aircrafts. Load factor = 0.8. Aircraft capacity = 19 pax. $t_{\text{charge}} = 1800$ s. 41
Figure 4.16 Captured demand of the optimized network in the full day case for different fleet sizes and charging times. 42
Figure 4.17 Captured demand of the optimal network in the relaxation case (no capacity minimum nor maximum). 43
Figure 4.18 Maximum demand captured by the optimal network against load factor and aircraft capacity. 43
Figure 4.19 Demand captured by the optimal network as a function of fleet size and charging time for different load factors and aircraft capacities. 44
Figure 4.20 Maximum captured demand for different values of the time slot resolution. 45
Figure 4.21 Demand captured by the optimal network for commuter flows double and quadruple of the nominal one. 46

List of Tables

Table 2.1 ISTAT commuting matrix field description 16
Table 2.2 Nominal parameters of the miniliner aircraft. 17
Table 2.3 Times associated to the airport. 17
Table 2.4 Nominal parameter value for the activation criteria. 17

Table 4.1 10 routes with more estimated demand in Italy. 35
Table 4.2 Nominal parameters of the Intercity transportation system. . . 39
Table 4.3 Potential and captured absolute demand and demand increments in cases with increased commuter flows ($t_{\text{charge}} = 1,800$ s. Fleet size 200 aircrafts). 46

Table A.1 List of Italian clustered airports with a cut distance of 50km. . 51

Chapter 1

Introduction

1.1 Motivation

Aviation has to face some deep changes in the near future. These changes have to respond to a series of challenges. The main challenge is climate change and keeping up with the green revolution happening at a worldwide level. From an objective, scientific, point of view, this is a mandatory issue to solve. The future of mankind is at stake if polluting activities are not limited. Better said, polluting activities have to transform themselves, finding alternatives to reach the same goals while being environmentally friendly. This is currently one of the main roots around which national and international policy is built and no industry branch is left outside of it.

Few months ago, in January 2020, European Parliament approved the European Green Deal. The European Green Deal is a comprehensive package of policies with the main objective of making European Union (EU) climate neutral by 2050. One of its main areas is sustainable mobility and, of course, aviation is included in that.

But these are not the first efforts at making aviation sustainable and environmentally-friendly. Commercial aviation has been included in the European Union Emission Trading Scheme (EU-ETS) since 2012 [3]. After, International Civil Aviation Organization (ICAO) introduced in 2016 the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which aims at a carbon neutral growth in aviation from 2020 [4].

It is evident that aviation is in the spotlight of the fight against climate change and has been vilified. This has led to episodes as that of Greta Thunberg, the Swedish climate activist, that crossed the Atlantic in a sailing yacht *twice* to avoid taking a plane [5]. This already belongs to pop culture. But, what if aviation could also be part of the solution to sustainable mobility?

Let us focus in the short-haul, regional mobility. The main alternatives in this range are private car, train and bus. In Europe there is a well developed train infrastructure and most of it is electrified, so it can be considered environmentally friendly in a first approach, without considered the energy mix behind it. However, existing infrastructure is generally old, imposing speed limitations. On the other hand, building new infrastructure (as in the case of new high speed networks) requires a large investment.

Cars and buses are lower density means (specially cars). In the European case, buses are generally relegated to areas in which train connections are not available, usually associated to low population density areas. Road transport is the largest single contributor to greenhouse effect gases emissions due to transportation, being responsible of up to 70% of the emissions [6]. It is true that automobile industry is shifting towards an electric propulsion model but their low density is associated to traffic congestion problems which, in some cases, can be quite severe. Hence, cars are not only polluting, but also slow as a consequence of infrastructure saturation (road congestion).

Congestion is associated to peak traffic hours, directly related to commuting. The reference scenario for this thesis will be the Italian case. To analyze the commuting phenomena in Italy, the data from 2011 Census [7] will be used. In Italy, more than 75% of the extra-urban commuting population (people that work or study in a different town than their residence town) does so by car. This is shown in Figure 1.1.

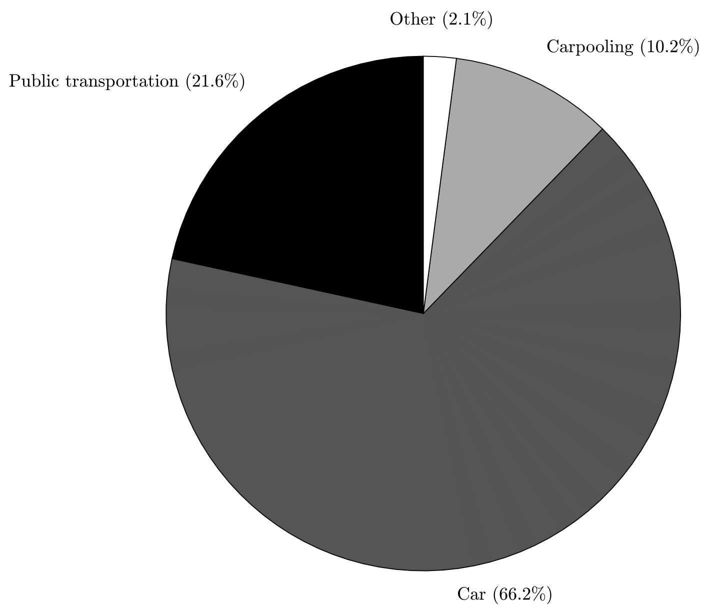


Figure 1.1. Extra-urban commuting distribution in Italy according to means of transportation used.

This shows that improvement of current solutions is not enough. A breakthrough has to come, and a new solution with it. This breakthrough is electric aviation and the solution proposed is a 19-seater hybrid-electric aircraft, the miniliner. In this way, an efficient, ecological, and fast transportation system is established.

This thesis takes the expertise and knowledge about electric aviation and sustainable aerial mobility developed over the last years with the Framework Programmes for Research and Technological Development (H2020) projects Modular Approach to Hybrid-Electric Propulsion Architecture (MAHEPA) and commUNIty FrIendly minilinER (UNIFIER19) and shapes it to study the feasibility and potential impact of such a solution.

1.2 MAHEPA project

MAHEPA is a European research project funded by EU's Horizon 2020 program aimed at studying and developing hybrid-electric powertrains to enable cleaner, quieter and more efficient aircraft propulsion. It is participated by different research institutions, private companies and universities, among which Politecnico di Milano is found.

Figure 1.2. MAHEPA logo.

MAHEPA is focused in two types of hybrid-electric powertrains. Both of them are propulsed by an electric engine connected to a propeller or fan. The difference lays in the auxiliary energy supply that complements the battery, connected in serial.

- The first one features an Internal Combustion Engine (ICE) powered by conventional fuel.
- The second one features a hydrogen fuel cell. The use of this architecture enables for a zero-emission aircraft propulsion plant.

This is paving the way to achieve clean aviation goal towards 2050, which is part of the already mentioned European Green Deal. MAHEPA is preparing the industry and the market for the actual implementation of hybrid-electric aircraft. One of its goals is to flight test the powertrains. First powertrain to be tested will be the one featuring the ICE, which has already completed all the pre-flight qualification tests[1]. Inspiration for hybrid-electric aviation applications as the one presented in this thesis stem from MAHEPA project.

[1]https://www.pipistrel-aircraft.com/major-milestone-announcement-mahepa-electric-drive-unit-completed-pre-flight-qualification-tests/

1.3 UNIFIER19 project

UNIFIER19 is also a H2020 funded project that grows around the very same concept which is treated here, the miniliner. This concept goes beyond just providing with a cleaner solution to existing commuters. Its main goal is creating an innovative NZE air mobility solution for European communities, specially aimed at those that lack of adequate infrastructures.

Figure 1.3. UNIFIER19 logo.

The miniliner is a 19-seater hybrid-electric aircraft defined as community friendly and targeted to small aerodrome operations. Power source distribution of the hybrid scheme is such that electric propulsion is only used during maximum power flight phases (taxi-out, takeoff and initial climb). As a consequence, the miniliner only pollutes during cruise, which is the most efficient flight phase and the point at which the aircraft design is optimized.

It is tagged as friendly not only because is cleaner, but also because is quieter. This is specially important considering that many small aerodromes are built close to populated areas.

The project is not only focused on the miniliner design, it is a comprehensive and ambitious proposal focused in many aspects of the transportation system as a whole. It covers, apart from aircraft design, market studies, emission analysis and cost analysis (studied by R. Ibrahim on his thesis [8]) not only from the operation point of view, but also considering the underlying infrastructure (as battery charging stations) problem.

Hence, there is no need to say that the problem addressed in this thesis and its results are framed as part of the UNIFIER19 project.

1.4 Microfeeder and Intercity problems

Rather than focusing in the design of the miniliner or the challenges posed by the hybrid-electric powertrain and its certification, this thesis treats the feasibility of an air transportation system based in the miniliner. Two types of miniliner-based transport systems have been studied so far.

- The Microfeeder: this concept consists in operating the miniliner to provide (feed) main airports (hubs) with passengers from relatively distant communities which would otherwise have to travel by private or public means to the airport before taking their traditional (whether domestic or international) flight. This approach reduces the total travel time, making aviation more competitive and contributing towards the 4 hours door to door Flightpath 2050 vision [9]. It lays the foundation of this work and was extensively studied by G. Magni [10] and before by D. Gabrielli [1]. Results on the microfeeder network definition are published in [11], where the optimization of the demand satisfied is assesed, and in [12], where the system is globally defined.

- The Intercity: The next logical step to the Microfeeder is to operate the miniliner not only as a support to current air transport networks but to create a new air transport network that competes with ground transportation. To approach it, the commuting problem is used. Socially and economically, only regular passengers would profit from being able to fly to their destination and avoid driving 100km or taking a train for more than 1 hour, and those passengers are commuters. Commuters live and work (or study) in different places. The most usual case is to find metropolitan areas where distances are not that large but, depending on the area, considerable groups of people even change province every day to work, which is the scenario in which the Intercity (or sometimes microcommuter) looks more promising.

This thesis focuses in the intercity concept focused in the commuting phenomena, and is divided in three main parts: potential demand estimation, network definition and network optimization. The scenario used is based upon the Italian market, but the approach is intended to be extended to all the European market in a systematic way.

Chapter 2

Potential demand estimation

In this chapter, the techniques and procedures applied to generate an indicator of the potential demand of the miniliner service are detailed. It is important to note that, even though the results obtained come from exact data and concrete operations, they should be taken with caution. Some important aspects have not been considered for the analysis, as the complexity of this part of the problem would increase to levels that would make impossible to analyze it from a broad perspective, as it is intended to be done. For instance, cost analysis, which definitely has an impact on demand, is not considered. More information about costs associated to the operation of the miniliner are found in R. Ibrahim thesis [8].

In particular, demand is estimated from data coming from the 2011 Italian census, performed by Istituto Nazionale di Statistica (ISTAT). Therefore, due to the nature of this data, at this point, it would be more adequate to refer to traffic flow rather than demand. Data of people commuting from one town to another using traditional means (private vehicle, train, bus..) is analyzed. At this stage, information regarding how interesting the alternative proposed is to current commuters is not available. To obtain this, the process to follow would not trivial.

First of all, a series of surveys should be done, sampling potential users and asking them about their Stated Preferences (SP), from which their travel behavior in a fictitious scenario could be obtained. Then, using the surveys results and knowing the SP, the parameters of the demand model are calibrated and the model would be ready to use. This is the standard when analyzing the viability of a new transportation option for a certain route [13].

It is evident that the goals of this project makes quite unfeasible using the SP to develop a demand model. The objective of the project is analyzing a network that can range from the regional to the international level, not a single route. Additionally, the geographical area covered is not socioeconomically homogeneous. The solution in order to implement the SP surveys approach, if any, would be to appropriately sample the targeted population. This would be a very complex task and clearly remains out of the scope of this thesis.

In addition to the complexity of sampling and surveying are *per se*, there are aspects needed to conduct them not available at this point. Specifically, the economical indicators are missing. For instance, the range in which the miniliner tickets price would lay is unknown.

2.1 Origin-Destination matrix

The first step in estimating the demand of the miniliner is to have an image of commuting habits. As it has been already mentioned, the Italian case will be the reference throughout this thesis. As part of the census ISTAT realizes every 10 years, a commuting matrix (*Matrice del pendolarismo*) is included. All the data is freely available at [7]. In particular, this thesis is based on the commuting matrix from the 15^{th} population and housing census from 2011.

Rather than a matrix, the "raw commuting matrix" is a list of entries/records. There are two types of records:

- "S" records: They have a general nature. They make reference to the total commuter flow (independently of the means of transport used). The count reported is an exact one
- "L" records: They have a more detailed nature. They segregate data by means of transportation used (*mezzo*), time of departure (*orario di uscita*), and the trip time (*tempo impiegato*). The count reported is an estimated one.

The commuting matrix is accompanied by a list of all the Italian towns and relevant information about them like population or the different Nomenclature of Territorial Units for Statistics (NUTS) classification, the EU's standard for geocoding.

In Table 2.1, a summarized explanation of the different fields of the commuting matrix is presented. To put it simple, let us look at an example of two of its entries.

```
L 1 024 005 2 1 2 024 094 000 08 2 1 0000008.00 ND
S 1 024 005 2 1 2 024 094 000 +  + + 0000012.00 0000012
```

The first line represent a detailed "L" record and the second one and "S" general record both referred to the same case. Second number indicates a family residence, 3rd and 4th fields indicate the residence location (origin), which in this case is in the province of Vincenza (024) and is the municipality of Altissimo (005). It follows female population (2), that commutes for studies (1) to another Italian municipality (2), which is also in Vincenza (024) and is San Pietro Mussolino (094). Commuting country code is 000 because it is in Italy. The next three fields are the differences between "S" and "L" records. In the "S" records, as per their general nature, they are omitted and replaced by plus (signs). From the "L" record we read commuting by car (as passenger) (08), departing between 07:15 and 08:14 and taking less than 15 minutes for the trip. Finally the estimated and total person number are stated, noticing that the last one is omitted in "L" records, because the data is not real, but estimated.

For the purposes of the thesis a general commuting traffic flow is desired, so the "L" records are discarded. Also, the counts of "S" records making reference to the same municipality pair (distinguished by gender or commuting reason) are added up.

Thus, the final results are the total traffic flow between any two Italian municipalities. This is arranged in the form of a typical Origin-Destination (OD) matrix ($\underline{\underline{G}}$) such that

$$\underline{\underline{G}} = \begin{bmatrix} g_{11} & g_{12} & \cdots & g_{1\mathrm{n}} \\ g_{21} & g_{22} & \cdots & g_{2\mathrm{n}} \\ \cdots & \cdots & \cdots & \cdots \\ g_{\mathrm{n}1} & \cdots & \cdots & g_{\mathrm{nn}} \end{bmatrix}, \tag{2.1}$$

where g_{od} represents the commuter flow from town origin which has index "o" in the municipalities list to destination with index "d". It is particularly interesting to note that commuter traffic flow is bidirectional. Those who travel in the morning will travel back in the afternoon/evening. The "afternoon" OD matrix is closely related to the "morning" OD matrix as

$$\underline{\underline{G}}_{\text{afternoon}} = \underline{\underline{G}}^T_{\text{morning}}. \tag{2.2}$$

2.2 Aerodrome clustering and selection

NOTE: *This section is taken from previous thesis work done by D. Gabrielli [1]. As this thesis is framed in the same project and is somehow a continuation of the aforementioned work, it was deemed necessary to include it in order to provide a full description of the methods used. Therefore, this implies by no means acts of plagiarism.*

One of the main advantages of the 19-seater miniliner aircraft is its ability to be operated without needing a fully developed infrastructure (e.g. it can land in a grass runway). As a consequence, the possible nodes of the network multiply. According to the OpenAIP database [14], there are 602 potential airports/aerodromes/airstrips in Italy that could be serviced by the miniliner. Opposed to this, the Italian Aeronautical Information Publication (AIP) [15], indicates that only 44 aerodromes are certified. Other than regulatory issues, there is no reason to stick to those aerodromes as it is technically feasible to operate from other, less equipped, facilities. In fact, the only design constraint considered here is the minimum runway length required for takeoff and landing.

However, these facilities are not necessarily uniformly distributed across the territory. Sometimes, two or more aerodromes can be close together and their simultaneous operation could result in unnecessary redundancy. The idea of clustering the aerodromes stems from here and its objectives are grouping aerodromes together attending to the distance between them and choosing a representative member of each group. This way, a more spatially uniform aerodrome network is obtained.

This is not a trivial task and there are different methods to accomplish it. The agglomerative method is used, which merges airports in an iterative way. The process followed is:

1. Initially, all the airports are considered individual clusters.
2. The closest pair of clusters are grouped into a new cluster.
3. The distance of the newly generated cluster to each of the old clusters is calculated. Each element of the new cluster has a different distance to the rest of the clusters. Three main strategies are available: taking the greatest distance (complete-linkage), the shorter one (single-linkage), or the average (average-linkage). Complete linkage is chosen.
4. The steps are repeated until a single cluster is obtained.

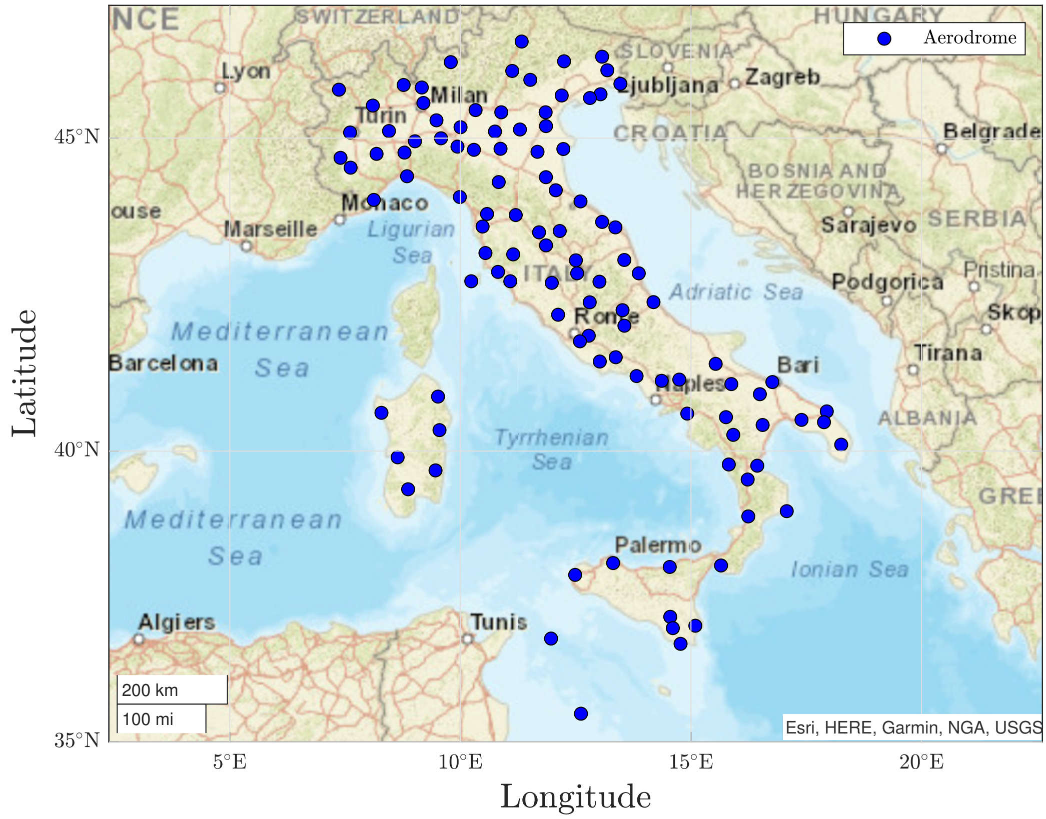
This process results in a dendogram like the one in Figure 2.2. The next step is to define a cut distance (i.e. a minimum distance between clusters) and cut the dendogram at that distance. For the analyses of this thesis, a 50km distance is used. This distance is not an orthodromic (great-circle), but road distance, which is obtained using the HereMaps Application Programming Interface (API). This is detailed in section 2.3.

Using the aforementioned 50km road distance cut to the Italian case, 109 aerodromes result. Coming back to the runway requirement constraint, these 109 aerodromes shall be filtered. The clustering result can be seen in Figure 2.1.

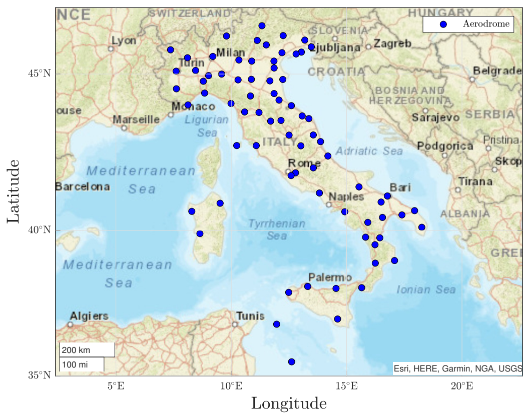
The 600m minimum runway length requirement does not really pose a limitation in the number of usable aerodromes (only Vercelli airport has a runway of less than 600 meters) so Figure 2.1a is actually the map of all the potential nodes (aerodromes) for the miniliner network problem.

2.3 Travel time comparison

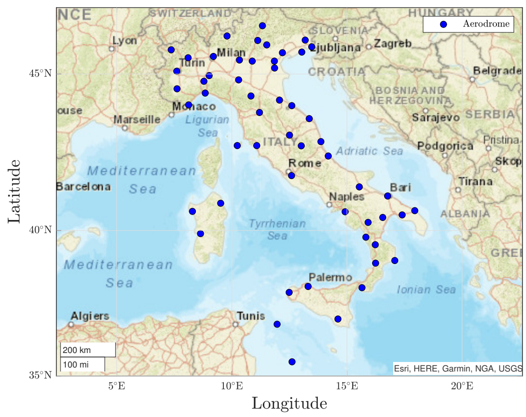
Until now, we have a set of commuter traffic flows for Italy and a set of airports that we can use. But that does not mean all the traffic flow will be redirected through



(a) Minimum runway length of 600 meters. 108 aerodromes.



(b) Minimum runway length of 800 meters. 75 aerodromes.



(c) Minimum runway length of 1,000 meters. 54 aerodromes.

Figure 2.1. Italian aerodrome selection after clustering

the intercity mininliner network. A set of criteria shall be established that measures somehow how advantageous the intercity solution against traditional transport. This will be done comparing travel time, and the reference travel time will be road time (travel time by car).

In order to retrieve road times, the HereMaps API is used. Each query takes a considerable amount of time (around one second). In order to save time and reduce future problem complexity without reducing results significance, only municipalities

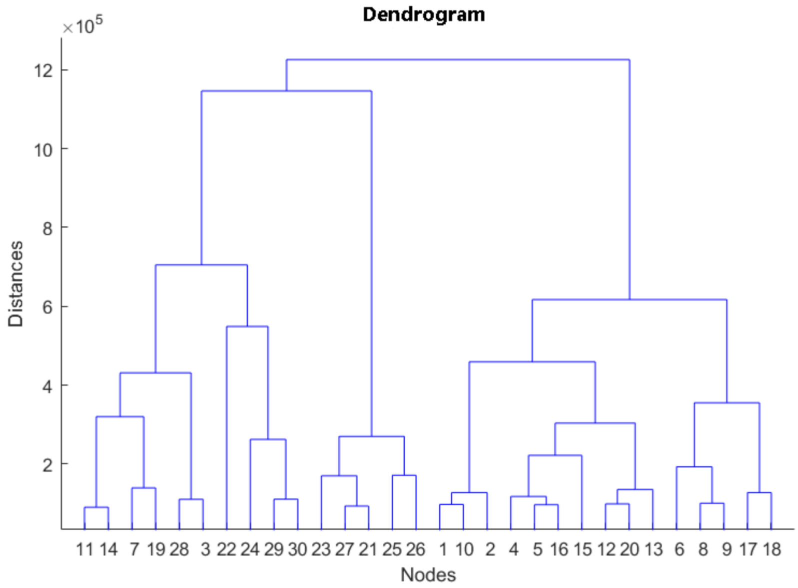


Figure 2.2. Example of the dendogram resulting from a clustering process. From [1].

with a population greater than 20,000 are considered. This allows to reduce the sets of data from nearly 8,000 municipalities to 519. A reduced OD matrix with only these towns is extracted from the original one.

The next step is to obtain an OD road time matrix whose generic element t_{od} represents the time it takes to travel by car from origin "o" to destination "d". This accounts for nearly 270000 queries to the Here API. While it may seem counter-intuitive, this matrix is not symmetric, but close to symmetric, as in some cases the reverse trip may take a different route. Regarding also how the route is calculated, it is important to note that traffic situation is not considered because traffic is a dynamic phenomena and cannot be generalized.

While road travel is straightforward, commuting using the intercity network is a bit trickier, as the trip comprises three different segments (Figure 2.3):

1. Travel by car from the origin municipality (A) to its assigned aerodrome (B).
2. Travel by air using the miniliner from the origin assigned aerodrome (B) to the destination assigned aerodrome (C).
3. Travel by car from the destination assigned aerodrome (C) to the destination municipality (D).

Therefore, to obtain the total travel time of the miniliner option, it is needed:

- The road time to/from the municipalities from/to the aerodromes.
- The flight time between the aerodromes.

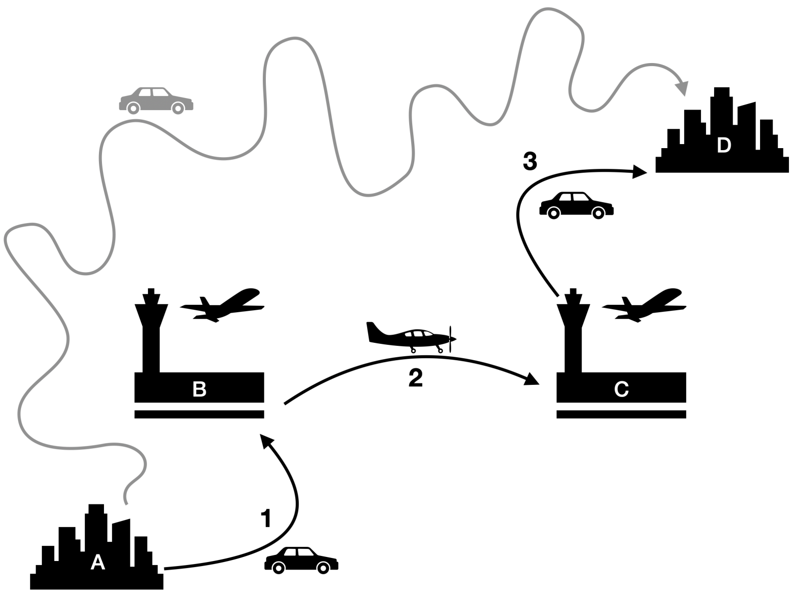


Figure 2.3. Scheme of the commuting trip phases using the miniliner aircraft as opposed to traditional commuting by car (grey).

Each municipality is assigned an airport on the basis of road travel time. That means that every municipality gets assigned the airport (out of the compatible ones according to runway length) to which the minimum time to drive is required.

The first item can be achieved in the same way it was done before: using the Here maps API. Proceeding in a similar manner, a 109x519 matrix is obtained whose generic element $t_{\text{am}}^{\text{airport}\rightarrow\text{town}}$ represents the time it takes to drive from aerodrome "a" to municipality "m". For this case, the inverse problem has been considered to be symmetric and therefore there is no need of calculating the road time from municipalities to aerodromes.

In order to allow for the realization of sensitivity analyses in a fast way, the data retrieved using the HereMaps API is stored and then loaded. This is possible because the road time is insensitive to the problem parameters. Thus, both the road times OD matrices, the 519x519 one corresponding to travel between municipalities and the 519x109 corresponding to travel between municipalities and aerodromes, are calculated in a preliminary process and then saved for posterior use.

The flight time is computed through the use of a function developed by F. Salucci (`Time2FlyDepressurized`). For this, basic aircraft parameters start playing a role. Specifically, cruise speed, target cruise altitude and climb/descent rates are necessary. Additionally, range limitations are imposed, both maximum (technical limitation) and minimum (operational limitation). Said function computes flight time for a given distance (airport to airport, considered to be an orthodromic distance). The target cruise altitude may not be reachable due to the flight being too short. In that case, the function will generate a flight profile with no cruise phase and will return maximum altitude in an optional output argument. The miniliner aircraft design is outside the scope of this thesis and is tackled in [16] and [17]. The nominal aircraft parameters are presented in Table 2.2.

The time of segment 2 is not limited to the flight time. There are times associated to the transit through the airport that also shall be considered, and have an important impact in the result. In particular, taxi, takeoff and landing times are important. Also, the time a passenger employs for the check-in and leaving the airport is relevant. The values selected for these times are reported in Table 2.3.

Total travel time using the intercity is calculated as (refer to Figure 2.3 for index reference)

$$t_{\mathrm{AD}}^{\mathrm{miniliner}} = t_{\mathrm{AB}}^{\mathrm{road}} + t_{\mathrm{BC}}^{\mathrm{air}} + t_{\mathrm{CD}}^{\mathrm{road}}, \tag{2.3}$$

where

$$t_{\mathrm{BC}}^{\mathrm{air}} = t_{\mathrm{flight}} + t_{\mathrm{check-in}} + t_{\mathrm{taxi-out}} + t_{\mathrm{takeoff-landing}} + t_{\mathrm{taxi-in}} + t_{\mathrm{turnaround}} + t_{\mathrm{leave}}. \tag{2.4}$$

Doing this in a recursive way it is possible to obtain a 519x519 (all the Italian towns with a population grater than 20,000) square time matrix whose generic element $t_{\mathrm{od}}^{\mathrm{miniliner}}$ is the total time required to travel from origin "o" to destination "d" using the miniliner solution. That is, driving to the airport, flying airport to airport, and driving to destination from the airport.

On the other hand, the same matrix was previously calculated but considering road time. That is, directly driving from origin to destination. Thus, it is now possible to compare both matrices and establish criteria under which the miniliner solution is considered potentially advantageous.

For this task, the same parameters chosen in D. Gabrielli's thesis [1] are used. Two parameters are used:

- Absolute time difference (t_{ref}): Defined as the difference between the traditional commuting solution time (road time from A to D) and the miniliner commuting solution total time (Equation 2.3).
- Relative time difference or time gain (k): Defined as the ratio between the traditional solution time and the miniliner solution time.

The values assigned to the parameters are defined in Table 2.4. The criteria is then established as

$$t_{\mathrm{AD}}^{\mathrm{road}} - t_{\mathrm{AD}}^{\mathrm{miniliner}} \geq t_{\mathrm{ref}}, \quad \text{and} \tag{2.5}$$

$$t_{\mathrm{AD}}^{\mathrm{miniliner}} \leq \frac{t_{\mathrm{AD}}^{\mathrm{road}}}{k}. \tag{2.6}$$

Putting it simple, and considering the nominal values from Table 2.4, in order for the miniliner solution to be considered advantageous over the traditional solution, two conditions have to be met:

- Miniliner solution has to be at least 30 minutes faster than traditional solution.
- Traditional solution has to take at least a 30% longer than miniliner solution.

Applying these criteria, the reduced OD matrix is filtered, selecting only those municipality pairs between which the miniliner could be a potential solution according exclusively to travel time. Moreover, considering that each municipality has been assigned an aerodrome, the OD matrix can be reduced. This way, the OD matrix flows corresponding to municipality pairs with the same airport pair can be grouped, making up an "airport" OD matrix. Thus, the complexity of the OD matrix is reduced as it can be appreciated in Figure 2.4.

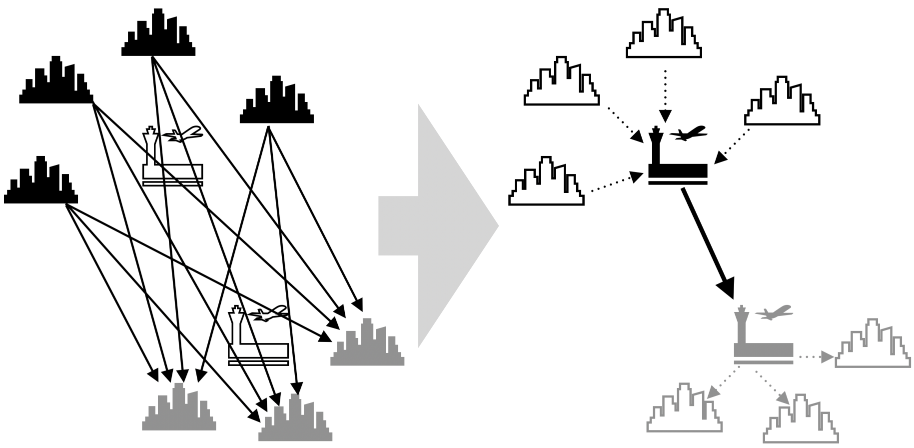


Figure 2.4. Transition from the original OD matrix to the aggregated aerodrome OD matrix

To sum up, the final result of the demand estimation is an origin-destination matrix with the potential commuter traffic flows of the intercity miniliner solution. The nodes are the compatible secondary aerodromes. These potential traffic flows take into account the technical characteristics and limitations of the aircraft, their time advantage over driving and the infrastructure limitations (runway length). This is no other than (and is treated in the code as) a weighted directed graph whose nodes are, as mentioned above, the aerodromes; its edges are the potential routes between the aerodromes and the weights the potential demand for that routes. It is assumed that the potential traffic flows transform 1:1 to demand. This is why, at the beginning of the chapter, caution is advised about it.

Field description	Starting column	Length	Values
Record type	1	1	S or L
Residence type	3	1	1: family 2: cohabitation
Residence province	5	3	Province code
Residence municipality	9	3	Municipality code
Gender	14	1	1: male 2: female
Commuting reason	16	1	1: studies 2: work
Commuting location	18	1	1: same municipality 2: Italian municipality 3: foreign municipality
Commuting province	20	3	Province code
Commuting municipality	24	3	Municipality code
Commuting country	28	3	Country code
Means of transportation	32	2	01: train 02: tram 03: subway 04: urban bus 05: interurban bus 06: school/company bus 07: car (as driver) 08: car (as passenger) 09: motorbike 10: bicycle 11: other 12: on foot
Departure time	35	1	1: before 07:15 2: 07:15-08:14 3: 08:15-09:14 4: after 09:14
Commuting time	35	1	1: $\leq$ 15 minutes 2: 16-30 minutes 3: 31-60 minutes 4: $>$ 60 minutes
Estimated person number	39	12	Count (for an "S" record)
Person number	51	10	Count (for an "L" record)

Table 2.1. ISTAT commuting matrix field description

Parameter	**Nominal value**
Range [km]	300
Cruise speed [KTAS]	200
Cruise altitude [ft]	4,000
Climb rate [ft/min]	500
Descent rate [ft/min]	250
Minimum range [km]	40

Table 2.2. Nominal parameters of the miniliner aircraft.

Phase	**Time [s]**
Check-in	600
Leave	300
Taxi in/out	300
Take-off/Landing	600
Turnaround	300

Table 2.3. Times associated to the airport.

Parameter	**Nominal value**
t_{ref} [s]	1800
k	1.3

Table 2.4. Nominal parameter value for the activation criteria.

Chapter 3

Optimal network definition

In this chapter, the network model and how its optimization is done are described. As it was already introduced in chapter 1, the type of network proposed is a point-to-point rather than a hub-and-spoke one. The hub-and spoke one has been already studied in the micro-feeder case ([1] and [10]).

The starting point for the network analysis is the network graph mentioned at the end of chapter 2. This graph is a weighted directed one with the folowing characteristics:

- Nodes: Secondary aerodromes with enough runway length that can funnel traffic flow from surrounding towns through them.
- Edges: Potential routes between aerodromes.
- Weights: Potential traffic flow.

3.1 Demand time distribution

Commuting is a periodic phenomena within the day. Specifically, with regards to commuting, a working day can be divided in three parts:

- A morning peak time in which people go to their work/study places.
- A valley time.
- An afternoon peak time in which people return home.

When the OD matrix was first analyzed in section 2.1, the information regarding the departure time was disregarded. However, it is clear that the network evolves with time. Considering that the traffic flow is constant throughout the day would violate the nature of commuting itself. Therefore, departure time has to be analyzed.

In Figure 3.1, the result of this analysis can be seen. To be able to assume the whole commuting population in Italy can be considered homogeneous with regards to their departure time, the analysis is done for different regions. To avoid biased results, these regions are selected spanning all Italy's geographical area. Specifically:

- Lombardia, in the north.
- Lazio, in the center.
- Puglia, in the south.
- Sicilia, in the south and with the peculiarity of being an island.

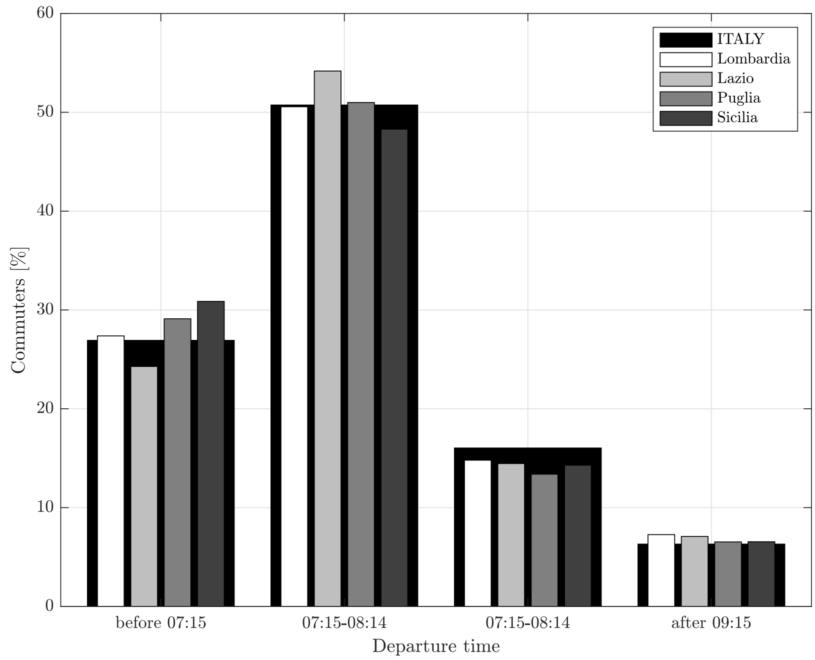


Figure 3.1. Distribution of commuters in Italy according to departure time.

It is concluded that commuting is spatially homogeneous across the country. Numerically, it is considered:

- 27% of commuters leave between 6am and 7am.
- 50.5% of commuters leave between 7am and 8am.
- 16% of commuters leave between 8am and 9am.
- 6.5% of commuters leave between 9am and 10am.

Commuting matrix lacks of information for the return time. This forces to make some assumptions about the afternoon rush hour. Supposing the first ones to leave in the morning are also the first ones to return in the afternoon seems reasonable enough. In terms of demand, for the network model, the time distribution along the day is depicted in Figure 3.2.

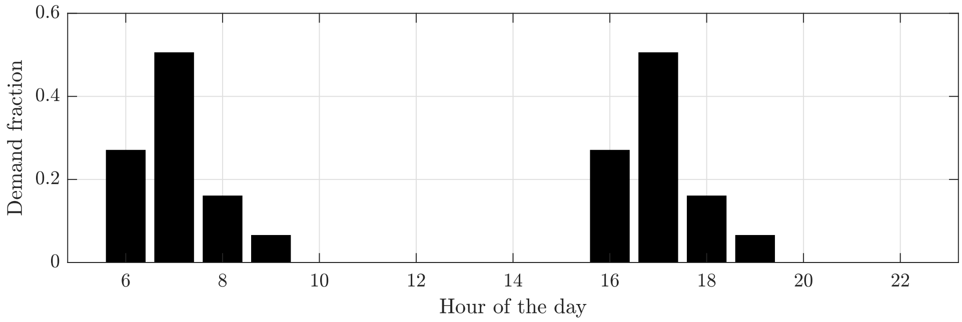


Figure 3.2. Distribution of intercity network demand along the day.

The sum of demand fractions is equal to 2. This is no mistake. The OD matrix provided with demand only for the morning rush hour. Under the assumptions made above, the demand for the whole day (morning and afternoon rush hours) shall be the double of the provided one. However, it is important to remember that the demand for the afternoon rush hour can't be extracted from the aerodrome OD matrix directly. It has to be extracted from the transposed OD matrix, as it was already noted in Equation 2.2.

3.2 Mathematical model

This subsection aims at describing how the network is modeled as a mathematical problem. Most of the work done is an adaptation of the model already developed for the microfeeder problem. In fact, little adaptation is done to the model itself. Most of the changes are done adjusting the input data to work with it.

3.2.1 String model

NOTE: *This subsection is taken from previous thesis work done by G. Magni [10]. As this thesis is framed in the same project and is somehow a continuation of the aforementioned work, it was deemed necessary to include it in order to provide a full description of the methods used. Therefore, this implies by no means acts of plagiarism.*

The string model is a binary ILP in which all the variables are binary) problem aimed at solving the microfeeder problem. Both the microfeeder and the intercity problem are versions of the GVRP, which is a Vehicle Routing Problem (VRP) with the added complexity of working with electric or alternatively fueled vehicles. In the case of the hybrid-electric miniliner, this complexity stems from the charging needs. The main parameter for this is the discharge ratio, which was assumed to be constant in chapter 1. A discharge ratio greater than 0.5 implies aircraft should be recharged after each flight. A discharge ration greater than 0.25 implies aircraft should be recharged after every two flights and so on. Charge time also plays an important role in this aspect. Currently, the number of flights per string is limited to two.

The concept behind the string model is building a series of sets of flights that can be flown consecutively without recharging. These strings constitute the elemental unit of the model and have an associated origin, destination, departure and arrival timeslot, and demand. A string can be repeated as long as there is enough demand. The standard miniliner capacity is 19 so, if there is a demand of 38 between an origin an a destination airport at a particular time (a flight), the string will be repeated twice.

For a string to be created, its demand has to be over a threshold. It is not profitable to dispatch an aircraft without a minimum number of passengers on board. The ratio of passengers over the aircraft capacity is the load factor and is another important parameter in the network. Let us see a set of strings as an example to fully understand it:

```
13 1 1 6 5 19 10.0 12.0 06 13 13 2
14 1 1 6 5 16 10.0 12.0 06 13 13 1
15 1 1 6 5 15 22.0 24.0 15 14 14 1
```

The different column meanings are:

1. String identification.
2. Number of flights in the string.
3. Origin airport.
4. Via airport (only relevant in 2-flight strings).
5. Destination airport.
6. Passengers.
7. Departure time slot.
8. Arrival time slot.
9. Maximum number of movements per time slot.
10. 1st Flight identification.

11. 2nd Flight identification (same as 1st flight for 1-flight strings).
12. Number of times the string can be repeated.

With that, in the example provided, it is possible to see that the two first strings are from the same flight. The first string are two aircraft at full capacity (repetition 2) and the second one considers the remaining demand (16 passengers). The third string represents a different flight with a demand of 15 passengers.

With regards to time, the model works with dimensionless time slots. Therefore, it is possible to work with different time resolutions without needing to change the model. However, the input data should be re-scaled appropriately. There is no evident relationship between the time slot number and the actual time. Time slot 12 could mean 12:00, but could also mean 10:20. It all depends on the starting time slot and the time resolution.

Without entering into details (refer to [10]), the mathematical form of the model introduces three main binary variables from which the results are obtained:

$$\alpha_{i,a} = \begin{cases} 1 & \text{if string } i \text{ is the initial string aircraft } a \text{ flies} \\ 0 & \text{otherwise} \end{cases} \tag{3.1}$$

$$\omega_{i,a} = \begin{cases} 1 & \text{if string } i \text{ is the last string aircraft } a \text{ flies} \\ 0 & \text{otherwise} \end{cases} \tag{3.2}$$

$$x_{i,j,a} = \begin{cases} 1 & \text{if string } i \text{ and } j \text{ are consecutively flown by aircraft } a \\ 0 & \text{otherwise} \end{cases} \tag{3.3}$$

Among the constraints the model includes, the most relevant ones are:

- String compatibility. Consecutive strings have to meet two conditions. A string destination has to be equal to the next's origin. Also, a string departure time slot has to be less or equal to the previous string arrival time plus the charging time.
- Airport blockage. There is a limit on the number of operations an airport can hold per unit time. In the case of the microfeeder, there was precise data of the available movements in the hub airports. There is no data for secondary aerodromes, and a limit of 30 operations per hour is assumed.

The only change made to the mathematical model to adapt it from the microfeeder to the intercity case is imposing that secondary aerodromes and hubs are the same set of airports. In the microfeeder case, there are two different sets for aerodromes and hubs as the network layout is hub-to-spoke. Although it is a crude solution, it transforms the problem to point-to point one in an efficient way.

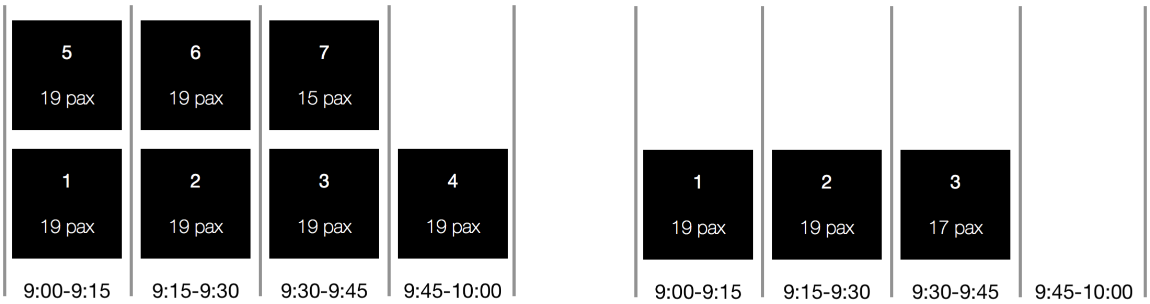
3.2.2 Demand splitting

In order to transform the demand data into a set of strings, some modifications have to be done. As it has been mentioned in section 3.1, the demand data is not segregated by time. Therefore, the most important task to do is to split that demand into the different time slots. These time slots may vary from run to run in both extension and resolution.

Thus, demand splitting has to be done in a flexible way. If the time slot resolution is one hour or lower, the solution is straightforward as the demand distribution by time is also hourly. However, if the time slot has greater resolution, which is the usual case, some kind of method to split it has to be defined.

The most straightforward method for that is to evenly divide demand between the time slots, but this has a main disadvantage. If, for example, the demand for a particular route at one hour is low enough to just fill an aircraft, splitting the demand into two (or more) additional time slots makes the demand not enough to fill one aircraft at each time slot. Therefore, where one aircraft would fly, no aircraft fly in the new situation.

Hence, a more elaborated, yet simple solution is applied. The demand is assigned in packages ordered from the first to the last time slot. These packages have the same capacity as the aircraft. In this way, if the case of only having demand for one flight, it will be assigned to the first time slot and the rest of the time slot will not have any demand assigned at all. If demand is enough to fill more than one flight per time slot, it cycles back to the first time slot. Evidently, all packages will be full except the last one, which may not be full provided the minimum load factor is satisfied. In Figure 3.3, two examples on the functioning of this algorithm are shown for the interval between 9:00 and 10:00.



(a) 129 passengers. (b) 55 passengers.

Figure 3.3. Example of the demand distribution after being splitted.

3.3 Optimization

For this last part, the network is optimized using the string model developed by G. Magni [10]. This is done using the software AMPL, and the state-of-the-art solver CPLEX. The way this solver works is completely outside of the scope of the thesis and will therefore not be discussed.

However, it is important to mention the parameters used to run the optimization cases. The only two parameters set are the gap and the time limit. The time limit is quite simple, if it is reached the iteration is stopped and the result assigned is the last one achieved, which is suboptimal. The gap makes reference to the difference between each iteration potential optimum and the upper bound assigned at each iteration step. When the relative difference between the potential optimum and the upper bound is less than the minimum gap specified, the iteration stops and the result is considered optimal. The time limit used is $3,600$ seconds (1 hour) and the minimum gap is 0.01.

With regards to the machine used to run the different cases, a Macbook Pro from 2016 was used, equipped with a 2-core 2.9GHz Intel Core i5 and 8GB of RAM. AMPL is called from MATLAB using the API. MATLAB version is R2019b Update 6, AMPL version 20191223 and CPLEX version is 12.10.

Chapter 4

Results

In this chapter, relevant results for the analysis conducted are presented. Three main areas have been tackled:

- Commuter flows between Italian towns coming from 2011 Census data.
- Potential demand of the intercity mininliner system, considering time advantage over traditional commuting.
- Actual demand captured once the network is optimized, along with network characteristics.

Therefore, this chapter is divided in three sections that more or less follow these challenges.

4.1 Commuter flows

The way Italian population commute certainly determines the success and utility of the intercity miniliner approach. One of the main advantages of the miniliner is that it is an ecological alternative to fossil-fuel based transportation, like cars, thanks to its hybrid-electric propulsion. Coming back to Figure 1.1, if we consider the population commuting out of their residence town, more than 75% of the commuting is done using private cars, with a very small fraction of them being shared (carpooling).

This is not an uniform phenomena though. As it could be expected, workers and students commute very differently. This is shown in Figure 4.1. Car predominance is even more intense in working population, which makes up to 66% of total commuting population. However, students preferred means of transportation is public. Students are approximately 33% of total commuting population.

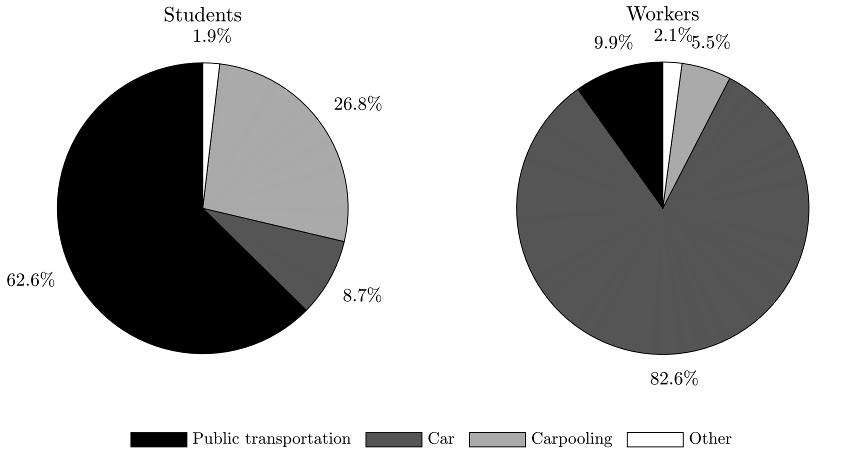


Figure 4.1. Extra-urban commuting distribution in Italy according to means of transportation and condition (student or worker).

Furthermore, it is not an spatially uniform phenomena. In Figure 4.2 the percentage of extraurban commuters with respected to region (NUTS 2 level) population is depicted for Italy. It is interesting to observe a clear North-South axis with respect to this. In Lombardy, 30% of the population commutes outside of its residence town, while in Lazio (where Rome is) only 12% does so. Thus, it is clear that this heterogeneity does not have to do with population, but with actual geographical and socioeconomic differences between regions.

A case specially interesting for the Intercity miniliner is inter-regional commuting. According as always to 2011 census, nearly half a million people change region every day to go to work or study in Italy (423,526 people, to be precise). Considering the criteria imposed in chapter 2, it is expected that the miniliner will be specially interesting in those cases where the commuting distance is higher, which aligns with inter-regional commuting. In Figure 4.3, relative commuters outflows for each region (i.e. people that commute outside of their residence region with respect to total extra-urban commuters) are presented, and a greater uniformity is revealed. The results are interesting and there is indeed a considerable potential target for the intercity service.

Nonetheless, from a European perspective (Figure 4.4)[1] and, according to this indicator, it is brought to light Italy would not be the best market. The Benelux, England and Wales look very promising to this respect. Norwegian case is particularly shocking and should be certainly considered at some stage.

For a complete visualization of the commuting flows in Italy collected in the 2011 Census, *flowmap.blue* can be used. It is a wonderful online tool for geographic flow visualization, including tools such as clustering, timeline or even filtering by drawing a polygon. The map showing all the commuter flows between towns with a population greater than 20,000 can be found here[2].

[1] It is important to take into account the percentages in Figure 4.4 are with respect to total employed population, while in Figure 4.3, the total extraurban population is used.

[2] Should the link not work, go here `https://flowmap.blue/1-3ZH3b-E3zc4Rvc9NgH4tlFRKZeq6HiLObHMJQ_TQSQ`

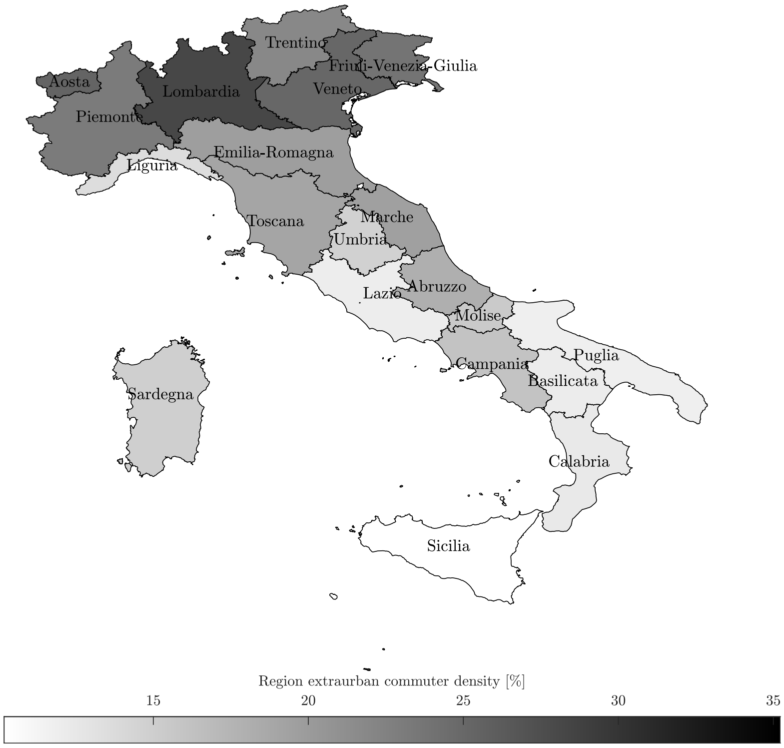


Figure 4.2. Extra-urban commuting distribution in Italy according to residence region (NUTS 2 level).

4.2 Potential demand estimation

The first step when analyzing the potential demand for the intercity miniliner transport system was obtaining OD matrices for both road time and total air time for all the pairs of the set of towns with population greater than 20,000. Here, road time meant time to travel from one town to another driving and was calculated using HereMaps API. Therefore, it considers actual road layout and speed limits. On the other hand, total air time makes reference to the complete scheme shown in Figure 2.3, including times associated to the airport transit.

Afterwards, two constraints (Equation 2.3) were applied in order to assess if the time advantage is enough for the passenger to select the miniliner as a travel option. In Figure 4.5, the town pairs are placed according to the road time and total air time using the aircraft and airport characteristics of Table 2.2 and Table 2.3 respectively.

The effect of the parameters t_{ref} and k are easily visible in Figure 4.5. Increasing or decreasing t_{ref} moves the time difference constraint boundary (the solid black line) up and down. However, this constraint has very little effect, if any, in the current configuration. Modifying k rotates the time gain constraint boundary (the dashed black line) around the origin. In particular, decreasing k makes the boundary steeper and hence, less restrictive. Also, increasing the aircraft performance or reducing the

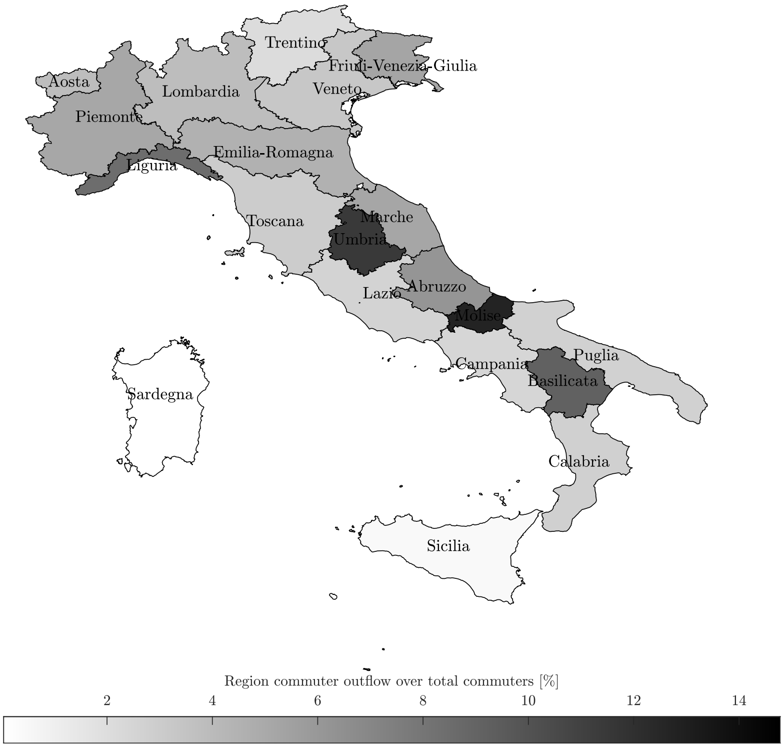


Figure 4.3. Commuter outflow distribution in Italy according to residence region (NUTS 2 level).

airport times (of which the nominal value add up to 40 minutes), moves down the cloud point making more potential town pairs.

The time advantage/saving of the miniliner is assessed in Figure 4.6 for all town pairs and put together with road distance. It is no surprise to find that time advantage increases with distance. However, the dispersion in the cloud point reveals the complexity of this problem. There are many aspects that prevent a more analytical treatment such as road layout or town and aerodrome geographical distribution. Also, the time difference constraint is clearly visible at the 30% time saving mark. This reassures the constraints are well defined.

The miniliner can be advantageous according to the 30% constraint from around 250km depending on the precise situation and it will be advantageous in most of the cases from 350-400km road distance.

4.2.1 Runway, cruise speed and range sensitivity analysis

The miniliner design process shall respond at the requirements for a successful application. The three main parameters are defined as relevant for the design. This is because they have a clearer, more direct influence in the potential demand of the intercity service, and are:

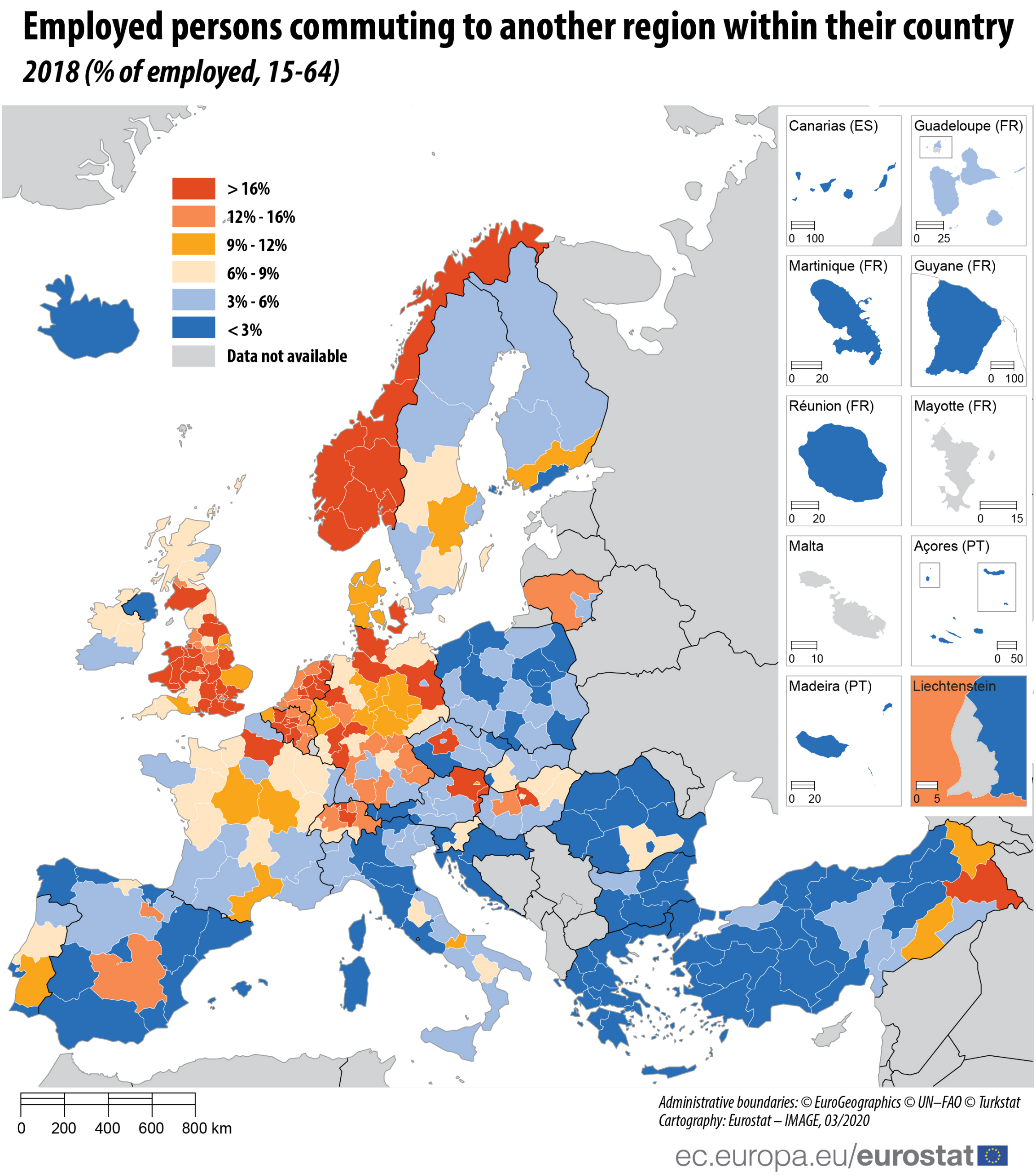


Figure 4.4. Employed persons commuting to another region within their country in Europe [2].

- Range: Above all, a greater range makes the miniliner able to connect more distant communities, in which it is more convenient.
- Cruise speed: Distance is not the key parameter that makes the service competitive, but time is. The fastest communities can be connected, the greatest the advantage will over land solutions.
- Minimum runway length required: The starting point for a network definition process is selecting its nodes. Aerodromes are the nodes in this case and their

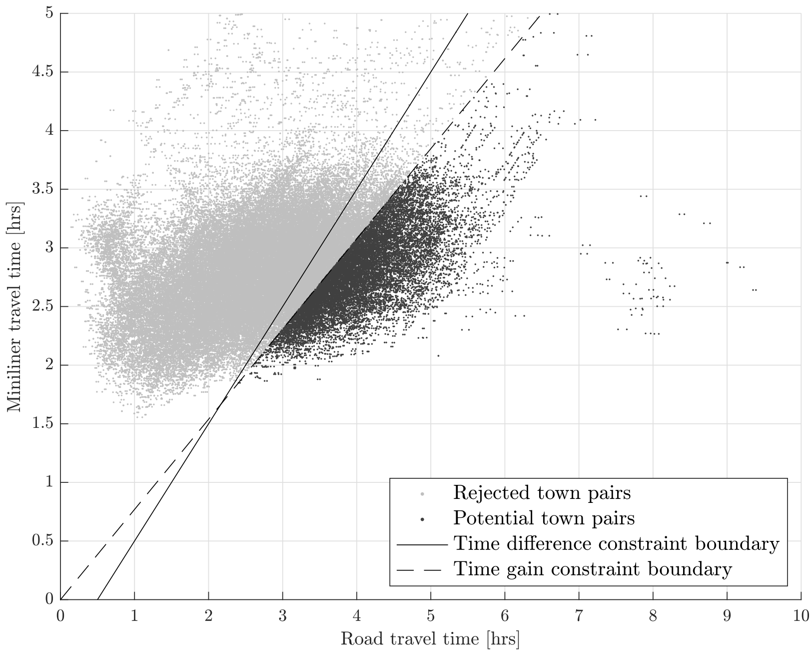


Figure 4.5. Miniliner travel time and road time for all the town pairs, including trip constraints.

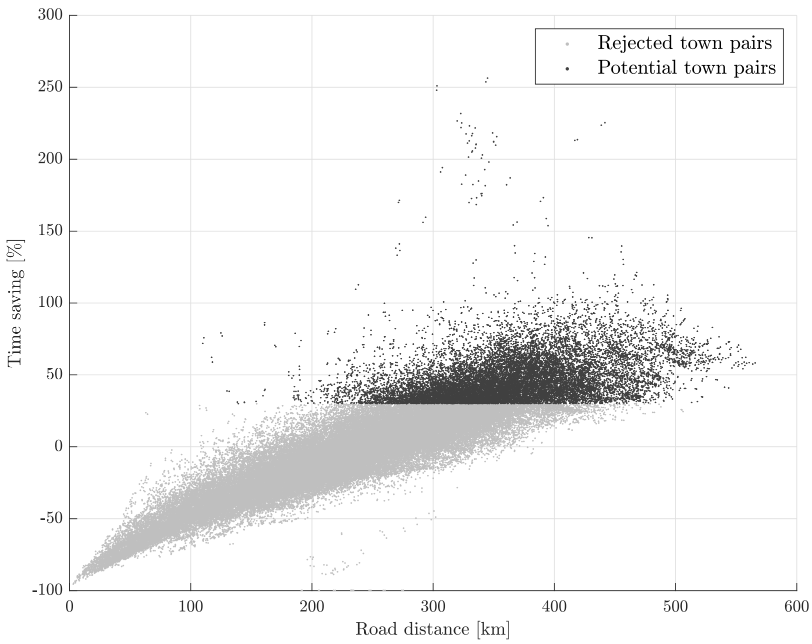


Figure 4.6. Miniliner time advantage with respect to road distance for all the town pairs.

runway is a constraint to which the miniliner has to comply.

Thus, a sensitivity analysis on the potential demand is carried out varying these parameters. The indicator for the potential demand is the commuter number that could benefit from the miniliner. Apart from that, other indicators of the complexity of the network are also obtained:

- Towns involved: the number of towns participating in the network providing or receiving commuters.
- Aerodromes involved: the number of aerodromes participating in the network acting as nodes.
- Population involved: the population of the towns involved.

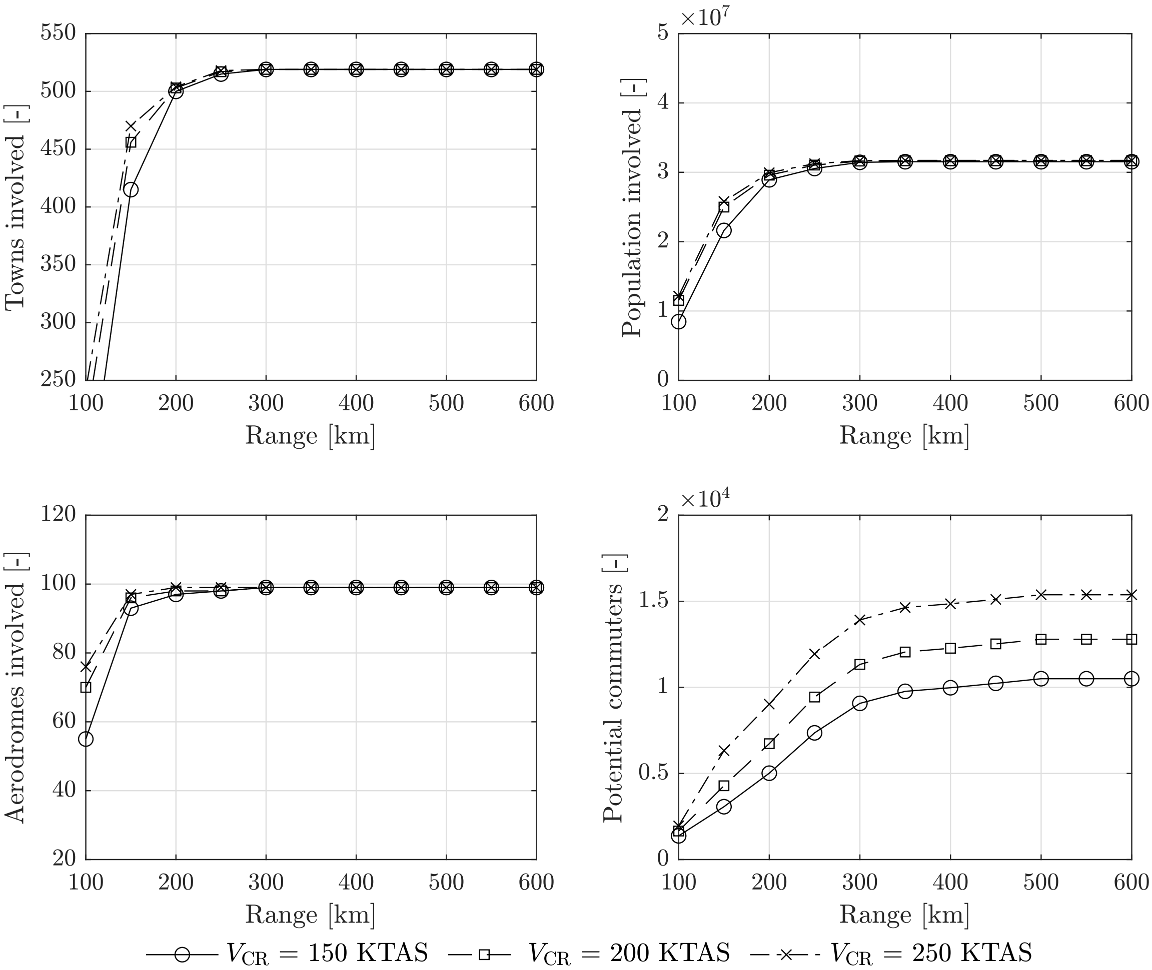


Figure 4.7. Potential demand sensitivity analysis against the aircraft design parameters results for minimum runway length of 600 meters.

In Figure 4.7, Figure 4.8, and Figure 4.9 the result of this analysis is presented for minimum runway lengths of 600, 800 and 1,000 meters respectively. The first thing that can be extracted from this is the number of towns (and consequently population) involved are not sensitive to any of the parameters but range. Even so, a saturation is reached for low values of range, around 200-250km. The behavior of the involved (or active) aerodromes is similar, but with the obvious restriction of the runway length, which limits the saturation to the maximum number of aerodromes that meet the requirement.

At first sight, this may seem incompatible with respect to the behavior of the commuters, which vary in a much more progressive way with range; and present

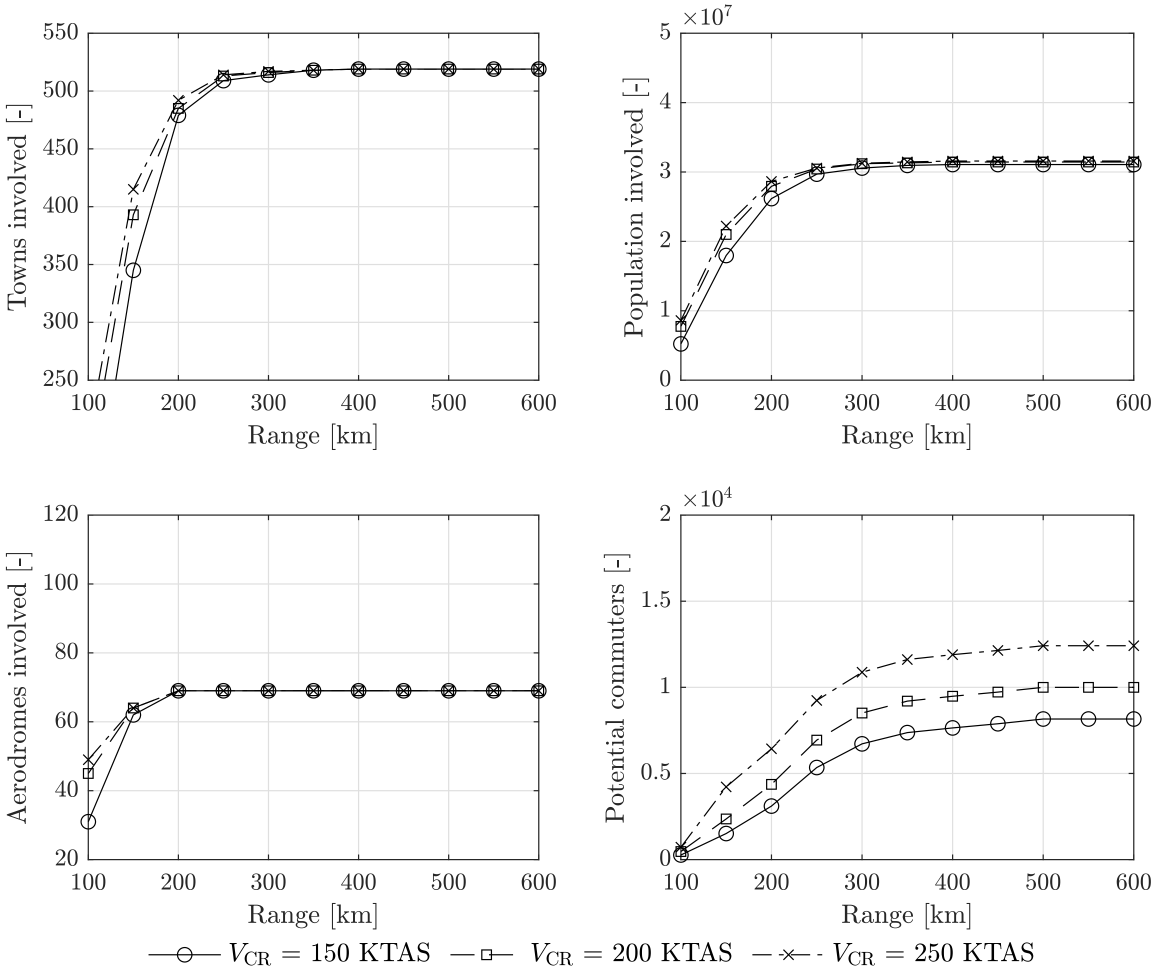


Figure 4.8. Potential demand sensitivity analysis against the aircraft design parameters results for minimum runway length of 800 meters.

significant variations with different cruise speeds and runway lengths. However, there is a relatively simple explanation for this.

Even for low ranges, there is a potential demand that, although is reduced, spans across the whole territory (Italy in this case). Hence, all the aerodromes, towns and population are put into play. For potential commuters, although the towns and the aerodromes they shall transit through are active, the range does not allow for a connection to their destination. Initially, a number of smaller 'isolated' networks are present which, as range is increased, become more interconnected, being able to absorb more demand. Some examples on how this happens in geographic terms are presented in Figure 4.11.

Additionally, in Table 4.1 the 10 routes with more demand are reported. The parameters for this study are those considered nominal in section 4.3, range of 300km, a cruise speed of 200KTAS and runway requirement of 800m. As it was predicted, all but the last route are fed with inter-regional commuting.

In Figure 4.10, the change in potential demand against runway required is shown

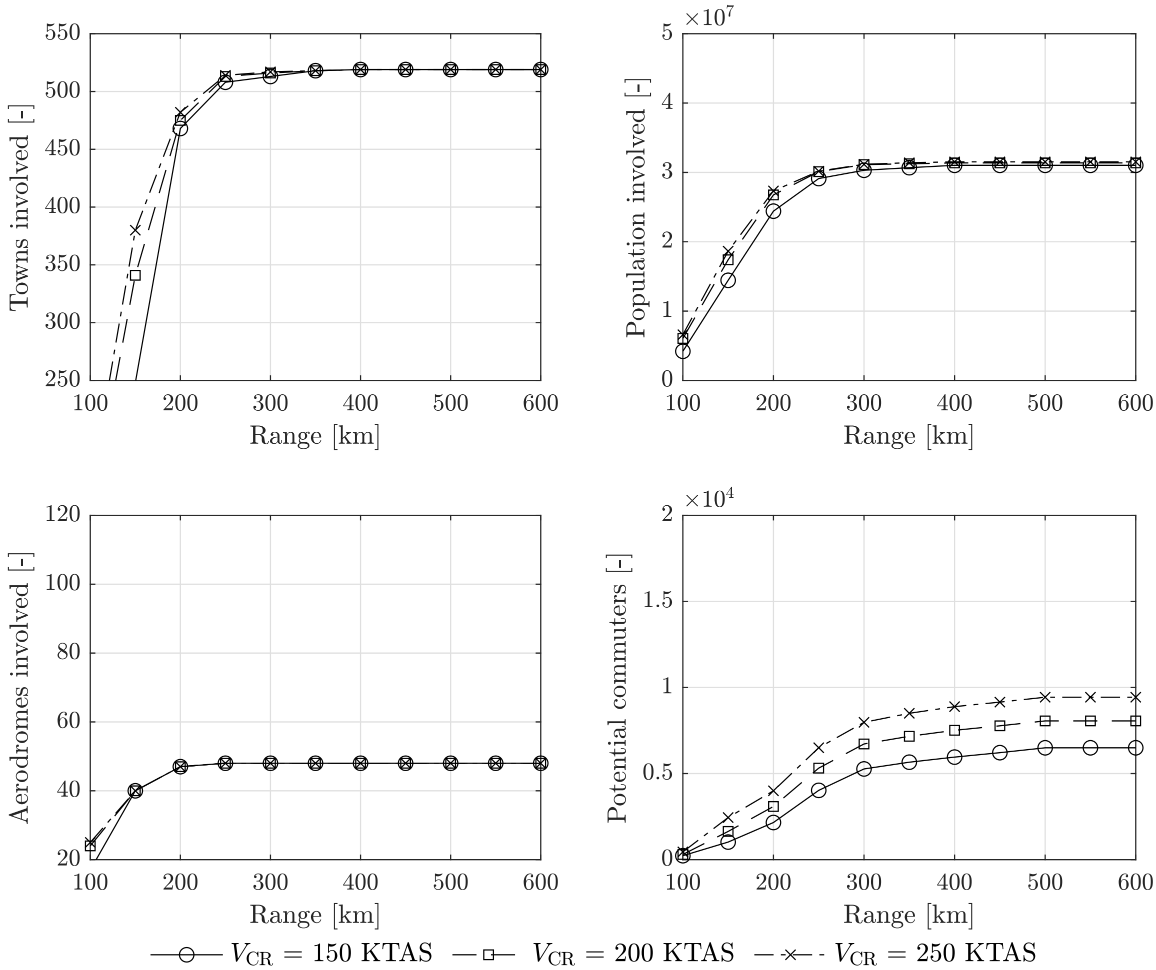


Figure 4.9. Potential demand sensitivity analysis against the aircraft design parameters results for minimum runway length of 1000 meters.

Route	**Est. demand**
Umberto Nobile → Roma Ciampino	323
Salerno → Roma Ciampino	236
Firenze Peretola → Roma Ciampino	199
Perugia S.Francesco → Roma Ciampino	162
Lucca Tassignano → Milano Bresso	155
Roma Ciampino → Firenze Peretola	151
Milano Bresso → Firenze Peretola	150
Roma Ciampino → Perugia S.Francesco	130
Firenze Peretola → Aero Club Piacenza	129
Grosseto → Firenze Peretola	124

Table 4.1. 10 routes with more estimated demand in Italy.

for different ranges in a qualitative way. It shows a linear dependency on runway required at least between 600m an 1000m (the range studied). As it was already seen, there is an increase in demand with range, but with an asymptotic behavior. This behavior is also shown in Figure 4.10, as range increases, the different data series

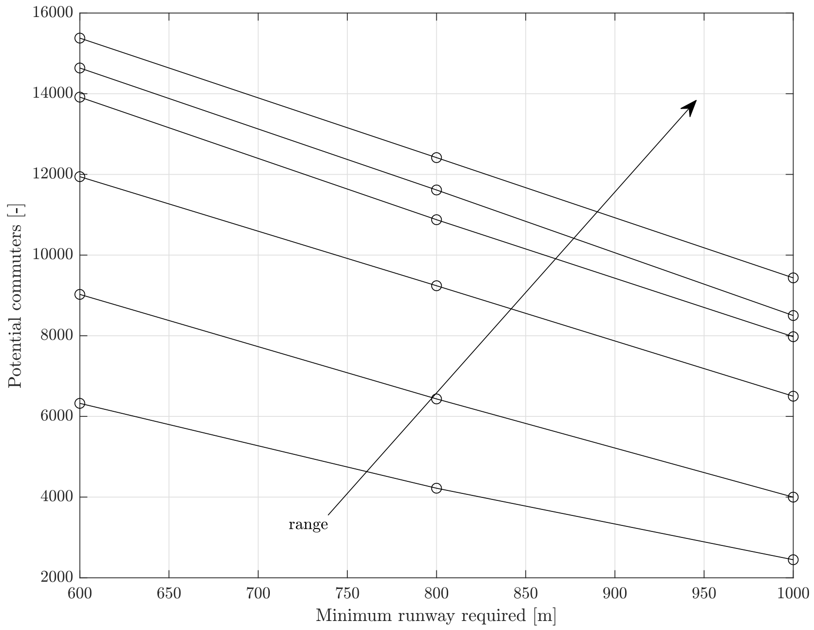


Figure 4.10. Potential commuter sensitivity against minimum runway length requirement and range.

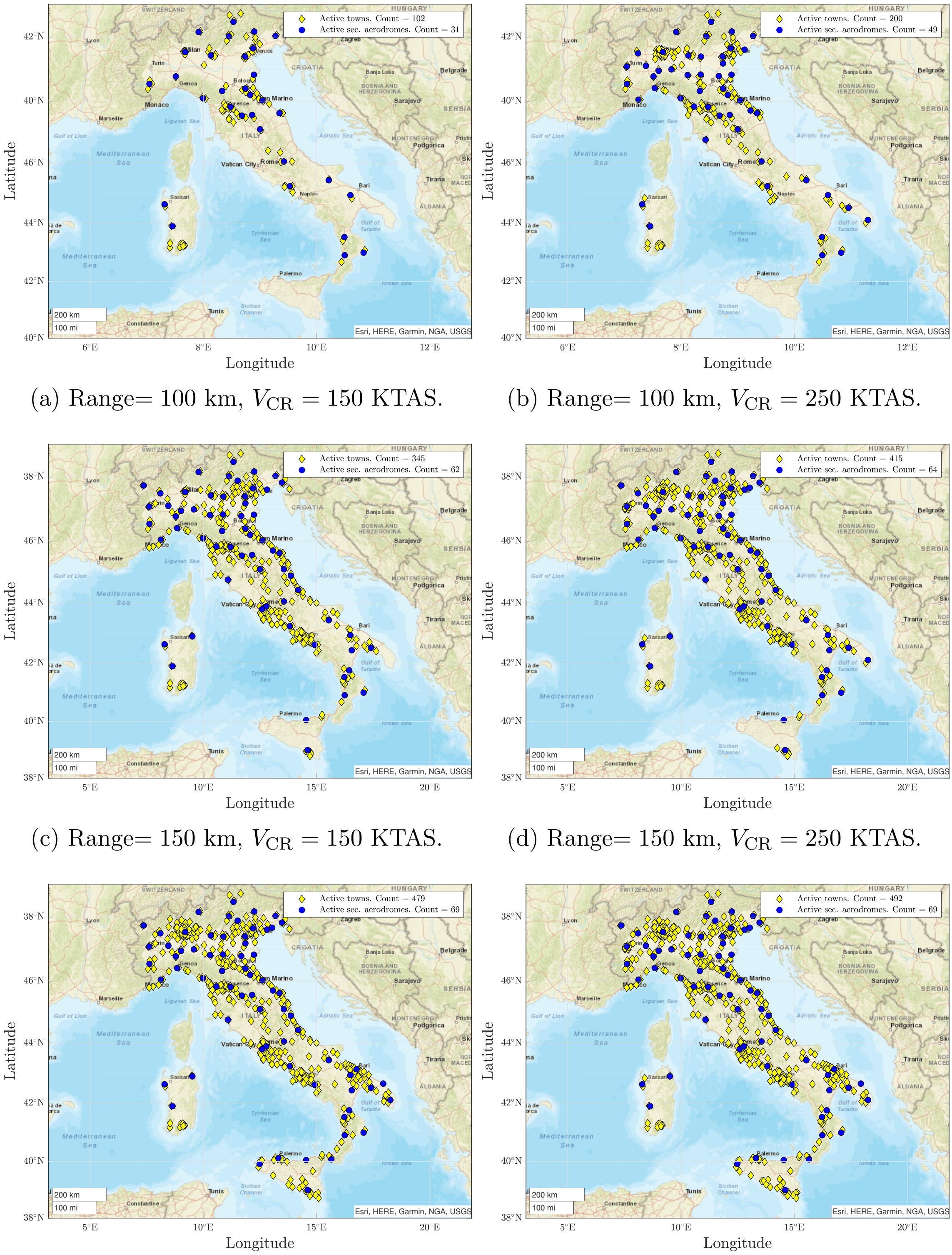
become more packed.

4.2.2 Airport times and time gain sensitivity analysis

As an additional analysis, the influence of the airport times (except charging time) and the time gain parameter k is analyzed. The absolute time difference t_{ref} is left outside because, its influence is lower. This is presented in Figure 4.5. The rationale behind this study is that nominal airport times (Table 2.3) were selected for the Micro-Feeder problem [1], in which the passenger continued its trip after disembarking the miniliner. In the Intercity Micro-Commuter this is no longer the case. The commuters are expected to be light travelers, so shorter check-in, turnaround and, in general airport associated times could be achieved. Also, time gain expectations may be as well different for commuters.

For this study, whose results can be found in Figure 4.12, a range of 200km, a cruise speed of 200KTAS and a minimum runway length required of 800m are chosen. Airport times are added up and treated as a block. This exposes the considerable impact airport times have on the potential demand. In the trivial case of no airport times at all, more than 22000 commuters are potentially willing to use the service. On the other hand, with airport times between 40 minutes (the nominal value) and one hour, this number is reduced by one order of magnitude, to 1,000-4,000 commuters. In the case of time gain parameter k there is indeed an influence, but it is not always relevant.

For a better visualization the impact of these parameters, a series of mini-plots



(a) Range= 100 km, $V_{\mathrm{CR}} = 150$ KTAS.

(b) Range= 100 km, $V_{\mathrm{CR}} = 250$ KTAS.

(c) Range= 150 km, $V_{\mathrm{CR}} = 150$ KTAS.

(d) Range= 150 km, $V_{\mathrm{CR}} = 250$ KTAS.

(e) Range= 200 km, $V_{\mathrm{CR}} = 150$ KTAS.

(f) Range= 200 km, $V_{\mathrm{CR}} = 250$ KTAS.

Figure 4.11. Active towns and aerodromes for different ranges and cruise speeds (minimum runway length 800m).

following the style of Figure 4.5 are presented in Figure 4.13. An increase in the airport time moves the point cloud upwards and the change in k rotates the dashed

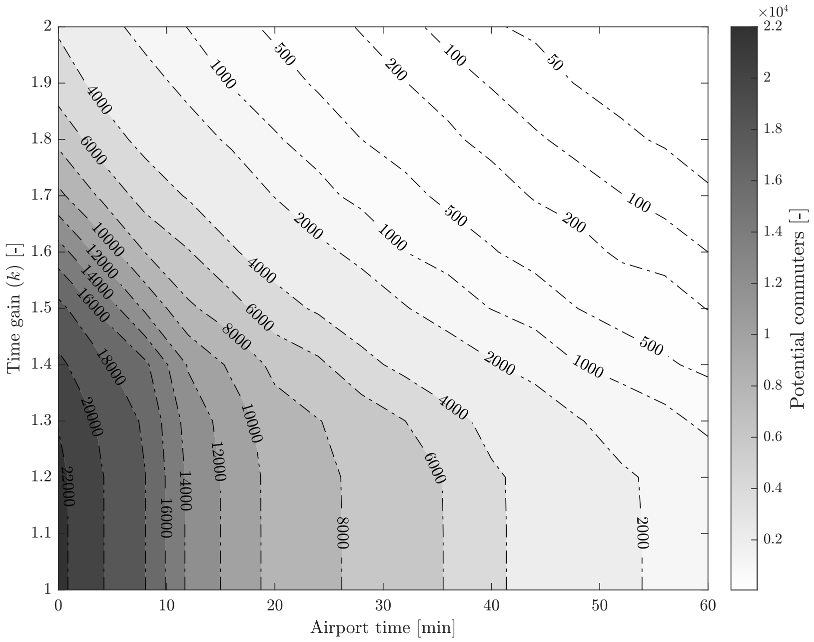


Figure 4.12. Potential commuters with respect to overall airport time and time gain parameter.

line around the origin. The solid line represents the constraint associated to t_{ref}. For low k values, between 1 (no time gain at all) and 1.3 results nearly do not vary. This is explained very well by looking at the bottom row of the figure, the constraint becomes redundant and no longer affects the city pair selection.

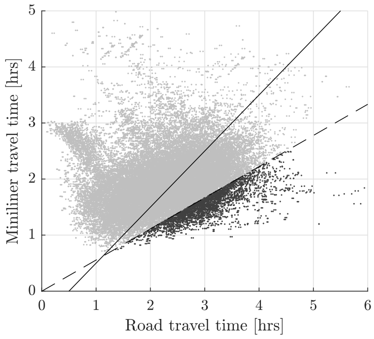
4.3 Optimal network definition

In this section, the final results of the thesis are presented. That is, the resultant Intercity miniliner network after the optimization process has concluded. The results for a nominal case will be analyzed along with:

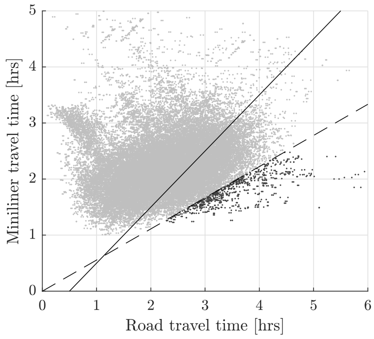
- the results of extending the problem to the whole day,
- the results of eliminating the load factor and aircraft capacity limits, and
- the results of a series of sensitivity analysis against relevant parameters.

Therefore, let us first establish in Table 4.2 the parameters of the nominal case. There are two additional parameters that are left outside of the sensitivity analysis because they are crucial for the system: fleet size and charging time. In Figure 4.14, its influence on the captured demand of the transportation system is presented.

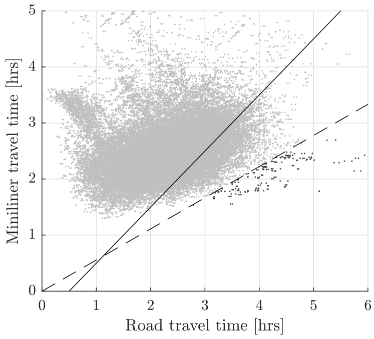
It is surprising to see that saturation is reached with very small fleet sizes. In fact, the situation is such that many aircrafts are not even selected to fly and remain



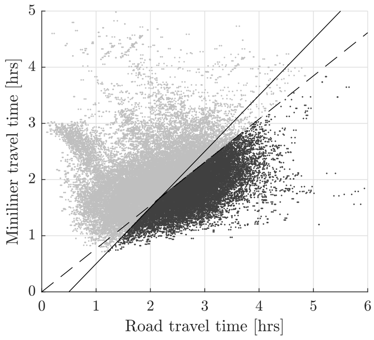
(a) $k = 1.8$, $t_{\text{apt}} = 20$ min.



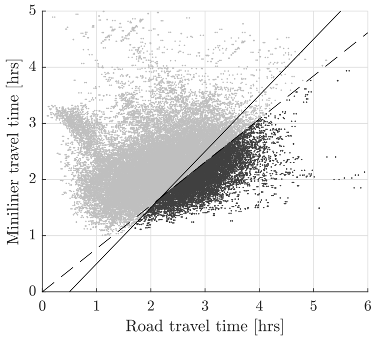
(b) $k = 1.8$, $t_{\text{apt}} = 40$ min.



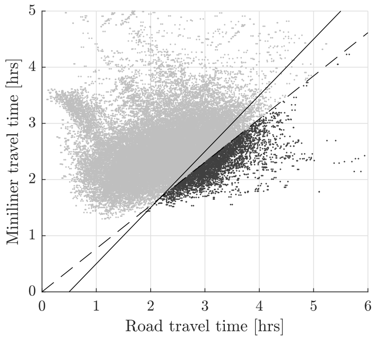
(c) $k = 1.8$, $t_{\text{apt}} = 60$ min.



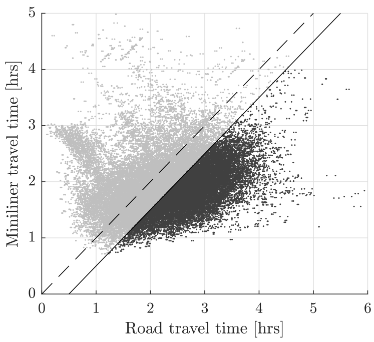
(d) $k = 1.3$, $t_{\text{apt}} = 20$ min.



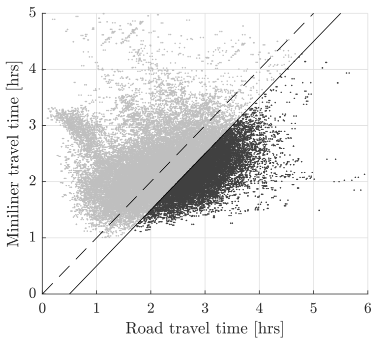
(e) $k = 1.3$, $t_{\text{apt}} = 40$ min.



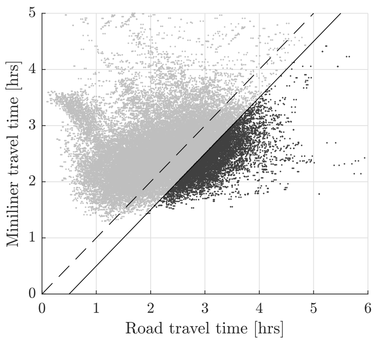
(f) $k = 1.3$, $t_{\text{apt}} = 60$ min.



(g) $k = 1.0$, $t_{\text{apt}} = 20$ min.



(h) $k = 1.0$, $t_{\text{apt}} = 40$ min.



(i) $k = 1.0$, $t_{\text{apt}} = 60$ min.

Figure 4.13. Town pair selection results for different values of the airport times and gain time parameter.

Parameter	**Nominal value**
Aircraft range [km]	300
Aircraft cruise airspeed [KTAS]	200
Minimum range [km]	40
Airport times (excluding charge) [s]	2400
Aircraft capacity [-]	19
Minimum load factor [-]	0.8
Time slot [min]	30

Table 4.2. Nominal parameters of the Intercity transportation system.

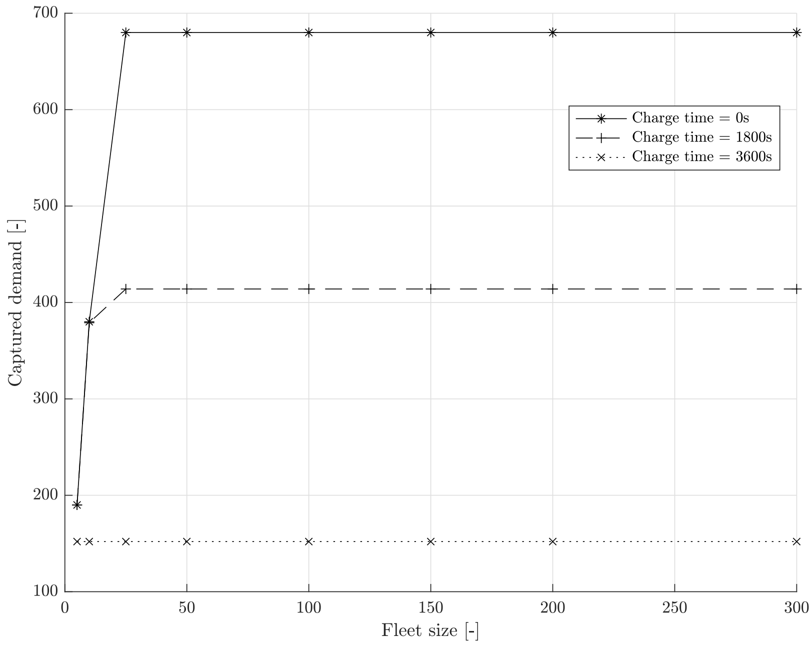


Figure 4.14. Captured demand of the optimized network in the nominal case for different fleet sizes and charging times.

grounded. Also, the paramount influence of charging time is brought to light. A charging time of 1 hour should be considered unacceptable in these conditions. But, even for no charging time (which could be considered the equivalent to operating a traditional aircraft), there is lot of potential demand that is not captured. From Figure 4.8, and considering the nominal parameters from Table 4.2, the potential demand is around 7,000-8,000 commuters, which is far from the maximum of less of 700 in Figure 4.14, and that is for no charging. If we settle with a charging time of 1,800 seconds, slightly over 400 passengers are captured.

In order to visualize the network better, the tool Flowmap.blue is used. In Figure 4.15, the case for a charge time of 1800s and a fleet of 200 aircrafts (saturation) is shown.

It should be taken into account that the aircraft parameters (range and cruise speed) chosen for these results are not the best in terms of potential demand, and remain unvaried throughout the different results here presented. Nonetheless, let us vary other parameters, performing some sensitivity analyses, with a double purpose:

- Find a way of maximizing the captured demand of the optimal network, and
- Understand better the results as a whole.

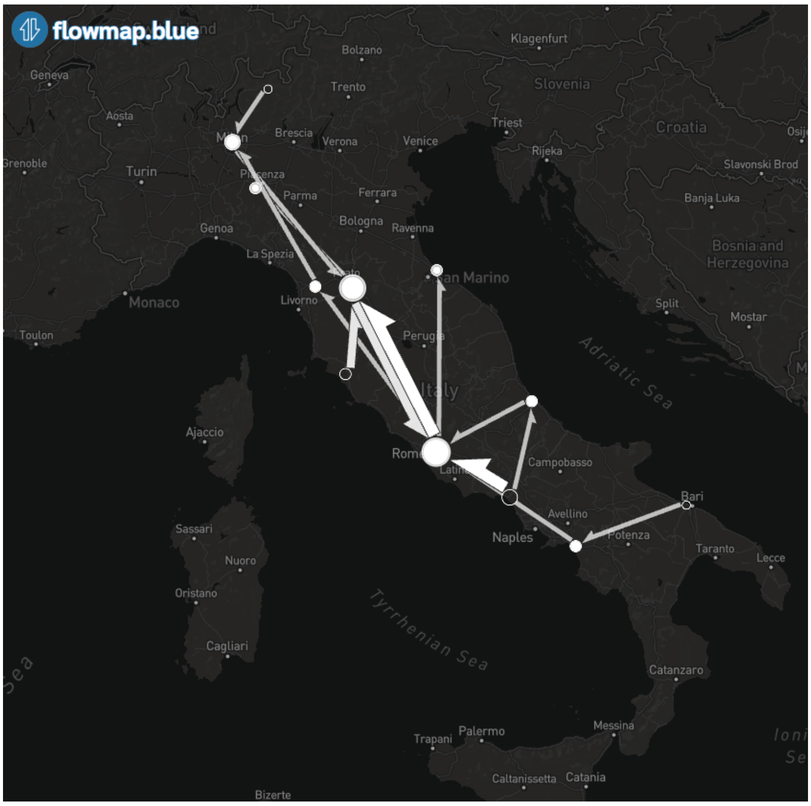


Figure 4.15. Optimal Intercity network. Fleet 200 aircrafts. Load factor = 0.8. Aircraft capacity = 19 pax. $t_{\text{charge}} = 1800$ s.

4.3.1 Full day case

Extending the case for the full day (the nominal case only considers the morning shift), including also the afternoon shift was the first situation considered. It has a problem associated, the aircraft trips are not symmetric. As commuting is a regular phenomena, one would want the aircraft to return to the airports from which it had departed in the morning during the afternoon. To achieve that, the model should be modified, and it is considered outside the scope of this work.

Evidently, the potential demand doubles. However, for an efficiency improvement, captured demand should be more than double of the nominal case.

The results are radically different. There is also a saturation limit, but it is reached for 150 aircrafts in the fleet instead of 25. Also, there is much less influence of the charging time, a saturation limit is the same for each charging time. Efficiency is increased. Captured demand limit is at around 6,000, which is 10 times the morning case. The explanation for this is not clear, but could be related to the fact that having more timeslots relaxes the problem. Once the afternoon shift is initiated, all aircrafts are ready to fly again. In the nominal case (without afternoon), aircrafts can perform only two flights due to time limitation and thus there are less possibilities.

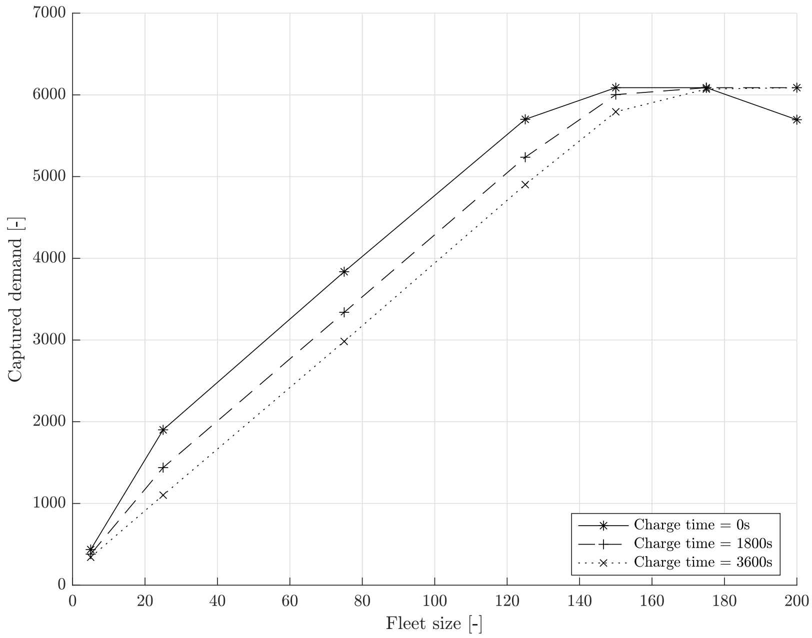


Figure 4.16. Captured demand of the optimized network in the full day case for different fleet sizes and charging times.

4.3.2 Capacity relaxation

Coming back to the nominal case, an interesting approach to check an upper bound for the objective function (captured demand) is relaxing the problem. This can be done either by changing the model, maybe removing some constraints, or by modifying its parameters to "virtually" remove said constraints. Here, the second option is explored and two parameters are relaxed by increasing them to values in which they no longer pose a limitation. Particularly:

- Aircraft capacity is increased to 100 passengers.
- Minimum load factor is reduced to 0.01, meaning each aircraft shall carry at least 1 passenger.

Assuming the most restrictive case ($t_{\text{charge}} = 3,600$ s), the demand dramatically increases and the curve takes the form one should have expected at the beginning, shown in Figure 4.17. Maximum captured demand increases from approximately 150 to nearly 2,500. Also, the increase in capture demand with fleet size is more progressive and, although there is a saturation, it is reached for a higher fleet size.

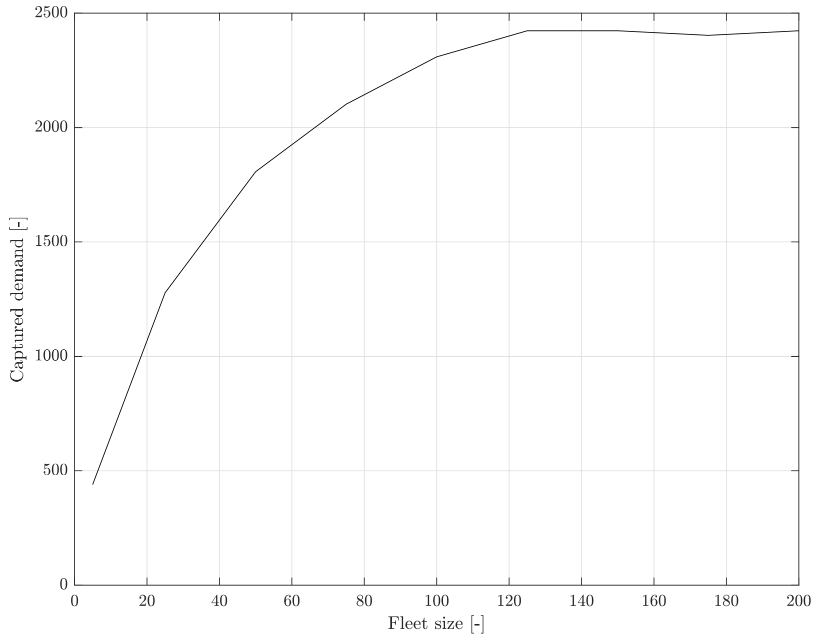
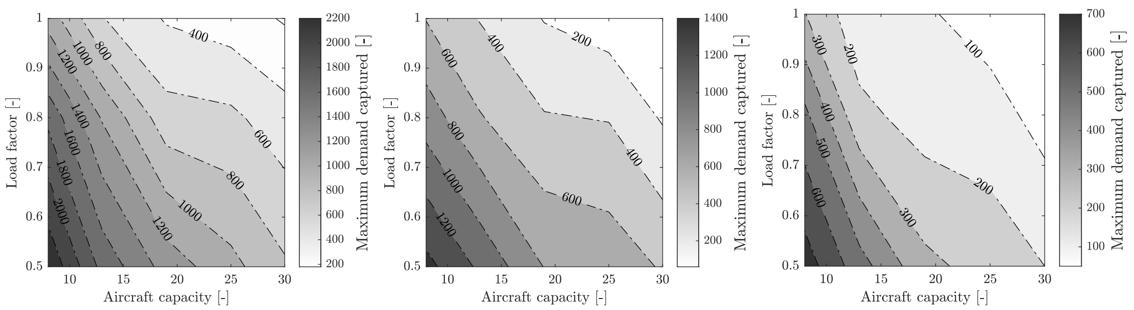


Figure 4.17. Captured demand of the optimal network in the relaxation case (no capacity minimum nor maximum).

4.3.3 Sensitivity analysis

Load factor and aircraft capacity

In Figure 4.18, the maximum demand captured (for a large fleet) for different minimum load factors between 0.5 and 1; and for different aircraft capacities between 8 an 30 passengers, is reported. In general, the dependence is based on the ratio between both quantities (the contour isolines are straight) rather than both parameters affecting independently the result. In the extremes (top-right and bottom-left corners), it is not that clear.

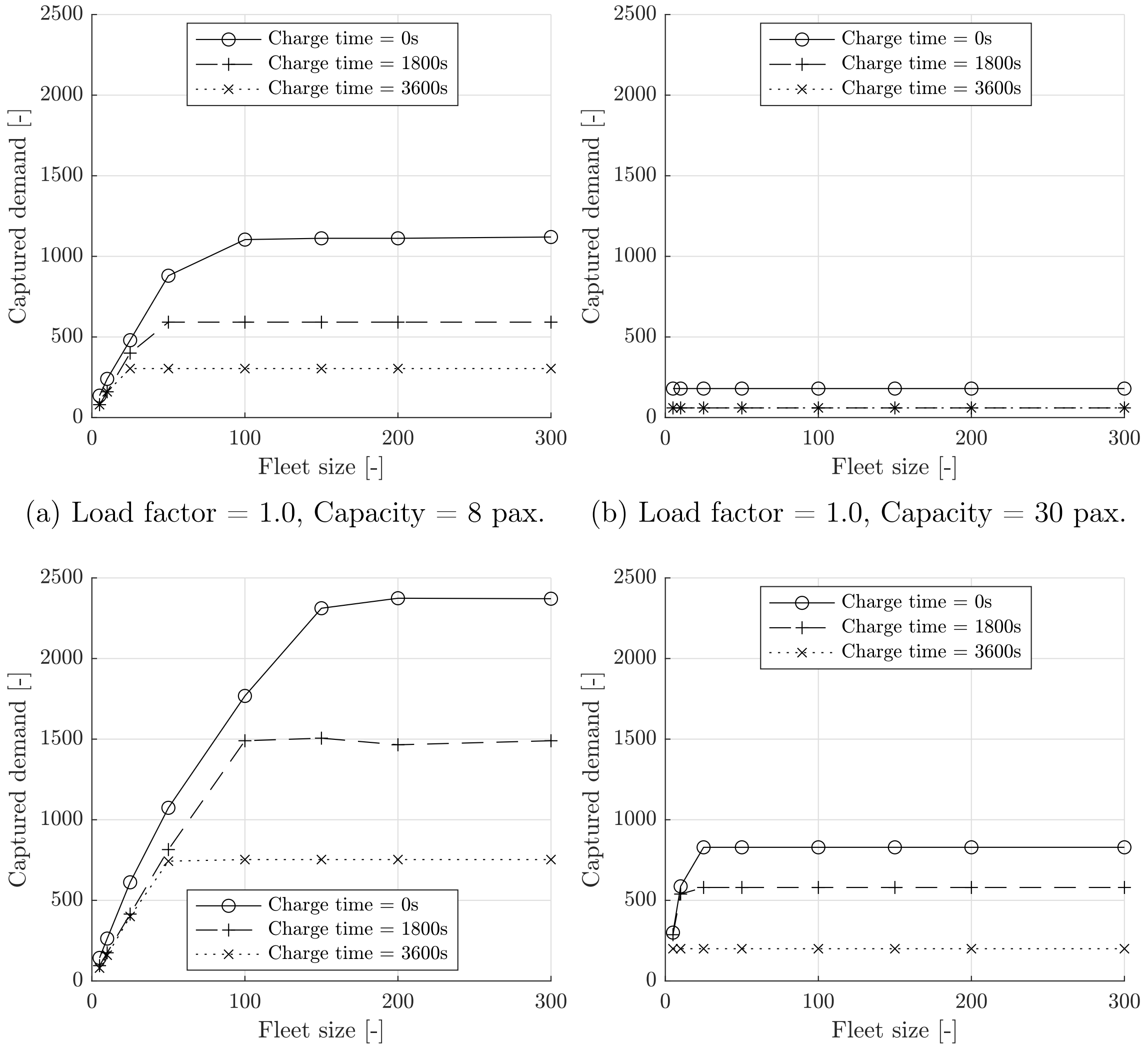


(a) $t_{\text{charge}} = 0$ s. (b) $t_{\text{charge}} = 1,800$ s. (c) $t_{\text{charge}} = 3,600$ s.

Figure 4.18. Maximum demand captured by the optimal network against load factor and aircraft capacity.

To have a more complete vision about this, full figures of captured demand against fleet size for the extreme values of load factor and aircraft capacity are reported in

Figure 4.19. With regards to the strange behavior of the captured demand, saturated even for low flights, it can be inferred that it may be an effect of the aircraft capacity. Lower aircraft capacity fleets can capture more demand. This a very interesting finding.



(a) Load factor = 1.0, Capacity = 8 pax. (b) Load factor = 1.0, Capacity = 30 pax.

(c) Load factor = 0.5, Capacity = 8 pax. (d) Load factor = 0.5, Capacity = 30 pax.

Figure 4.19. Demand captured by the optimal network as a function of fleet size and charging time for different load factors and aircraft capacities.

Time slot resolution

By varying the time slot resolution, the results should not change. However, it has an effect of the problem optimization and should be considered. In Figure 4.20, the maximum captured demands (for large fleet) for time slot resolutions of 5, 15 and 30 minutes is shown. It is particularly interesting to point out that the behavior completely changes depending on the charging time. For no charging, it shows a maximum at 15 minutes. However, the maximum for charging times of 1,800 seconds and 3,600 seconds is at 30 minutes (may be even higher for higher values). Nonetheless, the result variation is not game-changing.

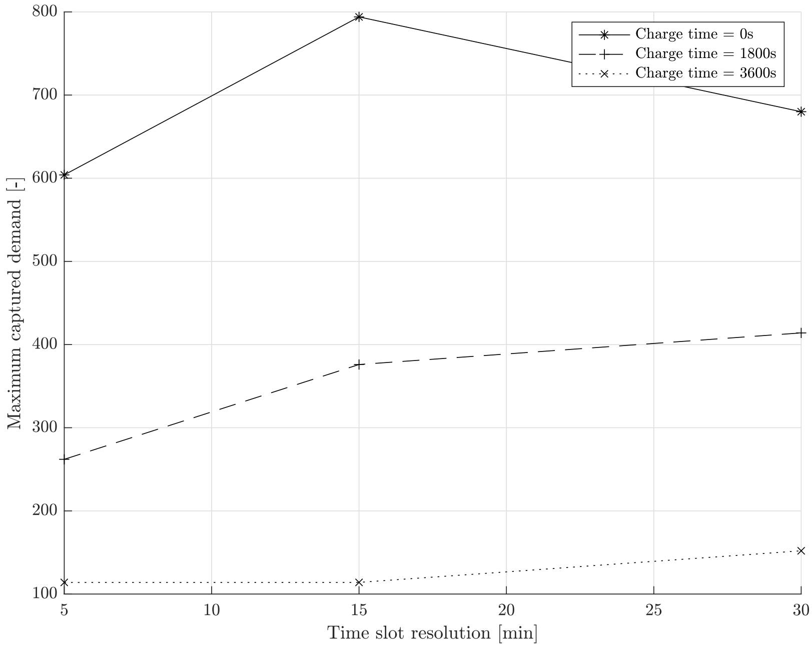


Figure 4.20. Maximum captured demand for different values of the time slot resolution.

Demand scaling

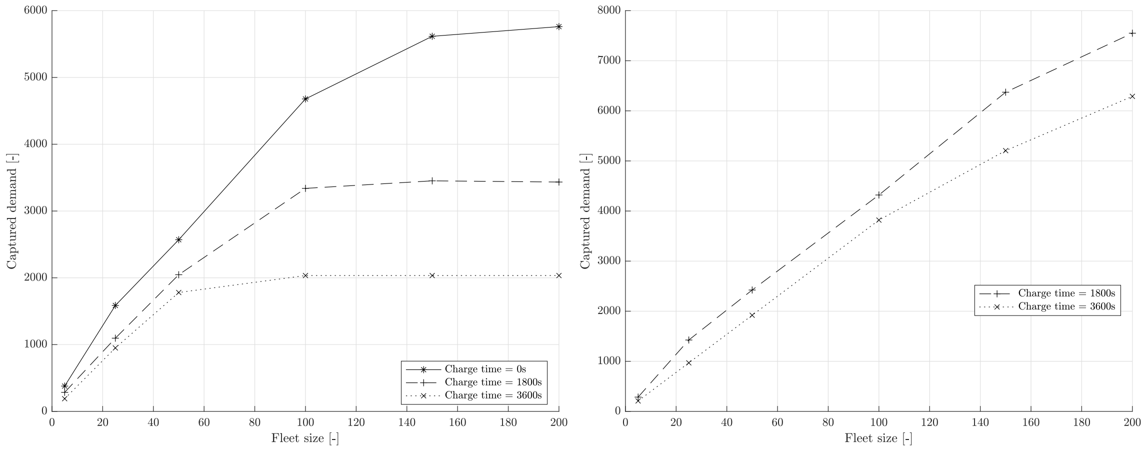
It is evident that results obtained in Figure 4.14, shall not be completely satisfactory. An absolute maximum captured demand of less than 700 passengers is too low, and the trend of the graph against the fleet size is strange. After studying the problem, it was discovered that this is caused by a low demand, consequence of low commuter flows.

To prove this, cases for commuter flows artificially doubled and quadrupled (i.e. multiplying the weighted graph adjacency matrix by 2 and 4 respectively) are produced. The results for this are presented in Figure 4.21[3]. It is important to remark than in this case, there is no evidence saturation is reached. Thus, for larger fleets the results could even be better.

Results are much better in the sense that captured demand increases overall and there is a increasing behavior with respect to fleet size. There is also a saturation limit but it correspond to much larger fleets. It is interesting to look, not only to absolute values, but to relative differences. It is obvious that if the demand is doubled, the captured demand will increase, but how much?

The results for the intermediate charging time scenario (1,800 s) and the largest fleet analyzed (200 aircraft) are shown in Table 4.3. Total potential demand ($\sum g_{\text{pot}}$), total

[3]The increase in complexity associated to the added commuter flows made the case much more time intensive. As a consequence, no data for the x4 case and 0 seconds charge time were obtained



(a) x2 (b) x4

Figure 4.21. Demand captured by the optimal network for commuter flows double and quadruple of the nominal one.

captured demand ($\sum g_{\text{cap}}$) and their increments ($\Delta \sum g_{\text{pot}}$ and $\Delta \sum g_{\text{cap}}$). When the commuter flows double, the potential demand more or less also double. However, the captured demand is quadrupled. Furthermore, if the commuter flows are quadrupled, the potential demands does not quadruples, but is multiplied by six, and captured demand is nearly 10 times the original one.

Hence, the improvement is not just proportional to the commuter flow increment, but larger (potentially much larger). The overall efficiency of the network obtained is increased this way.

Case	$\sum g_{\text{pot}}$ [-]	$\sum g_{\text{cap}}$	$\Delta \sum g_{\text{pot}}$ [-]	$\Delta \sum g_{\text{cap}}$[-]
Nominal	4820	788	-	-
Double	12581	3434	x2.61	x4.36
Quadruple	30532	7550	x6.33	x9.58

Table 4.3. Potential and captured absolute demand and demand increments in cases with increased commuter flows ($t_{\text{charge}} = 1,800$ s. Fleet size 200 aircrafts).

Chapter 5

Conclusion

The first important statement should be related to the current commuting situation. Car takes over 65% of commuting in Italy. This, altogether with the data about greenhouse effect gases emissions from transportation, reveals the paramount importance of alternative transport systems. It is true that there are alternatives to private car transportation but, if users do not choose them, an effort has to be made to find a more convenient choice. The Intercity miniliner has been proven to be:

- Clean: Its hybrid architecture makes the miniliner an ecological option. Also, noise reduction is a secondary outcome of this.
- Fast: Specially for inter-regional commuting, where car is more prevalent.
- Easy to implement: It can be operated on existing aerodromes, needing little or no dedicated facilities.

The demand estimation shows good prospects for the system. For Italy, around 10,000 potential users could benefit for its implantation. That is assuming relatively conservative aircraft parameters, that could be stretched a bit more in future work. The influence of time associated to transit through the airport also worth further study, it has a deep impact and not enough attention has been paid to it.

The optimal network definition, even though it shows some interesting results, needs of more insight to truly understand what lays behind the model. Aircraft parameters for which the network has been obtained are, as aforementioned, conservative. A broader, to a larger-scale sensitivity analysis may be interesting to analyze if potential demand translates proportionally to captured demand or not. If not, an optimum may be obtained. Additionally, for future work, introducing in the model *strings* of more than 1 flight should be a priority, as charge time has a very important influence. Being able to perform 2 flights on one charge could soften that influence, apart from being beneficial from the infrastructure perspective.

Precisely infrastructure has been skipped and, although one of the main advantages of the miniliner is its need for a very reduced infrastructure, charging installations are required. A sizing of those, altogether with a cost analysis could be a good complement.

Particularly, in the last sensitivity analysis, a considerable improvement in the results was observed if commuter flows were increased (Table 4.3). This led to further analysis and, by observing the data in Table 4.1, some conclusions were extracted relative to the adjustment of commuting population to the users of the miniliner. For instance, considering commuters, the route Firenze - Roma, has a potential demand of 199 passengers. However, 4 daily flights[1] and more than 15 high speed trains[2] only during the morning shift perform the same route.

It is thus evident potential users for the miniliner are more than commuters. It should be taken into consideration again that commuters are travelers that perform a certain route every working day. However, there are presumably more (business) people doing this route maybe not every day (and hence not considered commuters) but few times a week (for meetings, client visits...), ensuring a regular passenger flow. This passengers would also benefit for the miniliner. It is likely that this very same reasoning can be extended to most of the routes.

Therefore, they must be taken into account for future work. There is lack of information regarding passengers travelling to/from airports and/or train station in a detailed way. However, a demand model may be approached by setting the already analyzed commuter flows as a baseline, and adding an additional demand in depending on some parameters (maybe demographical and economical). In that way, the results would be more representative of the real picture.

Finally, this project has as a target market the whole European Union, but this work has been reduced to Italy. Expansion of the project to other countries, or even groups of countries to absorb trans-national commuters, is a must. However, this is no easy task. The advantage of the Italian case is having such a detailed OD commuting matrix available, which is not the standard for other countries. This is a problem even Eurostat confronts, as it is stated in the closing of the "European harmonised Labour Market Areas" report [18]. Hopefully, in the next years this data is produced and even a complete European OD commuting matrix is made available.

[1] Obtained from Alitalia's website on 15/09/2020

[2] Obtained from Trenitalia's website on 15/09/2020

Appendix A

Additional data

In this appendix, additional data is presented. This data was not included in the main body of the thesis to keep it clean and readable, but is part of the results nonetheless.

ID	Name	ICAO	Lat [°]	Lon [°]	Rwy [m]
1	Aeroporto Di Bari/Palese	LIBD	41.1375	16.7650	3000
2	Aeroporto Di Perugia/S.Francesco	LIRZ	43.0956	12.5050	2300
3	Aeroporto Di Udine-Campoformido	LIPD	46.0314	13.1869	1500
4	Aeroporto Di Voghera-Rivanazzano	LILH	44.9519	9.0158	1120
5	Aeroporto Di Vercelli	LILI	45.3117	8.4228	560
6	Cosenza		39.5261	16.2300	1000
7	Aero Club Piacenza		44.9978	9.5814	860
8	Bibione - Agriturismo Toniatti		45.6694	13.0392	1000
9	Massalengo		45.2731	9.4825	700
10	Marina Di Modica		36.7231	14.7750	600
11	Aeroporto Di Brindisi/Casale	LIBR	40.6567	17.9453	3048
12	Cascina Valentino		44.6975	7.4019	630
13	Grumentum		40.2694	15.9178	1110
14	Umberto Nobile		41.2353	13.8211	800
15	Aeroporto Di Lucca-Tassignano	LIQL	43.8253	10.5789	910
16	Aeroporto Di Verona/Villafranca	LIPX	45.3953	10.8875	3068
17	Guido Paci		43.1014	13.5553	800
18	Aeroporto Di Bolzano	LIPB	46.4625	11.3297	1294
19	Esperti		40.4789	17.8844	600
20	Aeroporto Di Rimini/Miramare	LIPR	44.0219	12.6053	3300
21	Aeroporto Di Prati Vecchi D'Agu	LIDV	44.7903	11.6731	800
22	Bolgheri		43.2114	10.5442	750
23	Valle Gaffaro		44.8333	12.2333	900
24	Divinangelo Primo		41.4719	13.0236	600
25	Aeroporto Di Pavullo Nel Frignan	LIDP	44.3225	10.8322	1190
26	Alituscia		42.2278	12.1197	700
27	Aeroporto Di Torino-Aeritalia	LIMA	45.0867	7.6092	1074

28	Aretusa Fly		37.0372	15.0953	630
29	Pittini A.V.R.O.		46.2358	13.0736	600
30	Il Borro		43.5375	11.7061	920
31	San Giorgio Di Cascia		42.7561	13.0164	1050
32	Aeroporto Di Belluno	LIDB	46.1667	12.2492	812
33	Scalea		39.7772	15.8208	1450
34	Aeroporto Di Brescia/Montichiari	LIPO	45.4289	10.3306	2990
35	Aeroporto Di Alzate Brianza	LILB	45.7717	9.1644	600
36	Dorgali		40.3478	9.5481	650
37	Valcesano		43.7006	13.0739	820
38	Centro Volo Serristori		43.3325	11.8581	600
39	Aeroporto Di Crotone	LIBC	38.9947	17.0772	2000
40	Aeroporto Di Albenga	LIMG	44.0450	8.1244	1432
41	Aeroporto Di Parma	LIMP	44.8208	10.2950	2124
42	Xptz - Decimoputzu		39.3631	8.8678	790
43	Aeroporto Di Pescara	LIBP	42.4300	14.1881	2419
44	Falcone		41.1042	15.8761	750
45	Aeroporto Di Marina Di Campo	LIRJ	42.7633	10.2369	1197
46	Olivola		41.1775	14.7472	650
47	Boglietto		44.7586	8.1833	645
48	Aeroporto Di Legnago	LIDL	45.1325	11.2925	610
49	Aeroporto Di Calcinate Del Pesce	LILC	45.8100	8.7708	600
50	Aeroporto Di Sarzana-Luni	LIQW	44.0903	9.9892	905
51	Aeroporto Di Trapani/Birgi	LICT	37.9125	12.4892	2695
52	Aeroporto Di Padova	LIPU	45.3953	11.8492	1122
53	Pegaso Flying Club		41.5417	13.3694	600
54	Enrico Mattei		40.4325	16.5544	1440
55	Aeroporto Di Salerno/Pontecagnan	LIRI	40.6203	14.9203	1654
56	Massarotti		37.1917	14.5511	700
57	Avio Club Chiusdino		43.1903	11.1458	700
58	Corte		40.1067	18.2583	985
59	L'Aquila		42.3008	13.5172	650
60	Minotaurus E Medusa		38.0481	14.5406	800
61	Aeroporto Di Asiago	LIDA	45.8869	11.5167	1120
62	Aviocaipoli		41.8903	12.7847	810
63	Aeroporto Di Firenze/Peretola	LIRQ	43.8086	11.2011	1750
64	Caiolo	LILO	46.1542	9.7925	1050
65	Aliquirra		39.6786	9.4619	650
66	Aeroporto Di Alghero/Fertilia	LIEA	40.6331	8.2894	3000
67	Aeroporto Di Foggia/Gino Lisa	LIBF	41.4339	15.5358	1438
68	Aeroporto Di Aosta	LIMW	45.7386	7.3681	1499
69	Aeroporto Di Pantelleria	LICG	36.8150	11.9669	2030
70	Aeroporto Di Lampedusa	LICD	35.4992	12.6156	1800
71	Ceraso		40.9389	16.4944	890

72	Sagrantino		42.8900	12.5328	720
73	Aeroporto Di Trieste	LIPQ	45.8272	13.4703	3000
74	Aeroporto Di Novi Ligure	LIMR	44.7781	8.7889	1050
75	Aeroporto Di Casale Monferrato	LILM	45.1089	8.4528	880
76	Sibari Fly		39.7569	16.4381	800
77	Cortina Di Alseno		44.8700	9.9378	720
78	Alicaorle		45.6125	12.8103	833
79	Aeroporto Di Milano Bresso	LIMB	45.5372	9.1997	1080
80	Aeroporto Di Comiso	LICB	36.9958	14.6078	2538
81	Aeroporto Di Taranto/Grottaglie	LIBG	40.5167	17.3975	3200
82	Aeroporto Di Cuneo/Levaldigi	LIMZ	44.5456	7.6208	2100
83	Pantano Di Pignola		40.5614	15.7592	600
84	Volturno Fly		41.1575	14.3669	630
85	Grecciano		43.6286	10.4828	700
86	Citta' Di Curtatone		45.1011	10.7506	750
87	Tronto		42.8894	13.8689	1499
88	Aeroporto Di Trento-Mattarello	LIDT	46.0214	11.1253	1130
89	Aeroporto Di Forlì	LIPK	44.1950	12.0697	2540
90	Aeroporto Di Lugo Di Romagna	LIDG	44.3983	11.8556	800
91	Aliscarlino		42.9122	10.8167	670
92	Bagnoli Di Sopra		45.1844	11.8575	1180
93	Aeroporto Di Roma/Ciampino	LIRA	41.8000	12.5933	2200
94	Aeroporto Di Carpi	LIDU	44.8367	10.8711	850
95	Alfina		42.7375	11.9831	750
96	Aeroporto Di Biella-Cerrione	LILE	45.4975	8.1022	1320
97	San Sepolcro		43.5583	12.1556	875
98	Vallesanta		42.4272	12.8053	785
99	Aeroporto Di Treviso/S.Angelo	LIPH	45.6508	12.1978	2459
100	Aeroporto Di Cremona-Migliaro	LILR	45.1675	10.0042	650
101	Aeroporto D'Olbia/Costa Smeral	LIEO	40.8997	9.5158	2445
102	Aeroporto Di Ancona/Falconara	LIPY	43.6156	13.3619	2965
103	Aeroporto Di Lamezia Terme	LICA	38.9064	16.2433	3017
104	Aeroporto Di Genova/Sestri	LIMJ	44.4131	8.8444	2916
105	Aeroporto Di Oristano/Fenosu	LIER	39.8969	8.6406	1199
106	Celano		42.0514	13.5572	830
107	Aeroporto Di Palermo-Boccadif	LICP	38.1144	13.3128	1224
108	Aeroporto Di Grosseto	LIRS	42.7633	11.0828	3007
109	Aeroporto Di Reggio Calabria	LICR	38.0733	15.6525	2061

Table A.1. List of Italian clustered airports with a cut distance of 50km.

Acronyms

AIP Aeronautical Information Publication

API Application Programming Interface

CORSIA Carbon Offsetting and Reduction Scheme for International Aviation

EU European Union

EU-ETS European Union Emission Trading Scheme

GVRP Green Vehicle Routing Problem

H2020 Framework Programmes for Research and Technological Development

ICAO International Civil Aviation Organization

ICE Internal Combustion Engine

ILP Integer Linear Programming

ISTAT Istituto Nazionale di Statistica

MAHEPA Modular Approach to Hybrid-Electric Propulsion Architecture

NUTS Nomenclature of Territorial Units for Statistics

NZE Near Zero Emission

OD Origin-Destination

SP Stated Preferences

UNIFIER19 commUNIty FrIendly minilinER

VRP Vehicle Routing Problem

Bibliography

[1] Davide Gabrielli. Scenario Studies for a Micro-Feeder Air Transportation Service. Master's thesis, Politecnico di Milano, dec 2019.

[2] Eurostat. Commuting between regions. https://ec.europa.eu/eurostat/en/web/products-eurostat-news/-/DDN-20200324-1.

[3] European Commission. Reducing emissions from aviation - European Commission. https://ec.europa.eu/clima/policies/transport/aviation_en, 2015.

[4] International Civil Aviation Organization (ICAO). Consolidated statement of continuing ICAO policies and practices related to environmental protection – Global Market-based Measure (MBM) scheme. page 8, 2016.

[5] The Guardian. Greta Thunberg arrives in Lisbon after three week voyage from US. https://www.theguardian.com/environment/2019/dec/03/greta-thunberg-arrives-in-lisbon-cop25-after-three-week-voyage-from-us, 2019.

[6] European Environmental Agency. Greenhouse gas emissions from transport in Europe — European Environment Agency. https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-12, 2018.

[7] ISTAT. 15 Censimento della popolazione e delle abitazioni 2011. https://www.istat.it/it/censimenti-permanenti/censimenti-precedenti/popolazione-e-abitazioni/popolazione-2011, 2013.

[8] Raouf Ibrahim. Market and Cost Analysis of Hybrid-Electric Aircraft. Master's thesis, Politecnico di Milano, dec 2018.

[9] Marek Darecki, Charles Edelstenne, Tom Enders, Emma Fernandez, Peter Hartman, Jean-Paul Herteman, Michael Kerkloh, Ian King, Patrick Ky, Michel Mathieu, Giuseppe Orsi, Gerald Schotman, Colin Smith, and Johann-Dietrich Wörner. Flightpath 2050. *Flightpath 2050 Europe's Vision for Aviation*, page 28, 2011.

[10] Gianluca Magni. Matheuristic and Bounding Procedures to Solve the Micro-Feeder Hybrid Electric Air Transport Problem. Master's thesis, Politecnico di Milano, apr 2019.

[11] Lorenzo Trainelli, Andrea Maria Marchionni, and Maurizio Bruglieri. Optimization of the demand satisfied by a “Micro-Feeder” Hybrid -Electric air transport service. In *XXV Congresso Nazionale AIDAA*, Roma, Italy, 2019.

[12] Lorenzo Trainelli, Maurizio Bruglieri, Carlo E.D. Riboldi, Francesco Salucci, and Davide Gabrielli. Optimal Definition of a Short-Haul Air Transportation Network for Door-to-Door Mobility. In *Aerospace Europe Conference (AEC)*, Bordeaux, France, 2020.

[13] Ennio Cascetta. *Transportation Systems Analysis, Models and Applications*, volume 10. 2009.

[14] OpenAIP. https://www.openaip.net.

[15] ENAV. AIP Italia, 2020.

[16] Alberto Rolando, Francesco Salucci, Lorenzo Trainelli, Carlo E.D. Riboldi, and Yashir M. Khan. On the design of an Electric-Powered microfeeder aircraft. In *Aerospace Europe Conference (AEC)*, Bordeaux, France, 2020.

[17] Lorenzo Trainelli, Carlo E.D. Riboldi, Alberto Rolando, and Francesco Salucci. Methodologies for the initial design studies of an innovative community-friendly miniliner. In *10th EASN International Conference*, 2020.

[18] Eurostat. European harmonised Labour Market Areas — methodology on functional geographies with potential 2020 edition. Technical report, 2020.