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Studies of Time and Cost Benefits for a Hybrid-Electric Commuting Air Transportation System

Tesi di Laurea Magistrale in Aeronautical Engineering
Ingegneria Industriale e dell'Informazione

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Abstract

The promising feasibility of a new hybrid-electric commuter aircraft, which would be able to operate in Europe through Microfeeder (hub to/from smaller airports) and Miniliner (intercity) services, sets the need to establish whether potential travellers will be willing to use it. This would significantly reduce car journeys, improving environmental sustainability and quality of life. While an assessment of travel time benefits with respect to ground vehicles has already been studied, little or no focus has been put yet on the predicted cost of the service. That is the motivation of the present approach to determine travel cost benefits for such future air services.

The work is based on the customization and extension of methods developed at the Department of Aerospace Science and Engineering, Politecnico di Milano. Furthermore, a Piaggio Aerospace cost model has been considered, and results have been compared with the cost methodologies employed in the Clean Sky UNIFIER19 project. These studies help predicting the potential demand for the foreseen short- and very short-haul air transportation market. Sensitivity analyses are performed to determine the effects of cost fluctuations, in terms of car travels, flight travels, and commuters' value of time. In order to do this, the original SHARONA-PDE algorithm has been modified and a constraint to include cost benefits was formulated and applied to realistic scenarios.

Keywords: UNIFIER19, Cost Models, Potential Demand, Ticket, DOC

Sommario

La promettente fattibilità di un nuovo velivolo ibrido-elettrico, il quale opererebbe in Europa come Microfeeder (hub verso/da aeroporti minori) e Miniliner (intercity), impone la necessità di stabilire se i potenziali viaggiatori saranno disposti ad utilizzarlo. Questo porterebbe ad una riduzione significativa dei viaggi in auto, migliorando la sostenibilità ambientale e la qualità della vita. Mentre una valutazione dei benefici temporali rispetto ai veicoli terresti è stata già studiata, poca o nessuna attenzione è stata ancora data alla stima dei costi del servizio. Questo è lo stimolo del seguente approccio, che si prefissa di determinare i benefici in termini di costo per i suddetti futuri servizi aerei.

Il lavoro è basato sull'adattamento e sull'estensione di metodi sviluppati al Dipartimento di Scienze e Tecnologie Aerospaziali, Politecnico di Milano. Inoltre, un modello di costo della Piaggio Aerospace è stato considerato, e i risultati sono stati paragonati con le metodologie di costo implementate nel progetto UNIFIER19 di Clean Sky. Questi studi aiutano a predire la domanda potenziale per il previsto mercato aereo di raggio corto e molto corto. Delle analisi di sensitività sono state eseguite per determinare gli effetti delle fluttuazioni di costo, in termini di viaggi in auto, viaggi in aereo, e valore del tempo dei pendolari. Per farlo, l'algoritmo originale SHARONA-PDE è stato modificato, e un vincolo che include i benefici di costo è stato formulato ed applicato a scenari realistici.

Keywords: UNIFIER19, Modelli di Costo, Domanda Potenziale, Biglietto, DOC

Contents

1 | Introduction

Aviation is one of the fastest-growing sources of pollutants: during 2017, its direct emissions accounted for 3.8% of total CO_2 emissions and for 13.9% of the emissions coming from the overall transport sector [1], which on their side account for a 25% of total greenhouse gas discharge [2]. According to ICAO (International Civil Aviation Organization), civil aviation consumed approximately 160 megatons of fuel in 2015 [3]. By considering an increase of 3.3 times growth in international air traffic (based on studies performed before the outbreak of the COVID-19 pandemic), fuel consumption is projected to increase by 2.2 to 3.1 times by 2045. Apart from CO_2, a climate impact is also made by the release of nitrogen oxides, water vapour, sulphate and soot particles at high altitude. To achieve climate neutrality, the European Green Deal [4] was presented on the 1st of December 2019, and establishes the need to reduce transport emissions by 90% by 2050 and by 55% by 2030 [2] (compared to 1990 levels): the aviation sector will surely have to contribute to this reduction by improving its operations.

1.1 Background and European Projects

1.1.1 CORSIA (International Civil Aviation Organization)

With the aim to introduce a global market based measure, ICAO confirmed in October 2016 the CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) program [5]. The baseline for the project was set during 2019 and 2020, when all aeroplane operators, having international routes and producing annual CO_2 emissions greater than 10 thousand tonnes, were required to monitor and report their release of pollutants. During the pilot phase (2021 - 2023) and the first phase of the project (2024 - 2026), requirements will be only applicable to flights between states that have volunteered to participate. The second phase will instead apply to all ICAO member states, with some exemptions. The aim is to achieve a carbon neutral growth in aviation with respect to 2020 values, as shown in Figure 1.2, with the help of operational improvements, aircraft technology, and, predominantly, sustainable aviation fuels.

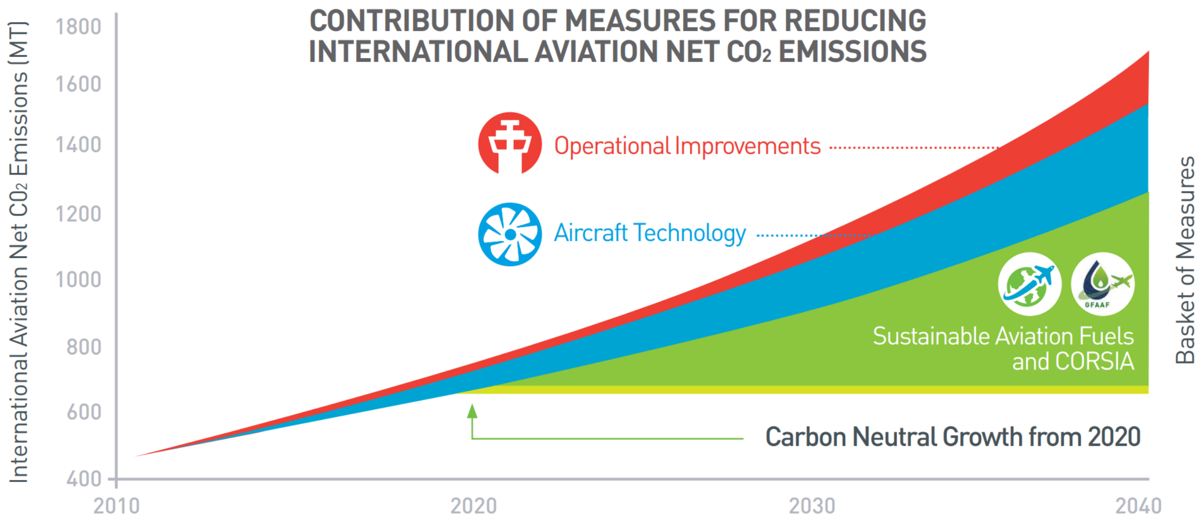


Figure 1.1: Carbon Offsetting and Reduction Scheme for International Aviation [5].

1.1.2 Flightpath 2050 and Clean Sky

Flightpath 2050 is an ambitious project, with main contributor the Clean Sky Program (second version, born in 2014) [6]. It sets the following main objectives [7].

- European citizens are able to make informed mobility choices.
- 90% of European travellers complete their journey, door to door, within 4 hours.
- Flights arrive within one minute of the planned arrival time.
- An air traffic management system is in place that provides a range of services to handle at least 25 million flights per year and for all types of vehicles.
- A coherent ground infrastructure has been developed.

Figure 1.2: Clean Sky Logo. Retrieved from [6].

Moreover, concerning about protecting the environment, the following five goals are set.

- In 2050, technologies and procedures available will allow a 75% reduction in CO_2 emissions per passenger kilometre, and a 90% reduction in nitrogen oxide (NO_x) emissions. The perceived noise of flying aircraft is reduced by 65%: this is relative to the characteristics of typical aircraft as observed in 2000.
- Aircraft movements are emission-free when taxiing.
- Air vehicles are designed and manufactured to be recyclable.
- Europe is established as a centre of excellence on sustainable alternative fuels, including those for aviation, based on a strong European energy policy.
- Europe is at the forefront of atmospheric research and takes the lead in the formulation of a prioritised environmental action plan and establishment of global environmental standards.

1.1.3 MAHEPA and UNIFIER19

MAHEPA stands for Modular Approach to Hybrid-Electric Propulsion Architecture, and was a project which aimed to develop and fly two new hybrid-electric powertrains, in order to enable cleaner, quieter and more efficient aircraft propulsion: the first used a fuel-driven generator to charge batteries and power an electric motor (ICE), while the second one relied on fuel cells (FC) to produce a complete zero-emission flight [8]. An attention was also paid to regulatory implications, airport infrastructure requirements, airspace procedural practices, operational safety, operating costs and emission models. MAHEPA has been an Horizon 2020 EU-funded project, along with UNIFIER19 [9].

(a) MAHEPA Logo

(b) UNIFIER19 Logo

Figure 1.3: MAHEPA and UNIFIER19 Trademarks. Retrieved from [8, 9].

The UNIFIER19 (Comm*uni*ty *Fri*endly Minilin*er*) project states that «the key enabling technology maturing in the next decade and the recently approved CS23 Amendment 5, enable the development and certification of a 19-passenger hybrid-electric commuter, designed in this project as a community friendly Miniliner» [9]. The main objective is to develop a conceptual design accounting for multiple cargo and passenger cabin layouts, powered by an hybrid-electric powertrain. Modularity is in fact a requirement, and therefore empowers the development of a single airframe, capable however of accommodating multiple combinations of propellers, batteries, and other components. Partners of UNIFIER19 are Politecnico di Milano, Pipistrel Vertical Solution, and Delft University of Technology. UNIFIER19 is a Clean Sky 2 embedded program. Targets are the following.

- Reduce CO_2, NO_x and acoustic emissions by at least 20% compared to similar vehicles which entered into service in 2014.
- Develop a commuter that is as easy to use as a bus: the aircraft can take advantage of the sparse underused small airports without overwhelming burdens for new ground infrastructures, providing communities with a new mobility opportunity.
- Define the design requirements by estimating the European mobility demand in at least two markets: the Miniliner market, aimed at connecting small airports among them via scheduled or on-demand services, and the Microfeeder market, where small community airports and unpaved airfields feed travellers to bigger airports served by regularly scheduled commercial flights.

1.2 Status Quo and Previous Studies

Rather than focusing on the Miniliner design and its specifications, the present work will instead emphasize the feasibility and the definition of its air transportation system. However, for the sake of having a clear overview of the entire project and to establish the starting point of the subsequent analyses, an introduction to the state of the art here follows. This will also help in establishing the objectives of this thesis.

1.2.1 Hybrid and Electric Propulsion

Powertrains architectures for electric aircraft can be grouped into two main categories, which are Pure-Electric (PE) and Hybrid-Electric (HE). In the first case, batteries are the only source of energy, while in the second, electric motors are fed by a Power Generation System (PGS), whose power can be produced by thermal engines or fuel cells, as stated in [10], section 1.1. The different configurations and sub-configurations can be distinguished with the use of two indicators, which go under the name of hybridization factors. They are defined as the ratio between power (or energy) of the non-polluting source of energy and the overall propulsion power (or energy).

$$H_P = \frac{P_m}{P_{tot}} \qquad\qquad H_E = \frac{E_b}{E_{tot}} \tag{1.1}$$

While current batteries are too heavy for aeronautics and hydrogen achieves very low burning efficiencies in thermal engines (around 25%), using hydrogen with fuel cells brings higher efficiencies, up to 60%, and only produces water vapour, as stated in [10]. A complete review of battery specific energies, hydrogen storage methodologies, and hybrid architecture components can be found in [10], chapter 1.

In UNIFIER19 Final Concurrent Design Report [11], chapter 7, after a close examination of all possible aircraft configurations, Politecnico di Milano candidate C7A was chosen over competitors for the subsequent phase of the project. It envisages a traditional lifting surface layout, along with Distributed Electric Propulsion (DEP), composed of 12 propellers, and a single pusher propeller on the tail.

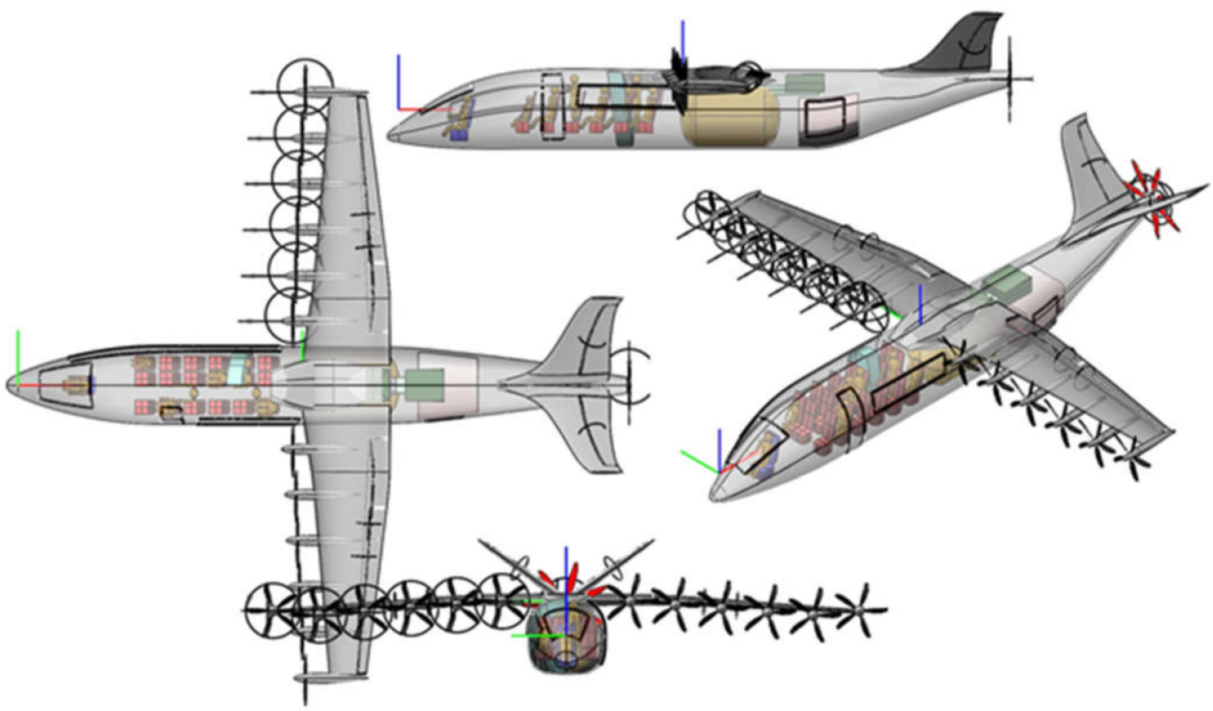


Figure 1.4: Candidate C7A: Top, Side, Front, and ISO. Retrieved from [11].

While the latter provides the full cruise thrust, the former are only intended to supply high lift during takeoff and terminal maneuvers, since they are turned off and folded backwards (in order to reduce drag) for the remaining portion of the flight [11]. The concept for this 19-seater Miniliner is shown in Figure 1.4, while its main characteristics and data are reported in Table 1.1.

Table 1.1: Specifications of Candidate C7A. Retrieved from [11], section 3.3.1.

Runway	800	[m]	**H_2 Tank Volume**	5.58	[m^3]
Cruise Speed	72.74	[m/s]	**Engine Power**	1188.2	[kW]
Cruise Range	350	[km]	**PGS Power**	635.3	[kW]
Maximum TOW	7953.7	[kg]	**DEP Power**	786.1	[kW]
Operative EW	5297	[kg]	**Engine Thrust**	24443	[N]
Cruise Altitude	1219	[m]	**Battery Weight**	586.3	[kg]

1.2.2 Selection of Hubs and Secondary Aerodromes

Hubs selection in Italy for Microfeeder and Miniliner proceeded based on the satisfaction of at least two of the following three prerequisites [12–14]: (1) decreto del Presidente della Repubblica 201 / 2015 [15], (2) TEN-T (Trans-European Transport Networks) [16], and (3) passengers per year greater than 5 million [17].

Concerning aerodromes instead, according to the OpenAIP database [18], there are 602 potential airports and airfields in Italy that could be serviced by the new 19-seater service [19]. Airfields do not exceed in length the value of 2000 meters, and most of them are below 900 meters, as specified in [12]. Concerning secondary airports, their maximum runway length is 3400 meters.

In order to avoid an excessive number of secondary aerodromes, which would lead to high operating costs, a clustering technique was adopted to group neighbouring, as formulated in [12], section 2.2: this grouping followed an agglomerating hierarchical clustering, based on car travel time between aerodromes, and gave as output a dendogram, potentially representing the grouping of all aerodromes up to a single one.

This allowed to cut the graph at a certain cluster distance decided by the user: in this case, a limit of 50 kilometers road distance was chosen (evaluated with the use of HereMaps API [20]), and the whole Italy was subdivided into 109 clusters. A complete list of the clusters can be found in Appendix A, while the dendogram is shown in Figure 1.5.

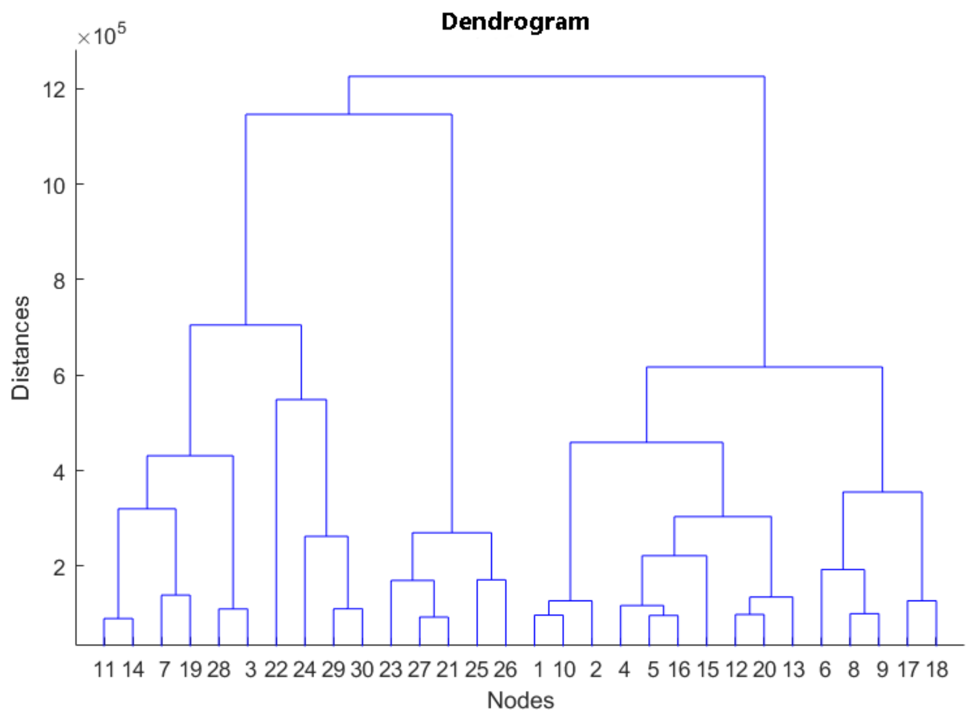


Figure 1.5: Dendogram for Aerodromes Clustering. Retrieved from [12], section 2.2.

1.2.3 Miniliner Problem

The Miniliner approach is aimed to create a transport network which could compete with ground transportation on a national basis. In [19] this concept was used to establish a potential demand estimation (PDE), based on commuting traffic.

The commuting matrix coming from the 2011 Italian census of population was used, provided by the Italian National Institute of Statistics [21]: this resulted in an origin-destination matrix representing the morning commuting flow, reasonably considered to be the transpose of the afternoon shift scenario. The generic element g_{od} in the following equation represents the flow of commuters from origin municipality o to destination d.

$$\bar{G} = OD_{am} = \begin{bmatrix} g_{11} & g_{12} & \cdots & g_{1n} \\ g_{21} & g_{22} & \cdots & g_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ g_{n1} & g_{n2} & \cdots & g_{nn} \end{bmatrix} = OD_{pm}^{T} \tag{1.2}$$

PDE was carried out by establishing a set of criteria which measure how advantageous the Miniliner is, against conventional ground means of transport. For computational time purposes, only municipalities with a population greater than 20 000 was considered, such that the set of municipalities was brought down from nearly 8 000 to 519. Then, a database containing road times T_{ground} between such municipalities was evaluated with the use of HereMaps API [20]: this matrix is not symmetric, but close to being so.

Concerning commuters using the Miniliner, their time to travel T_{air} is composed by: (1) travel by car from the origin municipality to the nearest aerodrome, (2) travel by air from the origin assigned aerodrome to the destination assigned aerodrome $T_{miniliner}$, and (3) travel by car from the destination assigned aerodrome to the destination municipality. In order to accomplish this segmentation scenario, also car times between municipalities and aerodromes had to be evaluated (now in a symmetric way).

Aside from actual flight time, $T_{miniliner}$ also incorporates airport times, namely for takeoff and landing, check-in, taxi, and leave time (which in this case is small since commuters are assumed to be light travellers). Reference data is shown in Table 1.2, while the overall Miniliner time is as formulated in the following equation.

$$T_{miniliner} = T_{flight} + T_{checkIn} + T_{taxiOut} + T_{TO\&LND} + T_{taxiIn} + T_{leave} \tag{1.3}$$

Table 1.2: Miniliner Potential Demand Estimation Data, as considered in [19].

$T_{ckeckIn}$ [s]	T_{taxiIn} [s]	$T_{taxiOut}$ [s]	$T_{TO\&LND}$ [s]	T_{leave} [s]	T_{ref} [s]	k [−]
600	300	300	600	300	1800	1.3

For establishing the Miniliner time efficiency, the same criteria as [12] was used, namely an absolute time difference T_{ref}, and a relative time difference k, to be defined as in Table 1.2. This points out that the Miniliner is required to be 30 minutes faster and to require at least 30% less time. Constraint are implemented as in the following equation.

$$T_{ground} - T_{air} \geq T_{ref} \qquad \wedge \qquad T_{air} \leq \frac{T_{ground}}{k} \tag{1.4}$$

The algorithm in charge of estimating potential demand and subsequently defining the relative optimal network is SHARONA (Short-Haul Air Route Optimal Network Assessment) [22], of which the first part will be used is this thesis, hereon to be referred to as SHARONA-PDE (Potential Demand Estimation) or simply S-PDE.

1.3 Thesis Outline and Summary

Commuters Data Preliminary to the cost analysis, a study on how potential demand would raise when considering also occasional business travellers is presented. Additional data has also been computed for Isola d'Elba, an island which will be of interest for the Piaggio Aerospace case study.

Cost Estimation Methodologies A literature review has been done in order to assess the main used methods for estimating aircraft operating costs. In particular, the different components of direct operating costs have been discussed, along with a focus on how they may vary when considering hybrid-electric technology.

Models for Cost Analysis Cost models are described for the Piaggio Aerospace case study and UNIFIER19 scenarios. A modified version of the original Piaggio Aerospace cost model will also be investigated.

Piaggio Aerospace Case Study Piaggio Aerospace network feasibility will be examined, along with travel time benefits and travel cost benefits, through S-PDE.

Miniliner Cost Analysis Results The Miniliner national scenario will be investigated, when applying both the time constraint and the cost constraint. Parametric studies will be developed, in order to account for fluctuations of the involved prices.

2 | Commuters Data

Heretofore, all analyses for the Intercity Miniliner case have been conducted with the use of the commuting origin-destination matrix (*Matrice del Pendolarismo*), from here on called OD Matrix, provided by the Italian National Institute of Statistics (ISTAT) [21]. Because of the high computational time required for evaluating road travel times between Italian municipalities with the use of HereMaps API [20], as anticipated, only cities with a population greater than 20 000 were considered: this allowed to reduce the OD Matrix from a total of more than 8 000 rows and columns to just 519. The aim of this chapter is to explain how, even though not expanding the matrix, a better estimation of the actual potential demand between those municipalities can be achieved.

People travelling in fact, not only account for commuting students and workers, but also for occasional travellers, that is for leisure or business matter. Although also recreational trips constitute a large amount of people and would therefore make a huge impact on potential demand estimation, their nature is seasonal. Business travels, on the contrary, have a more homogeneous root, both in temporal and spatial terms. That is why they are hereon considered for the analysis and the data enhancement.

2.1 Data Collection and Filtering

2.1.1 Incoming Accommodation Establishments Occupancy

ISTAT provides three main sets of data which can help in defining occasional business travel demand across Italy. The most important one consists of measurements about arrivals of clients into tourist accommodation establishments, sorted by type of establishment itself, number of Italian residents staying inside them, and the municipality of destination. All data refer to the year 2019, with an eye towards avoiding the effects of the COVID-19 pandemic, and can be found on the ISTAT website [23].

In Table 2.1 the following entries are shown (from left to right): region of destination of travellers, province of destination within the region, municipality of destination within the province, and total annual presences. The latter are classified in Italian residents arrivals

Table 2.1: Occupancy Data for Italian Accommodation Establishments in 2019 [23].

REGION	**PROVINCE**	**CITY**	**PRESENCES**								
			TOTAL			**HOTELS**			**OTHER**		
			R	**NR**	**T**	**R**	**NR**	**T**	**R**	**NR**	**T**
Piemonte	Torino	Ala di Stura	5 664	187	5 851	(a)	(a)	(a)	(a)	(a)	(a)
		...		...			...			...	
		Volpiano	10 559	352	10 911	(a)	(a)	(a)	(a)	(a)	(a)
		OTHER	95 489	37 779	133 268	(a)	(a)	(a)	(a)	(a)	(a)
	.	...		...			...			...	
	Biella	Biella	35 019	11 808	46 827	24 070	8 376	32 446	10 949	3 432	14 381
		...		...			...			...	
		Valdilana	725	316	1 041	(a)	(a)	(a)	(a)	(a)	(a)
		OTHER	14 360	6 002	20 362	(a)	(a)	(a)	(a)	(a)	(a)
...											
Sardegna	Sassari	Aggius	370	632	1 002	-	-	-	370	632	1 002
		...		...			...			...	
		San Teodoro	56 580	60 233	116 813	32 850	42 875	75 725	23 730	17 358	41 088
		OTHER	3 336	2 898	6 234	(a)	(a)	(a)	(a)	(a)	(a)
	.	...		...			...			...	
	Sud Sardegna	Arbus	8 939	9 759	18 698	4 467	3 815	8 282	4 472	5 944	10 416
		...		...			...			...	
		Villasimius	70 694	46 385	117 079	60 923	39 163	100 086	9 771	7 222	16 993
		OTHER	7 885	3 326	11 211	(a)	(a)	(a)	(a)	(a)	(a)

Entries marked as *(a)* denote records which were sealed due to statistical secrecy.

(R), non-Italian residents arrivals (NR), and total arrivals (T). Hence, since the travel flow to be evaluated refers to Italian citizens moving into all type of Italian establishments, the column of interest is the fourth, starting from the left. These entries will be referred to as $PAX_{IT \to DM_j}$, with DM_j standing for the $j-th$ destination municipality. Not all Italian cities are listed, as the number of rows accounts for 41.55% of all possible destinations.

The total number of Italians travelling in 2019 has been calculated to be $PAX_{IT \to IT} =$ 216 076 587, as the sum of all (R) entries. The reader may notice that at the end of each province section inside Table 2.1, there is an entry called *others*: this represents a grouping of travellers who accommodated inside some other municipality of that province, but anyway did not represent a significant incoming flow, which is hence not accounted for in the database. This said, flows of this type are discarded from the analysis, since it is not possible to associate them to a particular destination: the amount of discarded travellers is 4 360 555, which make up a total of only 2% of total presences.

2.1.2 Outgoing Travellers Flows per Region

The second database is represented by the number of Italian travellers moving to other municipalities of Italy, sorted by their region of origin [24]. Regrettably, no local or more refined data is made available to the general public. With reference to Table 2.2, the second column gathers the number of outgoing travellers, and will be here on referred to as $PAX_{OR_k \to IT}$, with OR_k standing for $k-th$ origin region.

The total amount of outgoing passengers from all regions, namely 216 076 587 people, is as one would expect equal to the total amount of Italians staying inside accommodation establishments, as declared in Section 2.1.1. The penultimate row of Table 2.2 specifies the number of travellers which origin region is unknown, and accounts for the 0.14%.

2.1.3 Italian Population Reference Information

To be able to match incoming and outgoing flows, a third data set is needed and can be found in [25]. It represents a list of all Italian municipalities, as showed in Table 2.3, along with their region and municipality codes and the number of residents on December 31, 2019. For the analysis afterwards discussed, latitude and longitude of municipalities were also added to the data set, with the use of HereMaps API [20] and its geocoding service.

Number of residents will be hereon referred to as A_{OR_k} or A_{OM_i}, depending on whether they refer to an origin region or origin municipality, respectively. It goes without saying that $A_{OR_k} = \sum_i A_{OM_i}$, with $OM_i \in OR_k$.

Table 2.2: Origin Region of Italian Travellers to Italy in 2019.

REGION	**TRAVELLERS**		
	TOTAL	**HOTELS**	**OTHER**
Piemonte	17 320 008	10 319 606	7 000 402
Valle d'Aosta	489 204	326 726	162 478
Liguria	5 172 696	3 414 510	1 758 186
Lombardia	46 766 901	31 439 363	15 327 538
Trentino - Alto Adige	5 196 528	3 014 589	2 181 939
Veneto	20 668 712	11 262 922	9 405 790
Friuli - Venezia Giulia	4 151 491	2 579 150	1 572 341
Emilia - Romagna	19 219 123	12 338 678	6 880 445
Toscana	14 329 768	8 439 307	5 890 461
Umbria	4 151 872	2 598 064	1 553 808
Marche	5 476 367	3 299 140	2 177 227
Lazio	21 721 565	15 297 023	6 424 542
Abruzzo	3 606 096	2 553 417	1 052 679
Molise	794 075	571 480	222 595
Campania	18 030 427	12 284 040	5 746 387
Puglia	10 542 495	7 463 868	3 078 627
Basilicata	1 640 736	1 183 999	456 737
Calabria	4 104 264	3 058 331	1 045 933
Sicilia	9 348 215	6 740 231	2 607 984
Sardegna	3 044 932	2 071 850	973 082
NOT DEFINED	301 112	120 472	180 640
TOTAL	216 076 587	140 376 766	75 699 821

Table 2.3: Italian Population Composition in 2019.

MUNICIPALITY	**REGION**	**ISTAT CODE**	**RESIDENTS**	**LATITUDE**	**LONGITUDE**
Agilè	01	1001	2 621	45.3636	7.7685
Airasca	01	1002	3 598	44.9173	7.4901
Ala di Stura	01	1003	441	45.3154	7.3051
...	...	...	...	...	...
Villasimius	20	111105	3 714	39.1421	9.5206
Villasor	20	111106	6 818	39.3826	8.9400
Villaspeciosa	20	111107	2 605	39.3128	8.9271

2.2 Regions to Municipalities Fluxes

To be able to continue with the model definition and achieve the desired OD matrix, a strong assumption has to be made. It is take for granted that municipality to municipality flows are represented by an homogeneous distribution, both in terms of space and in terms of time. This is actually an acceptable hypothesis in the case of business travellers, which do differ a lot from leisure movements, all of whom strongly depend both on origin and destination and on the period of the year. However, the model can be anyway considered conservative, for two reasons: (1) travels due to business reasons are only a small percentage of the overall Italian flows, and (2) data does not include one-day trips.

With this in mind, a proportionality relation can be established. The assumption is that passengers moving from region k are to the total of Italian travellers, as passengers moving from region k to municipality j are to passengers incoming municipality j. This results in the equation displayed below, which constitutes the base for the next step, that is evaluating individual municipalities to municipalities fluxes.

$$PAX_{OR_k \to IT} : \underbrace{\sum\nolimits_k PAX_{OR_k \to IT}}_{PAX_{IT \to IT}} = PAX_{OR_k \to DM_j} : PAX_{IT \to DM_j} \tag{2.1}$$

$$PAX_{OR_k \to DM_j} = \frac{PAX_{OR_k \to IT} \cdot PAX_{IT \to DM_j}}{PAX_{IT \to IT}} \tag{2.2}$$

2.3 Municipalities to Municipalities Fluxes

With the same homogeneity hypothesized in Section 2.2, the outgoing regional fluxes can be scaled to a municipality level, in relation to the portion of citizens of the municipality itself. This is made explicit in the following equation, in which the trimmed square brackets define the so-called *floor* function. Recall that $OM_i \in OR_k$.

$$PAX_{OM_i \to DM_j} = \left\lfloor PAX_{OR_k \to DM_j} \cdot \frac{A_{OM_i}}{A_{OR_k}} \right\rfloor \tag{2.3}$$

Since occupancy data is given for a total of 3288 municipalities, and since residence information is given for 7914 Italian cities, the total number of possible routes generated by the process is 26 021 232. Business travels are then filtered in two steps.

Table 2.4: Number of Travels during each Month of the Year in 2019.

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
4166	3466	3692	7283	4172	7666	8442	14082	4650	3940	3592	6102

First, according to the Italian National Institute of Statistics, the number of monthly departures (in thousands) is as shown in Table 2.4: referring to the entries as m_p, with $p = \{1, ..., 12\}$, the percentage of travels M_p during a single month can be retrieved. Furthermore, calling $n(p) = 12$ the cardinality of the set of the months, an average value $\hat{M}$ can be found, as if all trips were equally spread during the year.

$$M_p = 100 \cdot \frac{m_p}{\sum_p m_p} \qquad \hat{M} = \frac{\sum_p M_p}{n(p)} \tag{2.4}$$

The second step is to evaluate how much of these equally spread travels are to be accounted to business travellers. ISTAT gives an average percentage of travels due to work equal to 10.9% [26], with a maximum of 11.1% from south Italy.

Daily business passengers going from municipality OM_i to municipality DM_j can hence be computed as in the equation shown below, where the flows retrieved from Equation 2.3 are filtered by the working reason factor $\alpha_W = 10.9\%$ and transformed from passengers per year to passengers per day with the use of $\hat{M}/30$. A list of the most busiest routes in terms of passengers par day can be found in Appendix B.

$$PAX_{OM_i \to DM_j} = \left\lfloor PAX_{OR_k \to DM_j} \cdot \frac{A_{OM_i}}{A_{OR_k}} \cdot \frac{\hat{M}}{30} \cdot \alpha_W \right\rfloor \tag{2.5}$$

2.4 OD Matrix Reduction and Comparison

The resulting matrix $\bar{Z}$ is 7914 × 3288 (origins to destinations), and needs therefore to be reduced in order to be comparable with the 519 × 519 one constructed in [19] (from now on referred to as Original OD Matrix, with symbol $\bar{G}$). However, not all pairs $\{o, d\} \in \bar{G}$ can be found in $\bar{Z}$. The total number of missing occupancy data accounts for 56 municipalities: these will be set to have zero added travellers with respect to $\bar{G}$. One shall so define G as the sum of the original and occupancy OD matrices, as here shown.

$$G = \bar{G} + Z \qquad \text{with} \qquad Z \subsetneq \bar{Z} \tag{2.6}$$

The mean difference of potential passengers is $\left[\bar{G} - Z\right] = 54.58$. Original potential demand was $\sum_{i,j} \bar{G}\,(i,j) = 13\ 644\ 740$, while updated potential demand is $\sum_{i,j} G\,(i,j) = 13\ 649\ 805$, with an added demand of $\sum_{i,j} Z\,(i,j) = 5065$. This increment may seem small-scale, however it increases the number of passengers of about 1000 units during potential demand estimation (as it will be clear in Chapter 6), which not to say is a huge difference when considering a 19-seater aircraft aimed at flying national routes.

This happens because commuters belonging to $\bar{G}$ are of general nature, and as such they may also refer to commuting which happens within the same municipality. Occupancy added demand is instead a proper medium-haul travel the workers are doing.

To prove this, the reader may refer to Figure 2.1. The blue line represents the cumulative percentage of commuters arising from the Original OD matrix $\bar{G}$, varying with respect to car time to travel between the municipality pairs. The green line is instead the cumulative percentage of occasional business travellers. Finally, the black dashed vertical limit represents the $T_{ref} = 1800$ seconds time threshold for potential demand estimation. Commuters are mostly stacked near the y axis, meaning that more than 80% of potential passengers take a very few time to reach their work or study place, and are therefore discarded by SHARONA-PDE. Business travellers take instead much more time for their trip, which explains why their presence is of paramount impact. Notice that captured potential demand could be seen as the area between curves and the dashed limit.

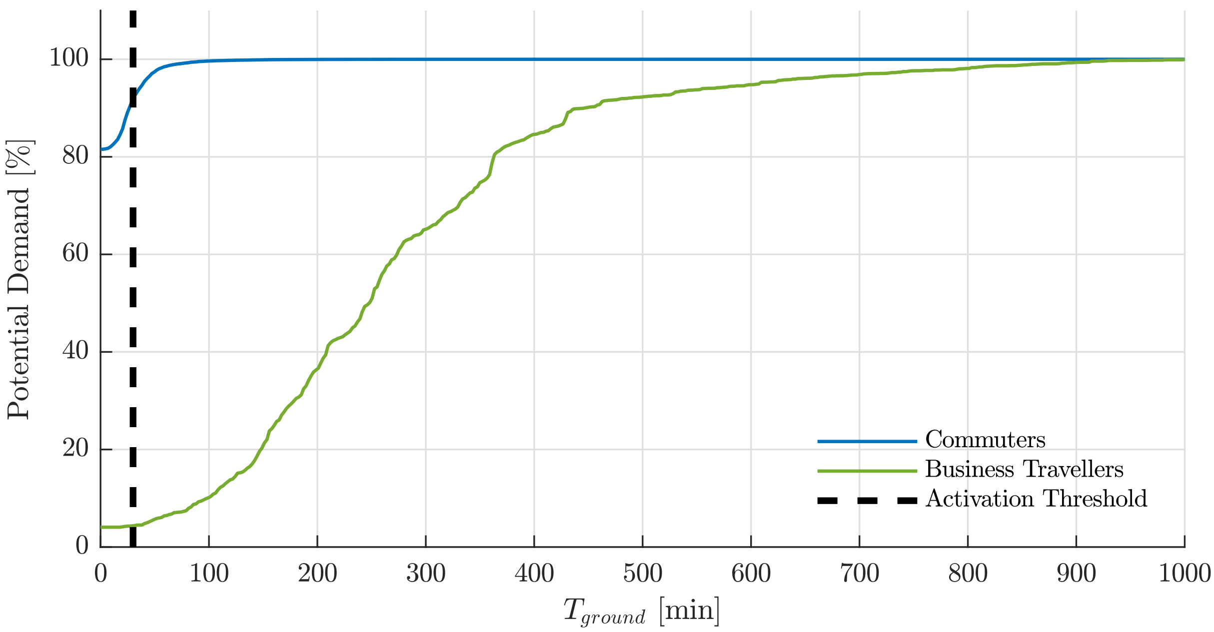


Figure 2.1: Commuters and Business Travellers varying with Car Time.

2.5 Isola d'Elba Supplementary Records

Isola d'Elba is the third biggest Italian island, located in the north of the country and between Corsica island and Italy west coast, in Livorno province. Having as reference Figure 2.2, six small cities belong to the island: Marciana (which eventually also embraces Marciana Marina), Campo nell'Elba, Portoferraio, Capoliveri, Porto Azzurro, and Rio (including both Rio Marina and Rio nell'Elba, starting from 2018). Table 2.5 contains residents data for the before mentioned municipalities.

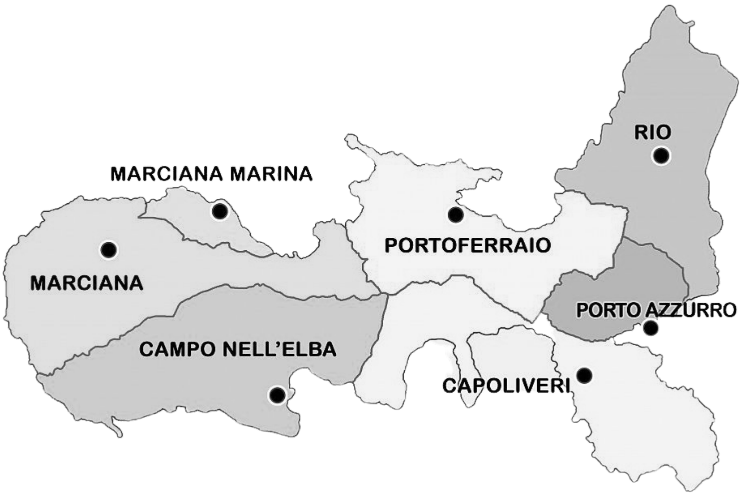


Figure 2.2: Isola d'Elba Municipalities and Subdivision. Retrieved from [27].

Table 2.5: Municipalities Residents Data for Isola d'Elba (in 2019).

Marciana	Campo nell'Elba	Portoferraio	Capoliveri	Porto Azzurro	Rio
2118	4691	11902	4018	3654	3364

2.5.1 OD Matrix Expansion for Isola d'Elba

No municipality overtakes the 20 000 limit threshold imposed by the potential demand algorithm, and hence none appears in the matrices $\bar{G}$, Z, and G. Still, data for these municipalities is of relevance for the Piaggio Aerospace case study analysed in Chapter 5.

Therefore, matrix G has to be expanded into being 525 × 525, christened G_E, such that $G \subsetneq G_E$. This expansion is done by taking into account both commuters and business travellers. All six extra cities are included in the 3288 municipalities for which occupancy data is available, hence the process does not increase the number of unknown municipality occupancy data, which continues being 56, as stated in Section 2.4.

The added potential demand in terms of incoming and outgoing commuters is 10 598. As regards business travellers instead, a total of 46 potential passengers is added. Further considerations will be done in Chapter 5, after the application of the S-PDE algorithm.

2.5.2 OD Matrix Including Leisure Travellers

For the sake of evaluating how much Piaggio Aerospace network would change if holiday trips were considered, an additional matrix was set up. This is an OD matrix which stays unchanged with respect to G_E in terms of number of commuters, but adds all potential passengers coming from occupancy data, not only considering business travellers. The total potential demand for travellers (both business and leisure) increases to 97 084. The matrix, which will be referred to as G_H, is proportional to G_E for the inverse of the business travellers percentage, as recalled in the following equation.

$$G_H \propto G_E \cdot \frac{1}{\alpha_W} \tag{2.7}$$

3 | Cost Estimation Methodologies

When talking about cost estimation for a new aircraft, two points of view have to be considered, which are the manufacturer and the operator perspectives. Manufacturer costs can be divided in fixed and variable: the former are non-recurring costs, mainly incurred during the design and the development phases of the new vehicle, while the latter mainly depend on the real quantity of aircraft produced, on the production costs, etc. [28]. Many models, ranging from simple to more complex, are available in literature. As a reference, manufacturing costs are described in Roskam [29], Nikolai [30], and Raymer [31]. However, considering the concern of this work, which strives to establish the price advantages for a new Miniliner service from the viewpoint of the final users, for the sake of not loosing the big picture, manufacturing cost models will not be further questioned.

3.1 Partitioning of Operating Costs

When wanting to evaluate travel costs benefits, an estimation of the price a potential user shall pay to use the service is essential, i.e. the ticket price for a particular route. This includes expenses for operating the flight, namely fuel, crew salaries, airport and navigation fees, ticket sales cost, catering for passengers, etc. Nevertheless, airline operators do face way more types of costs, which are related to owing the aircraft (usually fully purchased through a long-term financing), managing the airline (offices, managers, engineers, etc.), maintenance, and so on. General and well-accepted methods can be found in literature to asses how much operating a route will cost to the airline.

Methods based on Life Cycle Costs (LCC) are usually intended for the military sphere, giving the cost of the aircraft as a whole, from preliminary design stages to final disposal. These methods are not of much interest in the civil aviation context (even though they have been applied to some subsonic commercial airplanes [32]), since airlines would buy an aircraft and will only care on elements such as fuel efficiency, financing interests, potential revenues, and so on. Moreover, the airline will eventually sell the aircraft at the end of its useful life, based on its residual value. Therefore, what is relevant to carriers are the so-called operating costs [28], as shown in Figure 3.1.

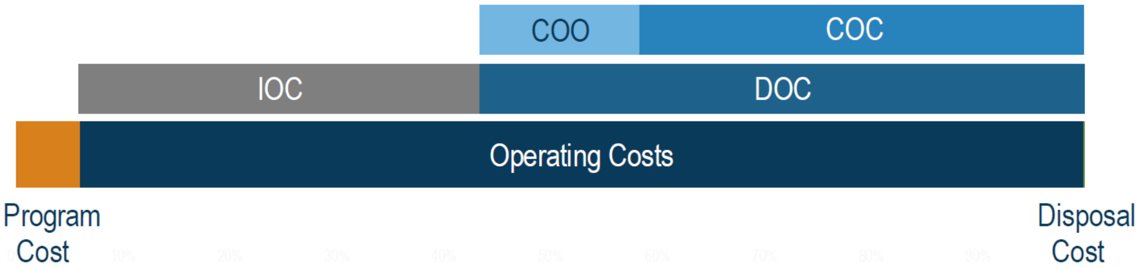


Figure 3.1: Typical Values of Life Cycle Cost Distribution. Retrieved from [33].

Operating costs can be split into DOC - Direct Operating Costs and IOC - Indirect Operating Costs. The latter may include cost elements such as sales, administration, accounts, general managements, property costs, and so on [34]. They are a complement of DOC, which on they side account for costs directly related to the aircraft. Even though separate models exist, a close examination shows that the allocation of costs to DOC or IOC is sometimes not very clear-cut [28], and research on cost definitions should be done before blind-using a particular method. Models based on TOC - Total Operating Costs do exist as well. Finally, COC - Chash DOC are direct operating costs without COO - Costs of Ownership. These may have a share up to 20% of DOC [33], and are of importance for those operators who do not purchase the aircraft, but rather lease it.

Methods based on DOC have become more widely accepted and used than others: their calculations started back in 1967 with ATA - Air Transport Association, whose model is now considered outdated [35]. Several methods exist nowadays, such as those of AEA - Association of European Airlines, NASA, and Fokker. The latter has been further developed by Airbus [36]. Moreover, AEA is presented in two flavours, one envisaging the development of short- and medium-range aircraft, the other for long-range vehicles.

Lowering Operating Costs. The main aim of an airline, especially low-cost ones, is to lower operating costs, and in such a way to gather more potential demand and raise revenues. Most of the cost reducing methods are based on the use of secondary airports, since this allows having low turnaround times (due to low passenger density), fewer slot problems, and relatively low fees with respect to major hubs [37].

Moreover, low-cost carriers offer simple one way tickets, have single class, an high-density seating, are mostly short-haul, use a single type of aircraft in order to reduce training costs, and do not rely on hubbing or connection flights [38]. Traditional network airlines are instead intended for long-haul flights, own more types of aircraft, offer connectivity through their main hubs, and so on and so forth.

3.2 Direct Operating Costs

To go further in details, each component of DOC needs to be examined. According to the AEA method [39], which is taken here as a reference, DOC have main contributions coming from ownership (namely, interest, depreciation, and insurance), fuel, maintenance (divided into powerplant and airframe), crew (cabin and cockpit), and fees (airport, landing, navigation, etc.). Most of the previously cited models take into account the same components, with some exceptions: as an example, Airbus Industries does not consider airport ground handling fees, and NASA does not consider interests.

3.2.1 Ownership: Depreciation - Interest - Insurance

Depreciation. Depreciation represents the periodic conversion of a fixed asset into an expense, as the asset is used during normal business operations [40]. It is therefore considered an operating expense. However, it is one of the few costs for which there is no associated outgoing cash flow (as happens with amortization).

Since depreciation is the distribution of the reduction in value of an item over the useful service life, the depreciation period DP has to be set in order to evaluate DOC, along with the final residual value of the vehicle $f_{RV} \cdot P_{aircraft}$ [€]. This is the price by which the airplane can be sold after the end of its use by the operator. Estimation methods do exist for determining the delivery price of the aircraft (based either on MTOW, OEW, or number of passengers), but knowing its exact value will for sure lead to more accurate results. In the context of the AEA method, $f_{RV} = 0.1$ and $DP = 14$ years: different values apply for other models, but the cost formulation remains formally unchanged.

$$DOC_{depreciation}\ [€] = \frac{P_{aircraft} - P_{residual}}{DP} = P_{aircraft} \cdot \left[\frac{1 - f_{RV}}{DP}\right] \tag{3.1}$$

Relating to hybrid-electric aircraft, depreciation could be distinguished in two annuity factors, namely for aircraft and batteries [41]. For the latter contribution, the depreciation rate would be as formulated in the following equation,

$$DP_{battery} = \frac{B_{cycles}}{F_{cycles}} \cdot S_{battery} \tag{3.2}$$

where $S_{battery}$ is the number of battery sets, B_{cycles} the lifetime cycles, and F_{cycles} the flight cycles. DOC component for depreciation can then be found by using a residual value factor of 40% [42]. Analogous formulations could be established for an entire PGS.

Interests. Interest costs frequently assume a new aircraft which is wholly financed from outside sources. This is a financial mathematics aspect [43], which has a defined formulation as shown in the following equation.

$$DOC_{interest}\ [€] = \left[IR \cdot \frac{(1+IR)^{DP} - k_n/k_0}{(1+IR)^{DP} - 1} - \left(1 - \frac{k_n}{k_0}\right) \cdot \frac{1}{DP}\right] \cdot P_{aircraft} \tag{3.3}$$

IR is the interest rate, equal to 8% for AEA method. It is assumed that the outside capital will be repaid in equal installments and annual payments over a number of years, which in a first approximation can be considered equal to DP. For simplicity, usually $k_0/k_n \approx f_{RV}$, even though the residual value of the outside capital is independent, and may therefore differ, from the residual value of the depreciation.

Insurance. Insurance can be expressed as a factor $f_{insurance} = 0.5\%$ of the aircraft price.

$$DOC_{insurance}\ [€] = f_{insurance} \cdot P_{aircraft} \tag{3.4}$$

TU Berlin [44] model uses the same formulation as AEA, while Gudmundsson [45] suggests an evaluation of insurance costs as in the equation displayed below.

$$DOC_{insurance}\ [\text{USD}] = 500 + 0.015 \cdot P_{aircraft} \tag{3.5}$$

The second part of Equation 3.3 is formally equal to Equation 3.1, when $k_n/k_0 = f_{RV}$: therefore, total ownership DOC can be expressed as follows.

$$\begin{aligned} DOC_{ownership}\ [€] &= DOC_{depreciation} + DOC_{interest} + DOC_{insurance} \\ &= P_{aircraft} \cdot \left[IR \cdot \frac{(1+IR)^{DP} - f_{RV}}{(1+IR)^{DP} - 1} + f_{insurance}\right] \end{aligned} \tag{3.6}$$

3.2.2 Fuel: Kerosene - Electricity - Hydrogen

Annual fuel costs are generally evaluated by considering a mass unit fuel price C_{fuel} [€/kg], and the estimated fuel mass needed for a flight F_{block}. Alternative approaches should be used in order to evaluate costs of the alternative energy sources.

$$DOC_{fuel}\ [€] = F_{cycles} \cdot C_{fuel} \cdot F_{block} \tag{3.7}$$

Electricity. A suggestion on how to evaluate these costs is found in [41], for an aircraft flying on conventional fuel and electricity, and as shown in the following equation.

$$DOC_{fuel}\ [€] = F_{cycles} \cdot (F_{block} \cdot C_{fuel} + E_{block} \cdot C_{electric}) \tag{3.8}$$

In the context of UNIFIER19 instead, a clear formulation is introduced in [10], section 3.3.4.3, as will be discussed later. Energy prices to be used could be referred to actual or predicted values, when for example considering the expected entry-into-service year of the new aircraft. In the US, the EIA - Energy Information Administration publishes a yearly forecast for the energy prices [46], and similar studies are also conducted in Europe [47].

Hydrogen. Cost of hydrogen liquefaction plants in current markets is estimated to range from 50 million USD to 800 million USD, for capacities ranging from 6 000 to 200 000 kilograms per day, respectively [48]. Its increasing demand will require the construction of new large-scale production and distribution infrastructures. This is of paramount importance, since as liquefier capacities increase, cost of hydrogen decreases, as can by seen in Figure 3.2. Final price will anyway have to account for distribution and storage. Transport can happen in terms of trucks or pipelines [10], but this second choice would require a continuous flow which should meet the required demand.

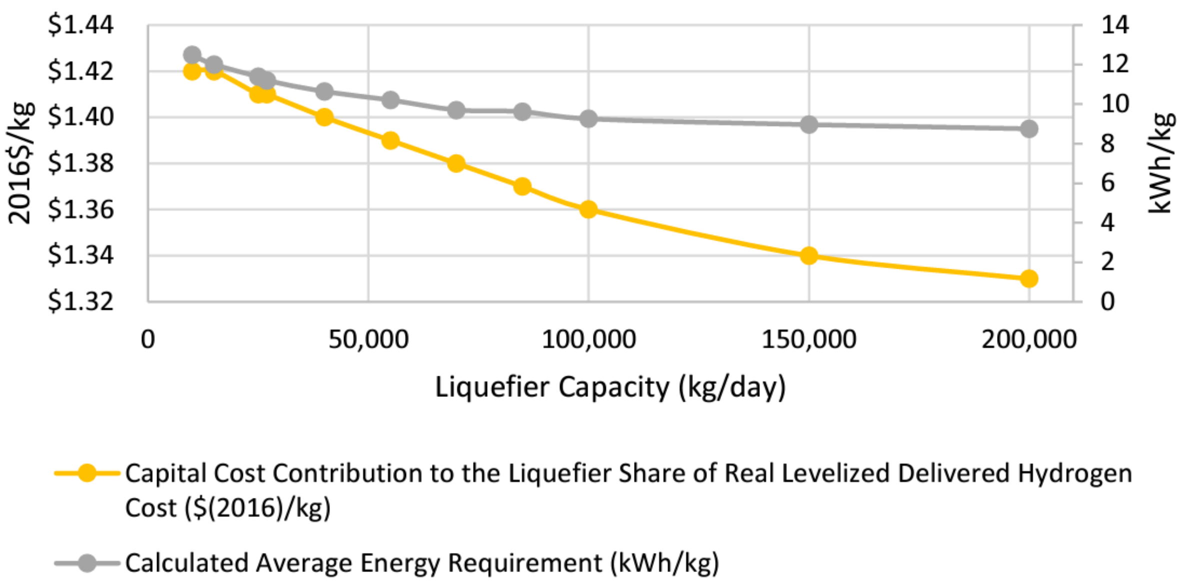


Figure 3.2: Average Liquefier Energy Requirement by Capacity. Retrieved from [48].

Considering liquid H_2 manufacturers in Europe, some in the East do not have nearby airports to supply, while on the opposite, some aerodromes in the North would not have nearby liquefaction stations. Central Europe has a large amount of suppliers [10].

Environmental Charges. The reduction in direct operating costs for hybrid-electric aircraft does not only attributes to a reduction in the cost of energy sources. Some airports in fact, around 60% in Europe, levy environmental charges in order to encourage the use of quieter or lower-emission aircraft by airlines [49]. These fees are not anyway related to global impact on emissions, but rather on local noise and/or air quality. Heathrow airport, as an example, charges an amount of 19.54 GBP as emission charge on landing [50]. Most likely, these fees will not be applied by smaller aerodromes and for aircraft of such category as C7A, but should eventually be considered, especially for the Microfeeder case, which envisages a major use of big hubs.

3.2.3 Maintenance: Maintenance Labor - Maintenance Parts

Maintenance costs usually account for scheduled maintenance (about 30%), and unscheduled maintenance [28]. Costs also distinguish between DMC - Direct Maintenance Costs, caused directly by the aircraft, and IMC - Indirect Maintenance Costs, incurred by operation of the maintenance organization, e.g. training of the personnel.

The usual formulation splits maintenance direct operating costs into cost of labour and cost of parts, as shown in equation below: f_{ease} is the maintenance man hours per flight hour, $C_{maintenanceLabor}$ [€/h] the labor rate, and U [h] the yearly utilization rate. Maintenance parts are often estimated as a sum of engine and airframe contributions.

$$DOC_{maintenance} \,[€] = (f_{ease} \cdot C_{maintenanceLabor} + C_{maintenanceParts}) \cdot U \tag{3.9}$$

For jet transport, and according to Nikolai [30], f_{ease} can be estimated as shown in the following equation. Other methods are discussed in [45], section 2.3.2.

$$f_{ease} = \frac{1.16}{U} + 6 \tag{3.10}$$

ATA and NASA methods also envisage a maintenance burden cost, defined as labour and material overheads, which contribute to overall maintenance costs through activities such as administration, controlling, monitoring, planning, testing, and tooling [51]. The two formulations shown in the equation below consider $\rho = 1.8$ or 2 for ATA and NASA, respectively. AEA has no burden cost included in its methodology.

$$IMC = \rho \cdot f_{ease} \cdot C_{maintenanceLabor} \tag{3.11}$$

On one side, it is expected that electric propulsion will lead to a decrease in maintenance effort with respect to conventional architectures. However, maintenance costs for propulsion will likely not differ between a conventional and a hybrid-electric system: this because, although electric motors require less checks and repairs, additional expenses to maintain two different systems might outweigh this advantage [52].

Furthermore, also electric engines have an overhaul maintenance as typical jet engines. This does not apply to the engines per se, but also to the useful life of fuel cells and batteries. This is why [53] states that maintenance costs could be even higher than conventional engines, because of PGS replacement. Nevertheless, not all motors may require an overhaul, as happens for DEP propellers of C7A configuration.

3.2.4 Crew: Cabin Crew - Cockpit Crew

Crew DOC can be divided into cabin and cockpit crew costs [28]. ATA formulation also includes a dependence on maximum takeoff weight, while NASA additionally accounts for the total crew complement needed to operate an aircraft, and distinguishes between domestic and international flights wages [51].

$$DOC_{crew}\ [€] = (C_{pilot} \cdot N_{pilots} + C_{attendants} + N_{attendants}) \cdot T_{block} \cdot F_{cycles} \tag{3.12}$$

The term C_{pilot} strongly depends on the business involved and can range from 50 to 150 USD/h. Some airlines could choose to hire full time pilots, with the associated annual salary and benefit costs, yet other businesses may keep only one full time pilot on board, and hire a co-pilot on a need-to basis [45]. No particular differences have been found in literature for crew DOC between conventional and hybrid-electric aircraft.

3.2.5 Fees: Navigation - Terminal - Ground Handling

Fees operating costs include landing fees, in order to use airports and their runways, navigation fees, for having direction by ATC - Air Traffic Control, and ground handling charges. This last component eventually includes ground services (connected with passengers, luggage, cargo, unloading, parking, etc.), technical services (refuelling, eventual de-icing, etc.), and flight advisory services [28].

Strictly speaking, costs incurred due to ground handling should be assigned to IOC [54], unless they are affected by specific design parameters of the aircraft. Nonetheless, some DOC methods also include these charges. AEA for instance.

Considering a payload PL [kg], a flight distance R [NM], and navigation, terminal and ground reference prices K_N, K_T and K_G, the formulation is as here shown.

$$DOC_{fees}\ [€] = \left[K_T \cdot MTOW + K_N \cdot R \cdot \sqrt{MTOW} + K_G \cdot PL\right] \cdot F_{cycles} \tag{3.13}$$

Navigation fees are evaluated by NASA and AEA methods as in the following equation,

$$(DOC_N)_{NASA} = 100 \cdot \sqrt{\frac{MTOW}{1000}} \qquad (DOC_N)_{AEA} = \frac{R}{2000} \cdot \sqrt{\frac{MTOW}{50000}} \tag{3.14}$$

retrieved from [51], where weights are now expressed in pounds. When instead flying inside Europe, which is the purpose of the Miniliner under analysis, Eurocontrol fees can be taken as a reference: detailed information are published each month [55].

Airports are allowed to charge way more fees to airlines than the ones here described. For instance, and with reference to SEA - Società Esercizi Aeroportuali [56], additional fees could be dictated by the use of reduced passenger capability airplanes, freight charges, airline terminal offices, warehouses, crew dressing rooms, etc.

3.3 Indirect Operating Costs

Indirect Operating Costs, as before mentioned, include the depreciation cost of ground facilities and equipment, sales and costumer service, and administrative and overhead costs. Since they are strictly related to how an airline decides to run its operations, they are very difficult to estimate by simple statistical analyses. They can range from being one third or about equal the direct operating costs [31].

The American Civil Aeronautics Board (CAB), in order to classify IOC, requires airlines to report the expenses associated with the following: aircraft and traffic servicing, promotion and sales, passenger services, general and administrative overhead, ground property and equipment maintenance and depreciation expenses [57].

Roskam [29] sets up a method for estimating indirect operating costs by assuming that IOC can be expressed as a fraction of DOC, as shown in the following equation,

$$IOC\ [€] = f_{IOC}\,(DOC) \tag{3.15}$$

where the factor f_{IOC} is said to be strongly proportional to the inverse of block distance.

4 | Models for Cost Analysis

For the sake of establishing which is the price to flight a particular route, and subsequently examine if UNIFIER19 would result advantageous with respect to car, not only in the matter of time saving, a cost model needs to be set up, eventually envisaging the new characteristics of the aircraft as opposed to conventional CS23 vehicles. The before mentioned models should be as complete as possible, in order to catch most of the flying and also non-flying related operating costs.

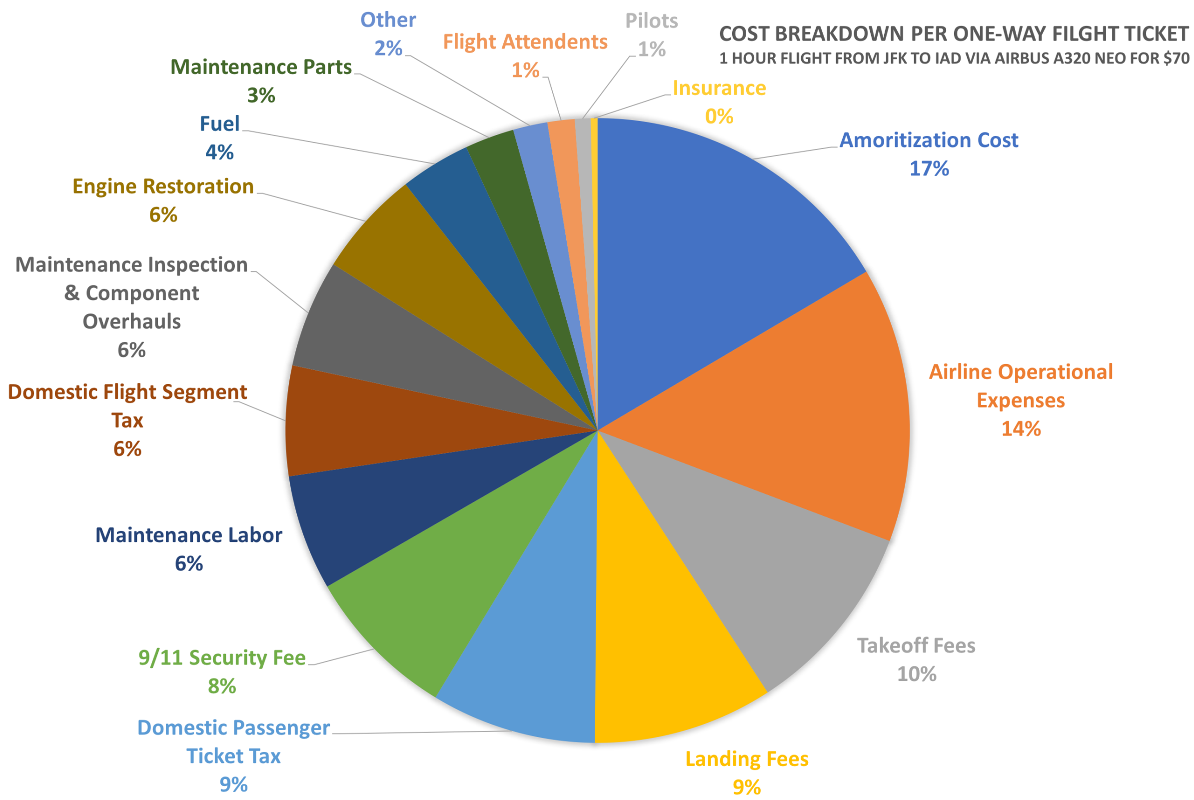


Figure 4.1: Example of Airline Costs Breakdown for a US Domestic Flight [58].

With reference to Figure 4.1, it is easy to notice how many components are involved in an airline costs breakdown. Operational expenses, costs for amortization, fees and taxes constitute about 71% of the total. Maintenance is instead accounted for a 21% (including labor, maintenance parts and engine restoration).

Piaggio Aerospace [59] has provided a detailed cost model to be used for assessments over a 19-seater aircraft, which characteristics are protected by a confidential agreement and cannot therefore be delivered in this work: nevertheless, the used methodology can be here reported. This model will be implemented in two flavours: the first one with the original structure and data set, and a modified version to best suit the specifications declared for UNIFIER19 in the WP2 deliverable [11]. Ultimately, the tailored cost model developed in the context of UNIFIER19 will also be highlighted.

4.1 Original Piaggio Aerospace Model

Piaggio Aerospace cost model for ticket price estimation is based on the evaluation of the cost per Revenue Passenger Kilometer (RPK) [€/km pax], which has to be multiplied by the mission range of the aircraft R, considered as an input to the algorithm.

The model gets to evaluate the annual variable costs per flight hour and the annual fixed costs per aircraft. The two give what are called the total operating costs, which summed to the prescribed profit percentage the airline has to achieve, return the total earnings the company should accomplish during a whole year.

4.1.1 Flight Information and General Operational Data

Considering a mission range R [NM], and a taxi time (both at departure and arrival aerodromes) T_{taxi} [min], here considered as being equal to 10 minutes, mission block time and flight time are estimated as in the following equations.

$$T_{block}\ [\text{min}] = 0.2613 \cdot R + 33.463 \qquad T_{flight}\ [\text{min}] = T_{block} - T_{taxi} \tag{4.1}$$

Block fuel and fuel consumption can then be retrieved as shown below. $\gamma_{L-KG} = 0.785$ represents the conversion factor from liters to kilograms for JET - A1 fuel, $\alpha_{GAL/H-L/H} = 3.785$ the conversion factor from gallons per hour to liters per hour, and $\alpha_{MIN-H} = 1/60$ the conversion factor from minutes to hours.

$$F_{block}\ [\text{kg}] = 1.0321 \cdot R + 66.172 \tag{4.2}$$

$$F_{consumption} \left[\frac{\text{gal}}{\text{h}}\right] = \frac{F_{block}}{T_{block} \cdot \alpha_{MIN-H}} \cdot \frac{1}{\gamma_{L-KG}} \cdot \frac{1}{\alpha_{GAL/H-L/H}} \tag{4.3}$$

Operational data include the number of departures per day D_{day}, the total number of departures per week D_{week}, the number of scheduled annual round trip departures D_{year}, and the number of successfully annual completed departures $\bar{D}_{year} = f_{departures} \cdot D_{year}$ (with $f_{departures}$ being the completion departure factor set to 98%).

$$D_{day} = \left\lfloor \frac{T_{DUH}}{T_{block} + T_{turnaround}} \cdot \frac{1}{\alpha_{MIN-H}} \right\rfloor \tag{4.4}$$

$$D_{week} = D_{day} \cdot WU \tag{4.5}$$

$$D_{year} = (52 - WMPY) \cdot D_{week} \tag{4.6}$$

$T_{DUH} = 14$ hours represents the number of daily utilization hours for the airplane, while $T_{turnaround} = 30$ minutes is the turnaround time. The value of T_{DUH} used in the context of the original Piaggio Aerospace project is also in line with the expected operating time for a commuting service, which ranges from about 5:30 A.M. to 7:30 P.M., as explained in [19], section 3.1. $WU = 7$ represents the weekdays utilization of the vehicle, here expected to be on duty from Monday to Sunday. Finally, $WMPY = 2$ is the amount of weeks the aircraft is expected to be on maintenance during a whole year.

The number of expected passengers in a year can be straightforwardly computed as the number of successfully completed departures multiplied by the minimum number of occupied seats on each flight: minimum load factor is set to $LF_{min} = 85\%$, as extrapolated by Piaggio Aerospace from [60], chapter IV. $PAX_{max} = 19$ is the maximum aircraft capacity.

$$PAX_{year} = f_{departures} \cdot D_{year} \cdot (PAX_{max} \cdot LF_{min}) \tag{4.7}$$

Yearly values can also be found for flight hours $FHPY$ and flown kilometers $KMPY$, as described in the following equations, where $\alpha_{NM-KM} = 1.852$ represents the conversion factor from nautical miles to kilometers.

$$FHPY = T_{flight} \cdot \alpha_{MIN-H} \cdot [D_{week} \cdot (52 - WMPY)] \tag{4.8}$$

$$KMPY = (f_{departures} \cdot D_{year}) \cdot R \cdot \alpha_{NM-KM} \tag{4.9}$$

It should be taken into account that these values are estimated considering a single vehicle and flying a particular route, as calculations including an entire fleet and different flown routes would be methodologically expensive for such a preliminary design stage.

Parking. Another preliminary cost assessment is relative to parking fees. For establishing the cost of parking hours inside aerodromes, the total time the airplane spends on the ground has to be evaluated. This is done in the following equation.

$$H_{parking}\ [\mathrm{h}] = 24 - [D_{day} \cdot (T_{block} \cdot \alpha_{MIN-H})] \tag{4.10}$$

Parking time per day is hence found by subtracting to an entire day the block hours, therefore the time during which the vehicle is supposed to be in the air. Taking into account a price factor $C_{parking}$ [€/TON h], the total cost of parking per year is therefore

$$P_{parking}\ [€] = [7 \cdot (52 - WMPY)] \cdot \frac{MTOW}{\alpha_{TON-LB}} \cdot (H_{parking} \cdot C_{parking}) \tag{4.11}$$

4.1.2 Annual Total Variable Costs per Flight Hour

Maintenance. In order to evaluate the total annual variable costs per flight hour, a first estimation of the cost of maintenance parts has to be assessed. $P_{maintenanceParts}$ [€/h] includes expenses as for airframe and avionics (i.e. cost of maintenance material for fuselage and systems), engine restoration (including HSI - Hot Section Inspection and engine overhaul at TBO - Time Between Overhaul), starter generator, propeller allowance, lubricants, etc. The total cost necessary for maintenance labor is instead expressed as the cost of labour per hour $C_{maintenanceLabor}$ [€/h], scaled by an ease of maintenance factor f_{ease}, which expresses the number of maintenance hours per flight hour.

$$P_{maintenance} \left[\frac{€}{\mathrm{h}}\right] = C_{maintenanceLabor} \cdot f_{ease} + C_{maintenanceParts} \tag{4.12}$$

Fees. Included in the costs per flight hour are aerodrome fees, parking fees and the fees an airline has to pay due to takeoff and landing operations. Price for takeoffs and landings can be evaluated considering the total completed departures per year $\bar{D}_{year}$ and the vehicle maximum takeoff weight $MTOW$ [lb], all divided by the annual expected flight hours. This is shown in the following equation, where $C_{LND\&TO}$ [€/TON] is the fee.

$$P_{TO\&LND} \left[\frac{€}{\mathrm{h}}\right] = \frac{2 \cdot \bar{D}_{year}}{FHPY} \cdot C_{LND\&TO} \cdot \frac{MTOW}{\alpha_{TON-LB}} \tag{4.13}$$

Regarding aerodrome fees, they refer to all boarding expenses for passengers going through the airport and which an airline has to pay: examples are aircraft boarding, security checks, baggage screening, and charge PRM (Person with Reduced Mobility). All of these quantities are accounted for in $C_{boarding}$ [€/pax]. The model also takes into account the check-in counters costs: this is the process during which the passenger, upon arrival at the airport, is given a boarding pass and hands over any baggage they are not allowed to carry inside the aircraft cabin. The cost of such fees are enclosed in $C_{checkin}$ for each departure, leading to a total cost per flight hour as shown in the following equation.

$$P_{boarding}\left[\frac{€}{\mathrm{h}}\right] = \frac{C_{boarding}\cdot PAX_{year} + \left(C_{checkin}\cdot \bar{D}_{year}\right)}{FHPY} \tag{4.14}$$

Finally, handling fees are estimated as 30% of total airport costs (30% handling and 70% airport taxes), and are summed to parking fees evaluated in Equation 4.11.

$$P_{handlingParking}\left[\frac{€}{\mathrm{h}}\right] = 0.3\cdot\frac{P_{boarding}}{0.7} + \frac{P_{parking}}{FHPY} \tag{4.15}$$

$$P_{aerodrome}\left[\frac{€}{\mathrm{h}}\right] = P_{TO\&LND} + P_{boarding} + P_{handlingParking} \tag{4.16}$$

Fuel. The price of the fuel is simply computed as the fuel consumption as evaluated in Equation 4.3, times the cost of the fuel C_{fuel} [€/gal].

$$P_{fuel}\left[\frac{€}{\mathrm{h}}\right] = F_{consumption}\cdot C_{fuel} \tag{4.17}$$

This said, the total annual variable costs per flight hour can be computed as in the following equation, where $P_{suppliesCatering}$ is the cost of supplies catering per flight hour.

$$VCPFH\left[\frac{€}{\mathrm{h}}\right] = P_{maintenance} + P_{aerodrome} + P_{fuel} + P_{suppliesCatering} \tag{4.18}$$

4.1.3 Monthly Total Lease Payment

Depreciation. Before evaluating the total annual fixed costs which an airline has to face for an aircraft, an estimation of the monthly lease payment is needed. Assuming no down-payment is disposed to the manufacturer, the NCC (Net Capital Cost) will equate the selling price of the vehicle. Assuming an useful life of $DP = 20$ years (which also coincides with the term of the loan), market depreciation will bring the residual value down to 10%, according to the Piaggio Aerospace model, namely $P_{residual} = P_{aircraft} \cdot f_{RV}$, with $f_{RV} = 0.1$. Therefore, a depreciation fee can be evaluated.

$$F_{depreciation}\ [€] = \frac{NCC - P_{residual}}{12 \cdot DP} \tag{4.19}$$

Financing. Financing fees are evaluated as in the equation below, and take into account the money factor, which is a method for determining the financing charges on a lease with monthly payments. It represents the financing charge a company will pay on a lease.

$$F_{financing}\ [€] = (NCC + P_{residual}) \cdot MF \tag{4.20}$$

When multiplying the money factor $MF = 0.0000125$ by 2400, the equivalent annual percentage rate is retrieved, namely the $IR = 3\%$. Finally, assuming a local sales tax rate of $f_{tax} = 7\%$, the total lease payment can be retrieved as in the following equation.

$$P_{lease}\ [€] = F_{depreciation} + F_{financing} + f_{tax} \cdot (F_{depreciation} + F_{financing}) \tag{4.21}$$

4.1.4 Annual Total Fixed Costs per Aircraft

Weather and Navigation. Weather service and navigation fees are estimated as in the following respective equations, retrieved by Piaggio Aerospace from [61].

$$P_{weather}\ [€] = \frac{700 \cdot FHPY}{450} \cdot \alpha_{USD-EUR} \tag{4.22}$$

$$P_{navigation}\ [€] = \frac{KMPY}{100} \cdot \sqrt{\frac{3.3}{50}} \cdot 66.02 \cdot \alpha_{USD-EUR} \tag{4.23}$$

Insurance. Moreover, there are costs related to insurance. These are evaluated depending on aircraft selling price $P_{aircraft}$, on the hull insurance rate $f_{insurance}$ (i.e. a policy designed for covering aircraft damage expenses) and on the SLL (Single Limit Liability).

$$P_{insurance}\ [€] = f_{insurance} \cdot P_{aircraft} + SLL \tag{4.24}$$

Sales and Refurbishing. Sales and promotion costs per ticket are expressed through C_{sales} [€]: hence, the total costs per year are evaluated as in in the following equation.

$$P_{sales}\ [€] = C_{sales} \cdot PAX_{year} \tag{4.25}$$

Refurbishing costs are computed considering a refurbishing labor time per seat of $H_{refurbishing}$ [h], and a labor cost of $C_{refurbishing}$ [€/h], as shown in the equation below.

$$P_{refurbishing}\ [€] = H_{refurbishing} \cdot C_{refurbishing} \cdot PAX_{max} \tag{4.26}$$

Cockpit Crew. It is considered an average wage per year and per pilot of C_{pilot} [€]. Yearly costs for freelance pilots are instead accounted for in $C_{freelancePilot}$ [€], envisaging the hiring on a need-to basis. Finally, $N_{pilots} = 2$ for the Piaggio Aerospace model.

$$P_{crew}\ [€] = (C_{pilot} \cdot N_{pilots}) + C_{freelancePilot} \tag{4.27}$$

Crew Training. For estimating the crew training annual price, all costs applied also to regular flights should be considered, namely, fuel, maintenance, insurance and ownership. The latter is estimated as in the following equation, with $P_{modernization}$ being the aircraft modernization costs after ten years of operations.

$$P_{ownership} \left[\frac{€}{\text{h}}\right] = \frac{P_{modernization} + P_{refurbishing} + 12 \cdot P_{lease}}{FHPY} \tag{4.28}$$

Annual training costs are split into two main contributions. The first is a fixed price, considering 7500 € for the training of 6 pilots for 5 hours each, namely 250 €/h for each pilot. The second part accounts instead for variable costs.

$$P_{training}\ [€] = 7500 + 6 \cdot 5 \cdot \left(P_{fuel} + C_{maintenanceParts} + P_{ownership} + \frac{P_{insurance}}{FHPY}\right) \tag{4.29}$$

Finally, the comprehensive annual total fixed costs per aircraft can be evaluated as described in the equation below, in which to the previous stated quantities are added: (1) the annual hangar rent price for a single aircraft P_{hangar} [€], and (2) the annual expenses for administrating the airline $P_{management}$ [€].

$$FCPAC\ [€] = P_{weather} + P_{navigation} + P_{insurance} + P_{sales} + \\ + P_{refurbishing} + P_{crew} + P_{training} + P_{hangar} + \\ + P_{modernization} + P_{management} + 12 \cdot P_{lease} \tag{4.30}$$

4.1.5 Ticket Price Estimation

The model then gives a simple way to evaluate ticket prices considering the typical mission. First of all, the AOC - Annual Total Operating Costs are computed considering the contributions of fixed annual costs per aircraft and variable costs per flight hour. Based on this, and taking into account a profit margin which the airline has to achieve during a whole year of $f_{profitMargin} = 20\%$, the PPY - Profit Per Year is retrieved.

$$AOC\ [€] = FHPY \cdot VCPFH + FCPAC \tag{4.31}$$

$$PPY\ [€] = f_{profitMargin} \cdot AOC \tag{4.32}$$

When diving the total financial return by the total kilometers flown per year and by the minimum number of passengers considered to fly on each route, the Revenue Passenger Kilometer is retrieved. Finally, multiplying RPK for the range of the mission, one obtains the single ticket price, as shown in the following equations.

$$RPK \left[\frac{€}{\text{km pax}}\right] = \frac{AOC + PPY}{KMPY \cdot PAX_{max} \cdot LF_{min}} \tag{4.33}$$

$$P_{ticket}\ [€] = RPK \cdot (R \cdot \alpha_{NM-KM}) \tag{4.34}$$

4.2 Updated Piaggio Aerospace Model

Once the original Piaggio Aerospace cost model is described and implemented in the Piaggio Aerospace study case, a modified version can be reworked, in order to compare results with the UNIFIER19 cost model, when applied to the Miniliner case. There will be now a description of the refashioned input data and formulas.

Operational Data. Minimum load factor has been changed from 85% to $LF_{min} = 80\%$, as the nominal value used for SHARONA-PDE. Moreover, since the Miniliner is intended for commuting purposes, weekdays utilization has been changed from 7 to $WU = 6$, excluding therefore Sundays. Turnaround time has been set to $T_{turnaround} = 5$ minutes. Landing fees are set to $C_{LND} = 35.74$ € per flight. Hence, to turn this value it into a cost per flight hour, Equation 4.13 has been changed as follows.

$$P_{TO\&LND}\left[\frac{€}{\text{h}}\right] = \frac{\bar{D}_{year}}{FHPY} \cdot C_{LND} \tag{4.35}$$

Miniliner Data. Selling price of the vehicle is now $P_{aircraft} = 8\ 826\ 328$ € (considering configuration C7A). Maximum takeoff weight is MTOW = 7953.7 kg. Ease of maintenance factor is $f_{ease} = 2.7$. Aircraft modernization costs have been set to a null value, as also refurbishing costs, which are already accounted for in the aircraft price. Single pilot operations are assumed, therefore $N_{pilots} = 1$.

Payments. Interest rate has been changed to $IR = 0.5$. Term of loan and useful life have both been changed to 15 years, keeping a residual value of $f_{RV} = 10\%$. Finally, insurance rate has been set to $f_{insurance} = 0.5\%$. Maintenance labor cost has been set to 50 €/h.

4.2.1 Liquid H_2 and Battery Energy Costs

Equation 4.17 cannot be used for estimating fuel price, as UNIFIER19 will use liquid hydrogen and battery energy as alternative energy sources. Regarding the batteries, according to the C7A typical mission, they will start the first flight with a 85% nominal level of charge, and will end the six planned hops with a residual 25% [11]. This means that the used percentage of battery capacity is $\chi_{battery} = 10\%$ per flight. Battery total energy is instead $B_{energy} = 152.44$ kWh. Energy price per flight hour is therefore evaluated as in the following equation, where $C_{electric} = 0.0855$ €/kWh is the energy price.

$$P_{energy}\left[\frac{€}{\text{h}}\right] = \left[\bar{D}_{year} \cdot (B_{energy} \cdot \chi_{battery} \cdot C_{electric})\right] \cdot \frac{1}{FHPY} \tag{4.36}$$

Regarding liquid hydrogen instead, consumption in [kg/h] is calculated as the equivalent of kerosene consumption for a conventional vehicle, by considering jet engine efficiency (25%), fuel cell efficiency (50%), and electric motor efficiency (90%). Hydrogen price is

$$P_{hydrogen}\left[\frac{€}{\text{h}}\right] = \frac{F_{block}}{T_{block} \cdot \alpha_{MIN-H}} \cdot \left[\frac{ED_{jetFuel}}{ED_{H_2}} \cdot \frac{\eta_{jetEngine}}{\eta_{fuelCell} \cdot \eta_{electricMotor}}\right] \cdot C_{hydrogen} \tag{4.37}$$

where $ED_{jetFuel} = 11.9$ kWh/kg and $ED_{H_2} = 39$ kWh/kg are the jet fuel and hydrogen energy densities. Liquid hydrogen nominal price is $C_{hydrogen} = 2$ €/kg.

4.2.2 Engine and PGS Overhaul

In C7A configuration, the tail engine is the only having a TBO - Time Between Overhaul which is smaller than the aircraft life cycle. DEP propellers are instead used only during non-cruise phases of the flight, which stands for an average 7 minutes per block time [11]. Maintenance parts will account for engine, fuel cells, and battery overhaul, considering a cost equal to 75% of the component. Restoration prices are evaluated as shown below.

$$C_{maintenanceParts}\left[\frac{€}{\text{h}}\right] = 0.75 \cdot \left[\frac{C_{motor}}{TBO_{motor}} + \frac{C_{fuelCell}}{TBO_{fuelCell}} + \frac{C_{battery}}{B_{cycles}} \cdot \frac{\bar{D}_{year}}{FHPY}\right] \tag{4.38}$$

4.3 UNIFIER19 Model

Finally, the cost model for UNIFIER19 described in [10] can be discussed. As the vehicle to be investigated is the same as in Section 4.2, same data apply also for the following formulation, and therefore will not be repeated.

4.3.1 Flight Information and General Operational Data

First, flight information and general operational data are retrieved. Block time and flight time have been estimated as in Equation 4.1, namely as in the original Piaggio Aerospace model. Mission range is still considered to be the input of the algorithm.

Flight cycles per year, which exclude regular and extraordinary maintenance, night curfew, and other restrictions, are set to a fixed value $F_{cycles} = 1311$ (which correspond to a yearly utilization of 1800 hours, when considering a block time of 1.59 hours [11]). This because empiric evaluations, such that of the AEA method shown in the following equation, have been demonstrated to lead to unrealistic higher results.

$$F_{cycles} = \frac{3750}{T_{block} + 0.5} \tag{4.39}$$

4.3.2 Ticket Price Estimation

Fuel. To estimate E_{block} and H_{block}, namely equivalent consumption of hydrogen and battery power, Equations 4.36 and 4.37 cannot be used, since Piaggio Aerospace model led to the evaluation of a cost per hour, while UNIFIER19 considers DOC per flight. Hence, the following formulations are used (F_{block} being the fuel consumption when considering conventional jet fuel, as shown Equation 4.2).

$$E_{block}\ [\text{kWh}] = B_{energy} \cdot \chi_{battery} \tag{4.40}$$

$$H_{block}\ [\text{kg}] = F_{block} \cdot \left[\frac{ED_{jetFuel}}{ED_{H_2}} \cdot \frac{\eta_{jetEngine}}{\eta_{fuelCell} \cdot \eta_{electricMotor}} \right] \tag{4.41}$$

$$DOC_{fuel}\ [€] = E_{block} \cdot C_{electric} + H_{block} \cdot C_{hydrogen} \tag{4.42}$$

Crew. The crew complement needed per aircraft, i.e. the number of full crews for a normal continuous operation, respecting maximum flight hours limitations, vacations, training, etc. is usually between three and five, here set to $N_{crews} = 3.5$. No flight attendant is required according to CS23 regulations, therefore $N_{attendants} = 0$. Considering an average pilot wage of $C_{pilot} = 65$ €/h, crew DOC are evaluated as follows.

$$DOC_{crew}\ [€] = N_{crews} \cdot \left(C_{pilot} \cdot N_{pilots} + \cancel{C_{attendants} \cdot N_{attendants}} \right) \cdot T_{block} \tag{4.43}$$

Ownership. Considering the same payment parameters for UNIFIER19 described in Section 4.2, capital DOC can be established as shown in the following equation.

$$DOC_{ownership}\ [€] = P_{aircraft} \cdot \left[IR \cdot \frac{1 - f_{RV} / (1 + IR)^{DP}}{1 - 1/(1 + IR)^{DP}} + f_{insurance} \right] \cdot \frac{1}{F_{cycles}} \tag{4.44}$$

Fees. Fees can be split into navigation and terminal fees. Formulas for evaluating the respective prices are given by Eurocontrol [62], and are here reported.

$$DOC_{navigation}\ [€] = K_N \cdot \frac{R}{100} \cdot \left[\frac{MTOW}{1000} \cdot \frac{1}{50} \right]^{0.5} \tag{4.45}$$

$$DOC_{terminal}\ [€] = K_T \cdot \left[\frac{MTOW}{1000} \cdot \frac{1}{50}\right]^{0.7} \tag{4.46}$$

$K_N = 59$ € is a rate that changes by country: for a conservative approach, it has been kept to its highest value (namely, the average for Western Europe). Instead, $K_T = 170$ € (values referred to January 2020). Terminal fees are usually only applied by major airports, but are anyway considered for a conservative approach.

Landing fees are averagely 71.50 € per flight. Ground handling fees include boarding, check-in, country taxes, PRM, security, infrastructures of the airports, meteorological services, etc.: the average price reported in [11] is 402.19 € per flight. Parking is usually free for the first two hours, and therefore will not be considered. Smaller airports served by the Miniliner will surely apply lower fees, and hence only 50% of the above prices is kept for DOC estimation, as shown in the following equation.

$$DOC_{airport}\ [€] = 0.5 \cdot (71.50 + 402.19) = 236.85 \tag{4.47}$$

$$DOC_{fees}\ [€] = DOC_{navigation} + DOC_{terminal} + DOC_{airport} \tag{4.48}$$

Maintenance. Maintenance data follow the same formulation as described in Section 4.2. As anticipated, no HSI is present, given the absence of thermal engines.

$$\begin{aligned} DOC_{maintenance}\ [€] = {} & f_{ease} \cdot C_{maintenanceLabor} \cdot T_{block} + \\ & + 0.75 \cdot \left(\frac{C_{motor}}{TBO_{motor}} + \frac{C_{fuelCell}}{TBO_{fuelCell}}\right) \cdot T_{block} + 0.75 \cdot \frac{C_{battery}}{B_{cycles}} \end{aligned} \tag{4.49}$$

Finally, by retrieving the sum of all DOC contributions per flight, ticket price can be easily evaluated by dividing the value by the number of passengers, i.e. $PAX_{max} = 19$.

$$DOC\ [€] = DOC_{fuel} + DOC_{crew} + DOC_{ownership} + DOC_{maintenance} \tag{4.50}$$

$$P_{ticket}\ [€] = \frac{DOC}{PAX_{max}} \tag{4.51}$$

For the UNIFIER19 typical mission, which has a range of 350 kilometers for a single hop, total DOC estimated in [11] are 1998.8 €. In the implemented algorithm, the result is 1923.1 €. This is due to how block time and fuel consumption are evaluated, in order to be applicable to all types of missions. The difference is 75.7 €, namely only 3.79%.

Piaggio Aerospace original model generally returns higher ticket prices, as can be seen in Figure 4.2. When UNIFIER19 data are used, P_{ticket} lowers: this could be seen as a first advantage of hybrid-electric vehicles with respect to conventional powertrains. Furthermore, this decrease in ticket price becomes slightly more marked as range increases.

Finally, UNIFIER19 cost model shows higher fares until a range of about 300 kilometers, and lower fares after this threshold. Moreover, its slope with respect to range appears more flattened compared to Piaggio Aerospace models, but it presents an higher intercept. All cost models show an approximately linear behaviour.

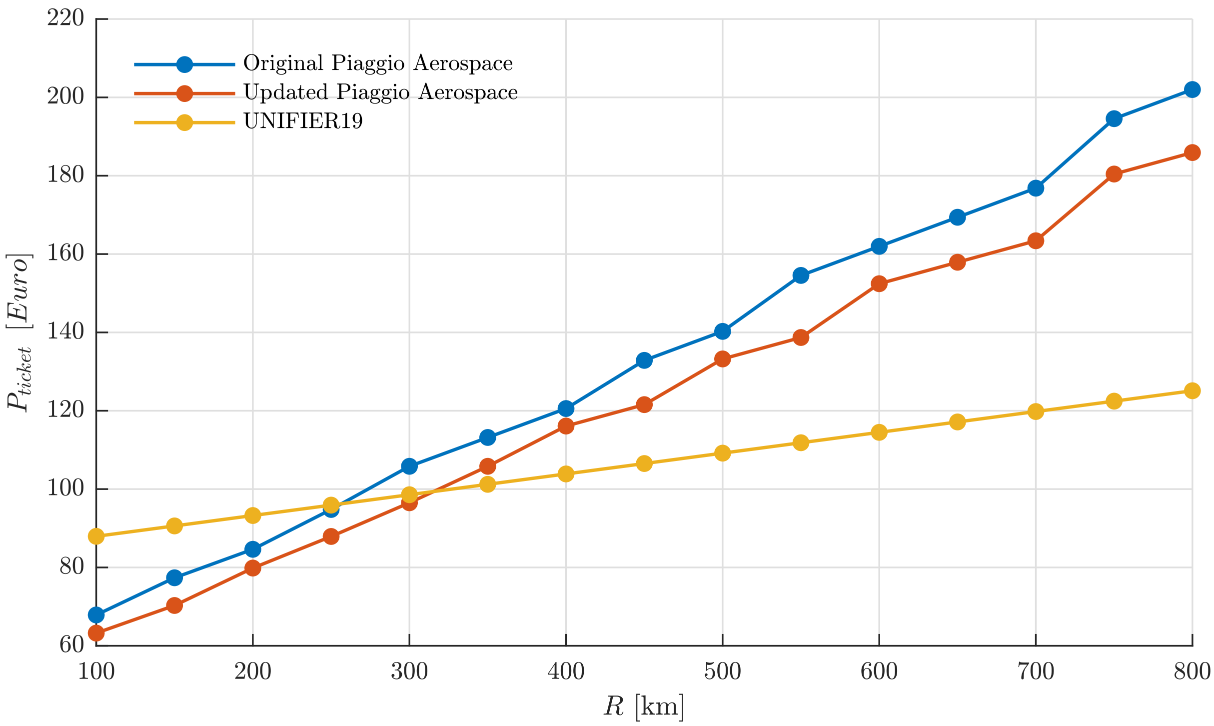


Figure 4.2: Cost Models comparison for R ranging from 100 to 800 kilometers.

4.4 Implementation of the Cost Models

Models for cost analysis now need to be implemented in the original SHARONA-PDE algorithm. This also involves finding car prices, such as to compare then with flight costs. Finally, an implementation logic has to be defined.

4.4.1 Car Prices for Municipalities and Aerodromes

Car prices between municipalities and between municipalities and aerodromes have been retrieved with the use of viaMichelin API [63]. This has been done considering the quickest route, as for estimating car times with HereMaps API, and favouring therefore the use of motorways. Two databases have been set up, namely for two common types of car, and having fuel consumptions defined by the consumption every 100 kilometers at different values of nominal speeds. Nominal fuel cost has been set to 1.6 €/L, as reported by the Ministry of the Ecological Transition [64], and referring to September 2021 average values.

$$CAR1 = [7.9, 6.9, 7.0] \text{ L/100 km @ } [50, 90, 120] \text{ km/h} \tag{4.52}$$

$$CAR2 = [9.0, 7.5, 8.0] \text{ L/100 km @ } [50, 90, 120] \text{ km/h} \tag{4.53}$$

Results from viaMichelin were saved in three different data sets, namely price of fuel $P_{carFuel}$, price of tolls P_{toll}, and price of Congestion Charge Zone P_{CCZ}, used for restricting access to some areas in bigger cities. In this way, fuel cost can be easily changed to a general desired value, by scaling the relative matrix when running the algorithm, as shown in the following equation, where λ is the desired scaling factor.

$$P_{car} = P_{toll} + P_{CCZ} + \lambda \cdot P_{carFuel} + P_{ferry} \cdot \delta_{od} \tag{4.54}$$

Moreover, viaMichelin does not take into account ferry prices when estimating trip costs: therefore, an average and rounded value has been considered for such trips [65]. These are shown in Table 4.1 (as a cost per trip from/to the mainland and including the transport of a vehicle on board). Notice that it is intrinsically assumed in the model that a trip involving two islands will pass through the mainland, without directly linking the two, and therefore applying the two relative prices. In Equation 4.54, $\delta_{od} = 1$ if the transfer involves at least one island, otherwise $\delta_{od} = 0$.

Table 4.1: Ferry Prices for Islands in Italy when moving from Mainland.

Sicilia [€]	**Sardegna [€]**	**Isola d'Elba [€]**	**Ischia [€]**
35	100	50	50

4.4.2 Value of Time Estimation for Commuters

In transport economics, the VoT (Value of Time) constitutes the amount of money a traveller would be willing to pay in order to save time, or, equivalently, the amount they would accept as a compensation for the time loss [66]. It is usually expressed in [€/h] and it is a crucial component in travel demand modeling: it needs therefore to be considered when comparing Miniliner and ground prices.

As stated in [19], commuters in Italy are 66% composed by workers, while the remaining 33% are students. In accordance with [67, 68], VoT for commuters is between 10 and 15 €/h, while for business travellers is between 20 and 35 €/h. The mean value has been taken for both categories, hence leading to the following result.

$$VoT\left[\frac{€}{\mathrm{h}}\right] = (0.66 \cdot 27.5 + 0.33 \cdot 12.5) \cdot f_{inflation} = 22.8 \tag{4.55}$$

$f_{inflation} = 2.4\%$ is the inflation from 2016 (year of computation of the before mentioned VoTs) and 2020 (keeping in mind that UNIFIER19 cost model refers to this year).

Value of time can also be evaluated as VBTTS (Value of Business Travel Time Savings) through Hensher equation [69], as done by Piaggio Aerospace. The Marginal Product of Labor (MPL) is the average wages plus on costs, while VL is the employee value of private travel time. r is the portion of business travel time that is used for leisure, p the proportion of travel time that is used for working, and q the relativity of the productivity of working while travelling to working at the workplace.

$$VBTTS = (1 - r) \cdot MPL + r \cdot VL - p \cdot q \cdot MPL \tag{4.56}$$

4.4.3 Implementation Logic and Formulation

Once having retrieved ground prices P_{ground} and air prices P_{air} (including ticket price and prices for car travels to/from the airports), the following constraint can be implemented.

$$P_{air} \leq P_{ground} + (T_{ground} - T_{air}) \cdot VoT \tag{4.57}$$

VoT is introduced as a penalty on ground prices, due to major travel times: notice that the penalty could actually be negative, when T_{ground} happens to be lower with respect to T_{air}. Two implementation logics will be discussed, namely the activation of the time and cost constraints with an AND or OR logic.

5 | Piaggio Aerospace Case Study

Piaggio Aerospace study case arises from the conference *Travel Time Benefits of Domestic Short-Haul Flights using a new 19-Seater Aircraft* [70], held in Villanova d'Albenga (Savona), Italy, on the 5th of July 2021. Politecnico di Milano, through this thesis, has collaborated in analyzing a potential demand scenario. This has also helped in establishing a cost model, which has been already discussed in Section 4.1. A description of the mentioned case study will here follow, along with SHARONA-PDE algorithmic modifications and main results, with and without the introduction of the cost model.

Figure 5.1: Piaggio Aerospace Logo. Retrieved from [59].

5.1 Study Case and Algorithm Reshaping

The study focuses on regional air transportation, and tries to assess travel time benefits of short-haul flights between hubs located in large metropolitan areas, and aerodromes placed in secondary destinations. It is important to specify that the aircraft being discussed in this chapter is a turboprop and has therefore no reference to an hybrid-electric powertrain.

5.1.1 Network Description

The network to be investigated is the one shown in Figure 5.2: possible routes are return journeys from Milano Bresso (LIMB) and Roma Urbe (LIRU), both situated at around 8 kilometers from the city center, served by public transport means, and with a runway of 1080 and 1084 meters, respectively. Possible connections are shown in Table 5.1.

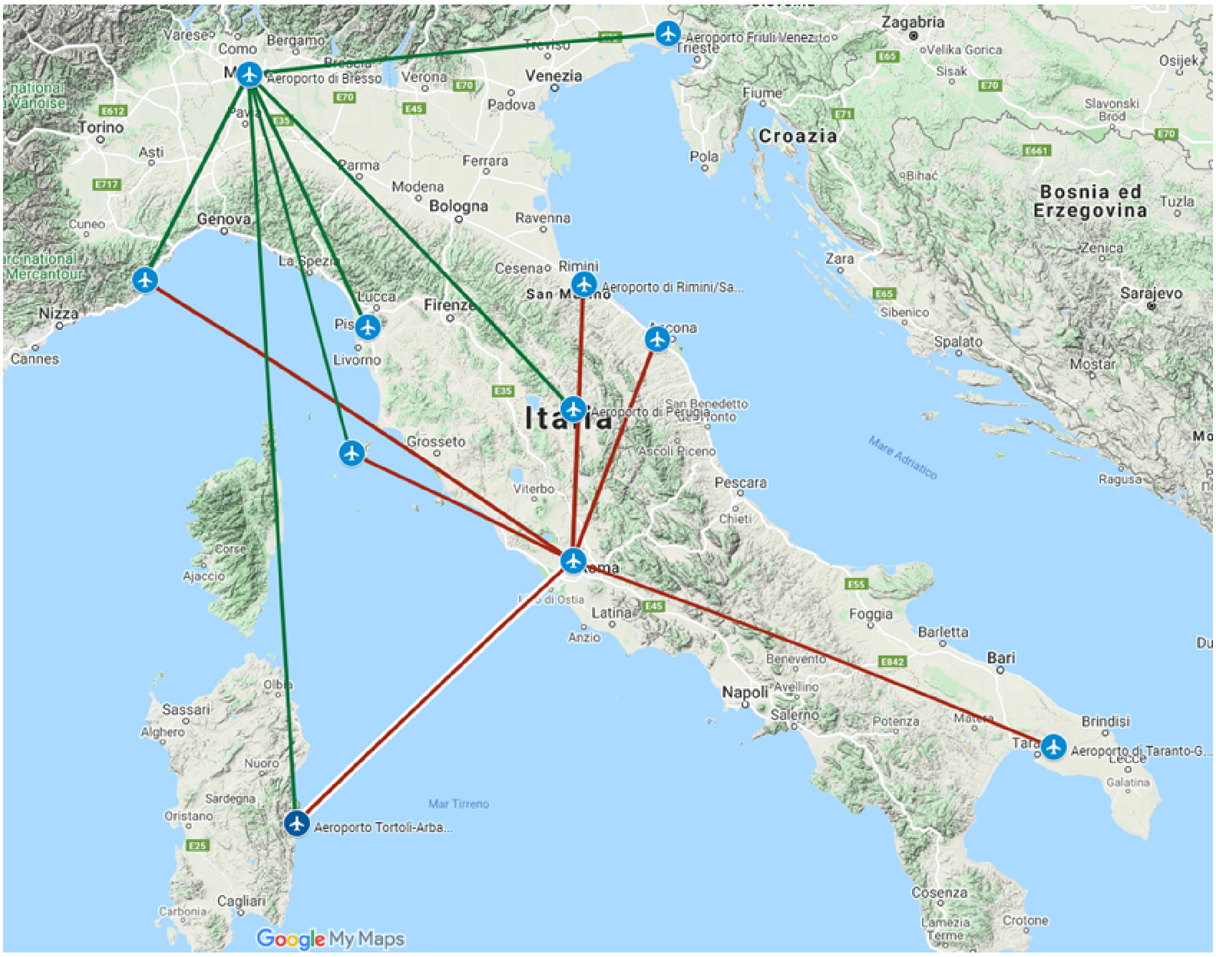


Figure 5.2: Routes Network for the Piaggio Aerospace Case Study. Retrieved from [70].

Table 5.1: Connections between Milan and Rome and Secondary Aerodromes.

SECONDARY AIRPORT	ICAO	LIMB	LIRU
Aeroporto di Albenga - Riviera	LIMG	✓	✓
Aeroporto di Pisa - San Giusto	LIRP	✓	
Aeroporto di Perugia - San Francesco	LIRZ	✓	
Aeroporto di Trieste - Ronchi dei Legionari	LIPQ	✓	
Aeroporto dell'Elba - Marina di Campo	LIRJ	✓	✓
Aeroporto di Tortolì - Arbatax	LIET	✓	✓
Aeroporto di Ancona - Falconara	LIPY		✓
Aeroporto di Rimini - Miramare	LIPR		✓
Aeroporto di Taranto - Grottaglie	LIBG		✓

Metropolitan areas and hubs were selected based on the following criteria: (1) high values of potential passenger traffic, (2) low airport operating costs, (3) quick and efficient airport operations, (4) convenient slot times and turnaround facilities, (5) airport with great potential to attract business and leisure passengers, (6) proximity of the airport to the city center, and (7) availability of public transport to connect city center to the airport [70]. The Minilner case is substantially reduced to a Microfeeder one, even though potential demand formulation does not follow its rules, but is applied to SHARONA-PDE.

Piaggio Aerospace states that having a sustainable business case depends on achieving a cost-efficient regional air transport, through different factors: (1) low DOC with cost effective green new technologies, (2) efficient airline company with high level of digitalization to reduce IOC, (3) use of already existing secondary airports infrastructures, (4) considerable time saving with respect to other travel modes (at least 2 hours door to door), and (5) VBTTS (Value of Business Travel Time Saving) to have premium fares.

5.1.2 SHARONA-PDE Major Reworkings

SHARONA-PDE had to be modified in order to be applied to the Piaggio Aerospace case study. It goes without saying that the database containing the municipalities had to be expanded from 519 to 525 entries, as new cities were considered for Isola d'Elba. Furthermore, the initial cluster table was substituted with a new one, containing the 11 aerodromes under analysis for this particular case. Databases containing car times and prices between municipalities and between municipalities and aerodromes were modified accordingly, with the use of HereMaps API [20] and viaMichelin API [63].

Modified input data are listed in Table 5.2: if not specified, other inputs are the same as the Miniliner case. Aircraft range has been roughly evaluated starting from maximum flight time and cruise speed: however, this is of little importance for the algorithm, since it is assumed that Piaggio Aerospace already studied the feasibility of the routes in terms of distance. Climb and descent rates have been doubled with respect to the original S-PDE, and their values are considered reasonable for a vehicle of such characteristics: they have however little impact on travel time. Minimum travel time and minimum runway to takeoff have been set to null, again considering that a study of the feasibility of the routes has already been carried out by the company. Activation factor has been set to unitary value, since the case only focuses on an absolute time gain. Finally, takeoff and landing times have been set to zero, since Piaggio Aerospace incorporates them into taxi time.

Table 5.2: Specifications for Piaggio Aerospace applied to SHARONA-PDE.

Cruise Speed	230	[knots]	**Required Runway**	0	[m]
Maximum Range	850	[km]	**Activation Factor**	1	[–]
Cruise Altitude	10000	[ft]	**Activation Threshold**	2	[h]
Climb Rate	1000	[ft/min]	**Check-In Time**	10	[min]
Descent Rate	500	[ft/min]	**Leave Time**	5	[min]
Number of Seats	19	[–]	**Taxi Time**	10	[min]
Minimum Load Factor	85	[%]	**TO/LND Time**	0	[min]
Minimum Travel Time	0	[s]	**Turnaround Time**	30	[min]

5.2 Preliminary Studies on OD Matrices

As already specified in Chapter 2, if no data is added to the original OD matrix and no expansion is performed, no commuters will be associated with Isola d'Elba municipalities, and the island potential demand will be equal to zero. When the expansion is performed, 10 598 commuters enter the analysis: excluding inner island flows, this number drops down to 317. The number of added occasional business travellers is instead 46.

Two extreme cases have been analyzed for the purpose of having an idea of the general trend of commuters: case one considers a $T_{ref} = 0$, while the second a $T_{ref} = 7200$ seconds (2 hours). The two have been run considering both Piaggio routes and all possible OD routes, and with the main OD matrices of interest (namely $\bar{G}$, G, and G_E).

When considering $T_{ref} = 0$, as one would expect, potential demand is maximum if G_E is considered and all possible OD routes are included in the network: complete results are shown in Table 5.3. With a focus on the last case, namely only Piaggio routes and G_E matrix, a more in-depth analysis of the potential passengers can be done. Looking at the Isola d'Elba aerodrome, the algorithm output shows that 14 commuters are travelling from Milano Bresso to Elba, 29 from Roma Urbe to Elba, and 31 from Elba to Roma Urbe. This means that, by far, the route Elba to Milano Bresso could already be considered not viable, since a null number of commuters is associated with it.

$T_{ref} = 7200$ seconds brings of course to a potential demand reduction, which is even more marked when only Piaggio routes are considered. The use of matrix G_E shows that 31 commuters would move from Elba to Roma Urbe, 9 from Milano Bresso to Elba, and 23 from Roma Urbe to Elba. Overall potential demand results are shown in Table 5.4.

Table 5.3: Potential Demand and Feasible Routes for $T_{ref} = 0$.

	$\bar{G}$ [pax]	G [pax]	G_E [pax]	**Routes**
All OD Routes	5895	9276	9322	107
Piaggio Routes	2392	3627	3668	24

Table 5.4: Potential Demand and Feasible Routes for $T_{ref} = 7200$ seconds.

	$\bar{G}$ [pax]	G [pax]	G_E [pax]	**Routes**
All OD Routes	765	2330	2373	87
Piaggio Routes	362	941	982	21

Speaking about the whole network instead, clearly demand increases when more expanded and defined matrices are used, and when considering all OD routes instead of only Piaggio routes. This happens mainly because of the removal of the route Milano Bresso - Roma Urbe, which could instead catch an high number of potential passengers.

Maximum number of activated routes are shown in Table 5.3 and Table 5.4. With an eye to the Piaggio Aerospace network, all its flights are activated when considering a null time threshold, while this number drops to 21 when $T_{ref} = 7200$ seconds. As a reference, remind that all OD routes are 110, while Piaggio Aerospace routes are 24 (considering round trip journeys). The two networks are shown in Figures 5.3a and 5.3b. Both cases result anyway in a number of activated aerodromes equal to the maximum value. Unless differently specified, all analyses will be hereon run considering G_E and Piaggio routes.

(a) Network with $T_{ref} = 0$.

(b) Network with $T_{ref} = 7200$ seconds.

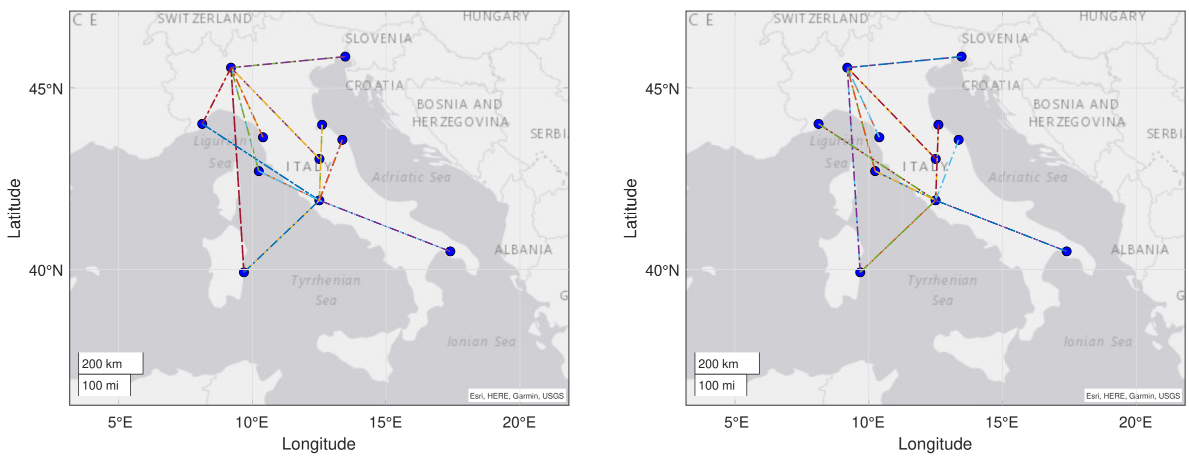


Figure 5.3: Piaggio OD Routes for the Two Cases under analysis and considering G_E.

5.3 Travel Time Saving and Potential Demand

It has already mentioned that the number of activated routes is not always equal to the maximum value. When $T_{ref} = 7200$ seconds, Milano – Albenga, Albenga – Milano and Rome – Ancona require more time by plane with respect to road trips (remind that road time is not symmetric, which is why the route Ancona – Rome is still declared feasible).

To understand at which point this route loss happens, a parametric study has been conducted, letting T_{ref} vary from 0 to 7200 seconds with a time-step of 800. Results are shown in Figure 5.4, along with potential demand: in accordance with data retrieved in Section 5.2, maximum potential passengers range from 3668 to 982.

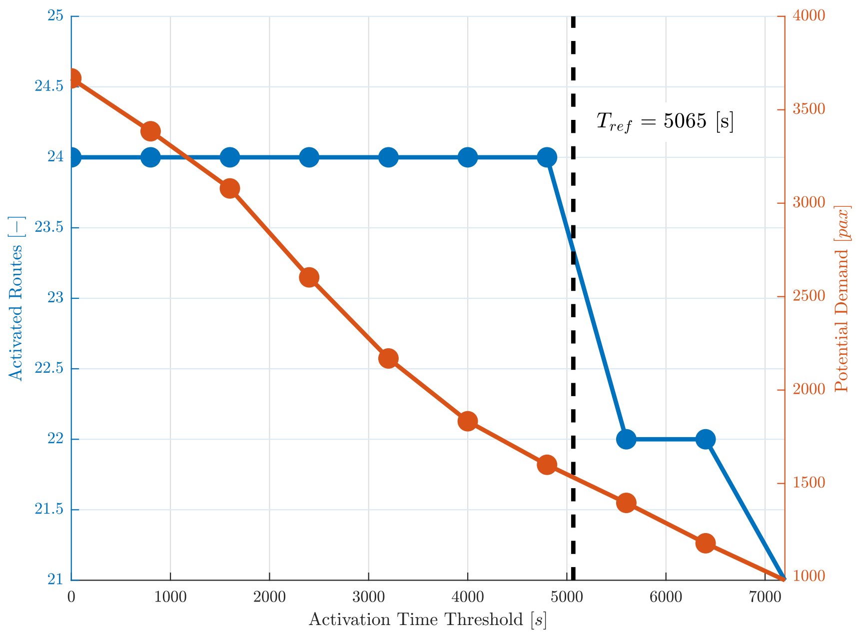


Figure 5.4: Parametric Analysis for T_{ref} varying from 0 to 7200 seconds.

5.3.1 Relaxing of the Activation Time Threshold

Results show that until 5065 seconds (namely 1 hour and 24 minutes and 20 seconds) all 24 Piaggio routes are activated, and for this case potential demand is equal to 1527. With respect to the maximum potential demand, namely when considering a null time activation threshold, the number of potential passengers is reduced by 58.4%, while it increases by 55.5% with respect to the case of $T_{ref} = 7200$ seconds.

Therefore, to be able to fly all routes and to keep all aerodromes activated, one could hence state that the time gain limit should be lowered to about one hour and a half.

To establish which of the feasible routes would have a potential demand such as to satisfy the minimum load factor imposed by Piaggio Aerospace, refer to Table 5.5. For an activation time threshold of about one hour and a half, all 24 routes are active, but still 5 out of 24 have a potential demand which does not reach 85% (as highlighted in bold).

Table 5.5: Potential Commuters for Piaggio Routes with $T_{ref} = 5065$ seconds and G_E.

O / D	**Milan**	**Rome**	**Albenga**	**Pisa**	**Perugia**	**Trieste**	**Elba**	**Tortolì**	**Ancona**	**Rimini**	**Taranto**
Milan	-	-	**0**	69	18	22	**14**	**9**	-	-	-
Rome	-	-	42	-	-	-	29	23	44	615	49
Albenga	**3**	68	-	-	-	-	-	-	-	-	-
Pisa	103	-	-	-	-	-	-	-	-	-	-
Perugia	22	-	-	-	-	-	-	-	-	-	-
Trieste	29	-	-	-	-	-	-	-	-	-	-
Elba	**0**	31	-	-	-	-	-	-	-	-	-
Tortolì	27	38	-	-	-	-	-	-	-	-	-
Ancona	-	33	-	-	-	-	-	-	-	-	-
Rimini	-	98	-	-	-	-	-	-	-	-	-
Taranto	-	141	-	-	-	-	-	-	-	-	-

However, as a way of stating that some of the non-viable routes could be still activated by an airline company, potential demand could be expanded in such a way that matrix G_H is considered, namely also containing occasional leisure travellers in Italy. The reader should keep in mind that, in this case, occupancy data are retrieved from a theoretical approach, which assumes that leisure travellers are equally spread in terms of time and space during the year and on the national territory.

With reference to Table 5.6, the 5 non-viable routes drop down to 3 when leisure travellers are added: still, Albenga - Milano, Milano - Albenga, and Elba - Milano are discarded. Potential demand raises to 13 357, with an increment of 774.7% with respect to G_E.

Table 5.6: Potential Commuters for Piaggio Routes with $T_{ref} = 5065$ seconds and G_H.

O / D	**Milan**	**Rome**	**Albenga**	**Pisa**	**Perugia**	**Trieste**	**Elba**	**Tortolì**	**Ancona**	**Rimini**	**Taranto**
Milan	-	-	**1**	527	399	135	335	236	-	-	-
Rome	-	-	586	-	-	-	372	272	330	6333	488
Albenga	**3**	670	-	-	-	-	-	-	-	-	-
Pisa	227	-	-	-	-	-	-	-	-	-	-
Perugia	253	-	-	-	-	-	-	-	-	-	-
Trieste	168	-	-	-	-	-	-	-	-	-	-
Elba	**4**	41	-	-	-	-	-	-	-	-	-
Tortolì	148	211	-	-	-	-	-	-	-	-	-
Ancona	-	173	-	-	-	-	-	-	-	-	-
Rimini	-	868	-	-	-	-	-	-	-	-	-
Taranto	-	577	-	-	-	-	-	-	-	-	-

Mid-term conclusions are the following. In order to activate all 24 possible routes, time gain has to be reduced from 2 hours to about one hour and a half: otherwise, routes Albenga - Milano, Milano - Albenga, and Rome - Ancona are not feasible in terms of time benefits. Regarding potential demand, routes Milano - Albenga, Albenga - Milano, and Elba - Milano do not satisfy the minimum load factor.

5.4 Introduction of the Cost Bound

Heretofore, the time constraint was the only one considered in all the before described analyses. Ascertained that, by reducing the activation time threshold, almost all routes are made viable in terms of time and potential passengers, one may now speculate about what happens when the original Piaggio Aerospace cost model is applied to the algorithm.

The analysis focused on understanding how potential demand, activated routes, and activated aerodromes vary, when the logic by which the cost constraint is applied changes. This has been done, for the sake of comparison, both for all OD routes and for Piaggio routes. VoT is equal to 22.8 €, as described in Chapter 4. Fuel consumption has been set to [9 7.5 8] L/100 km, while fuel price is at the nominal value of 1.6 €.

Results are listed in Table 5.7 and Table 5.8, while a visualization of the trends is shown in Figure 5.5. In all cases of the Piaggio Aerospace network, all 11 aerodromes are activated, thanks to the reduced time activation threshold. Moreover, number of routes never falls below the maximum value of 24. The average RPKs are 0.3166 and 0.3141 €/km pax, for all possible origin-destination routes and Piaggio routes, respectively.

Table 5.7: Potential Introduction of Piaggio Aerospace Cost Model: all OD Routes.

COST LOGIC	**POTENTIAL DEMAND** [pax]	**ACTIVE ROUTES**
TIME ONLY	3740	98 out of 110
AND	2535	97 out of 110
OR	4115	102 out of 110

Table 5.8: Potential Introduction of Piaggio Aerospace Cost Model: Piaggio Routes.

COST LOGIC	**POTENTIAL DEMAND** [pax]	**ACTIVE ROUTES**
TIME ONLY	1527	24 out of 24
AND	1176	24 out of 24
OR	1532	24 out of 24

The most restrictive case is the one considering Piaggio routes with the AND logic. On the contrary, as one could expect, a time saving OR a price saving constitute the most relaxed scenario. The TIME ONLY logic stays in between the two before mentioned. With reference to Figure 5.5, the slope of potential demand varying with the logic is more marked when considering AND and TIME ONLY logics, while it is more flattened when considering TIME ONLY and OR logics. This will be also discussed in Chapter 6.

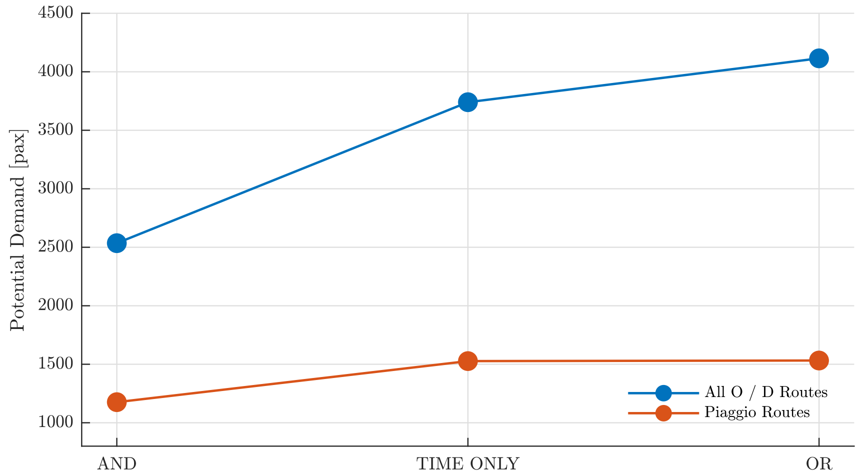


Figure 5.5: Potential Demand with Cost Bond and varying Time-Cost Logic.

For the AND case, even if there is a reduction in terms of potential passengers, the minimum load factor is satisfied for the same routes as before: this was predictable, since Piaggio Aerospace checked the cost model on its routes, but it helps in assessing the right functioning of the implementation inside SHARONA-PDE. Finally, potential demand was before 1527, while now is 1177, with a reduction of 22.9%.

5.5 Conclusions arising from SHARONA-PDE

Piaggio Aerospace study case is made up of 24 possible routes, resembling a Microfeeder approach, which has however been analyzed with the use of SHARONA-PDE. The parametric study on T_{ref} shows how potential demand increases when considering more expanded matrices and all OD routes, instead of only the Piaggio Aerospace network.

When the nominal declared time gain is used, namely 2 hours, only 21 routes out of 24 are feasible in terms of time benefits: excluded pairs are Milano Bresso - Albenga, Albenga - Milano Bresso, and Roma Urbe - Ancona. Reducing T_{ref} to 5065 seconds enables instead the feasibility of all routes: potential demand is in this case 1527. Moreover, all 11 involved aerodromes are activated.

In terms of minimum load factor, 5 routes out of 24 do not reach the minimum aircraft filling of 85%, even with the relaxation of the time activation threshold. This number drops to 3 routes when also occasional leisure travellers are considered. Excluded pairs are: Albenga - Milano Bresso, Milano Bresso - Albenga, and Elba - Milano Bresso.

The introduction of the cost model reduces potential demand by 22.9%, when considering the AND logic, while the OR logic has minor effects which are comparable with the TIME ONLY logic. However, feasible routes in terms of time benefits and potential demand do not change. Activated routes and aerodromes stay to their maximum value.

5.6 Comparison with Piaggio Aerospace Results

Once defined the model according to the Miniliner algorithm, a comparison with Piaggio Aerospace results can take place. In Table 5.9 are listed car times and aircraft times.

No information has been reported about how Piaggio Aerospace evaluates car times and by which elements they are composed. In the Miniliner case instead, times have been evaluated considering as origin and destination the municipalities where the aerodromes are located. Since car times are not symmetric, they have been taken considering the average of the return trips between pairs of municipalities.

Table 5.9: Comparison between Piaggio Aerospace and SHARONA-PDE Time Savings.

ROUTE	**PIAGGIO AEROSPACE** [h : min]				**S-PDE** [h : min]		
	T_{ground}	T_{train}	T_{flight}	ΔT	T_{ground}	T_{flight}	ΔT
Milan - Albenga	3:50	3:45	2:30	**1:15**	2:28	1:27	**1:01**
Milan - Pisa	4:10	4:18	2:36	**1:34**	3:11	1:31	**1:40**
Milan - Perugia	6:00	5:14	2:58	2:16	4:47	2:00	2:47
Milan - Trieste	5:30	5:20	2:51	2:29	4:34	2:13	2:22
Milan - Elba	8:20	8:00	2:49	5:11	5:19	1:50	3:28
Milan - Tortolì	16:50	22:35	3:32	13:18	18:55	2:54	16:01
Rome - Ancona	4:20	4:43	2:32	**1:48**	3:20	1:44	**1:36**
Rome - Rimini	5:20	4:53	2:36	2:17	4:11	1:38	2:33
Rome - Elba	6:48	6:54	2:33	4:15	4:20	1:39	2:41
Rome - Taranto	6:40	7:17	3:06	3:34	5:49	2:18	3:31
Rome - Albenga	8:10	8:03	3:04	4:59	6:26	2:05	4:22
Rome - Tortolì	14:14	18:59	2:50	11:24	14:27	2:16	12:11

Mean difference between Piaggio Aerospace and SHARONA-PDE car times is 1 h and 2 min, resulting in a deviation of 14.72%. Mean difference between aircraft times is instead 52 min, meaning a deviation of 35.99%. These differences balance, since average Piaggio Aerospace delta time (considering also train means of transport) is 4 h and 32 min, while average Miniliner delta time is 4 h and 31 h, with a difference of 1 minute (0.17%).

SHARONA-PDE showed that Milano - Albenga and Rome - Ancona were not viable routes in terms of a two hour time saving. This is confirmed by Piaggio Aerospace results, which however also declare not feasible the route Milano - Pisa. The potential demand algorithm hence enables one more route (actually two, considering round trips) since it involves some more complex evaluations, and also considers time savings for the surrounding cities. If the single route between municipalities shows a time saving of 1 hour and 40 minutes, SHARONA-PDE process shows savings up to 2 hours and 7 minutes, hence a 27% more.

Moving to prices instead, still no information has been reported about how Piaggio Aerospace evaluates car prices. In SHARONA-PDE, as before, prices have been assessed considering the average of the return trips. As usual, prices include CCZ costs, fuel costs, and toll costs, considering a fuel price of 1.6 € and a VoT of 22.8 €/h. In Table 5.10, car and aircraft prices are listed for the two approaches.

Car prices from origins to destinations according to SHARONA-PDE are on average 27.5 € higher than Piaggio Aerospace, while ticket prices are on average 24.5 € lower. The difference in ticket prices, even if the original Piaggio Aerospace model was used, could be due to a different application of VoT, eventually discriminating between car and airplane values. In SHARONA-PDE instead, a single values is used, applied to the difference in time between the ground and air modes of transports.

The route Milano - Albenga is the only one which does not end in a cost saving for SHARONA-PDE. Piaggio Aerospace gets this result also for Milano - Pisa, Milano - Perugia, Milano - Trieste, and Roma - Albenga. However, when discarding trains, which are more competitive in terms of prices, all these mentioned routes are still less expensive with respect to car and a match with respect to SHARONA-PDE is found.

Finally, the value of time for time savings declared in Chapter 4 appears to be in line with Piaggio Aerospace: this is shown in the following equation, when considering second and fourth columns of Table 5.9, and third column of Table 5.10.

$$\overline{VoT}\left[\frac{€}{\mathrm{h}}\right] = \frac{1}{12} \cdot \sum_{i=1}^{12} \left[\frac{VoT}{T_{ground} - T_{flight}}\right]_i = 22.03 \tag{5.1}$$

Table 5.10: Comparison between Piaggio Aerospace and SHARONA-PDE Costs.

ROUTE	PIAGGIO AEROSPACE [€]								SHARONA-PDE [€]				
	CAR			TRAIN			AIRCRAFT		CAR			AIRCRAFT	
	COST	VoT	SUM	COST	VoT	SUM	TICKET	Δ€ [%]	COST	VoT	SUM	TICKET	Δ€ [%]
Milan - Albenga	43.4	32.8	76.2	23.9	23.9	47.8	99.0	52	55.1	23.0	78.1	82.7	05.56
Milan - Pisa	66.9	38.5	105.5	58.6	32.4	91.0	108.0	02	78.7	38.1	116.8	91.6	-27.51
Milan - Perugia	80.1	75.1	155.2	73.0	43.3	116.3	147.0	21	96.9	63.4	160.3	117.6	-36.31
Milan - Trieste	72.7	65.5	138.2	58.9	47.3	106.2	136.0	22	96.7	53.8	150.5	110.7	-35.95
Milan - Elba	85.4	136.1	221.5	87.4	98.9	186.3	133.0	-40	148.5	79.1	227.6	108.8	-109.19
Milan - Tortolì	190.7	130.9	321.6	155.6	210.9	366.5	211.0	-52	187.3	365.3	552.6	165.8	-233.29
Rome - Ancona	60.0	44.5	104.5	21.9	41.8	63.7	101.0	-03	71.8	36.5	108.3	84.4	-28.32
Rome - Rimini	75.5	67.4	144.9	83.0	43.5	126.5	109.0	-16	94.2	58.1	152.3	91.8	-65.90
Rome - Elba	98.6	104.9	203.6	84.8	83.0	167.9	103.0	-98	92.0	61.3	153.3	85.7	-78.88
Rome - Taranto	98.5	87.9	186.4	61.9	79.8	141.7	163.0	-14	121.4	80.3	201.7	131.5	-53.38
Rome - Albenga	115.8	125.9	241.8	59.4	95.3	154.7	160.0	03	136.8	99.4	236.2	129.3	-82.68
Rome - Tortolì	183.7	83.9	267.6	65.4	155.9	220.9	134.0	-100	132.0	277.9	359.9	109.9	-227.48
AVERAGE	**97.6**	**82.8**	**180.6**	**69.5**	**79.7**	**149.1**	**133.7**	**-18.6**	**109.3**	**103.0**	**208.1**	**109.2**	**-81.11**

6 | Mililiner Cost Analysis Results

Before evaluating which are the effects on potential demand after the application of a cost model, a study has to be set up in order to understand which is the new baseline when only the time constraint is present. This has to be done since SHARONA-PDE now takes as input a different OD matrix with respect to [19], as described in Chapter 2.

If not otherwise specified in the analyses, nominal data are to be considered as in Table 6.1. Standard fuel consumption is CAR2. For brevity, updated Piaggio Aerospace and UNIFIER19 cost models will be referred to with the acronyms UPA and U19, respectively.

Table 6.1: Nomial SHARONA-PDE Data for Parametric Analyses.

RWY	SPEED	RANGE	k	T_{ref}	$P_{carFuel}$	VoT
800 m	200 knots	300 km	1.3	1800 s	1.6 €	22.8 €/h

6.1 Comparison between OD Matrices

Sensitivity analysis for new baseline assessment regards potential demand varying with aircraft speed, range, and minimum runway to takeoff, as done in [19]. Apart from the number of involved passengers, other indicators will be described, such as towns, aerodromes, and population involved in the resulting networks.

With reference to Figure 6.1, and consistently with what was said in [19], the number of towns, and subsequently the population involved, are not very sensitive to any of the parameters but range: saturation can be observed at around 250 km. Achievement of maximum value of involved aerodromes is instead dictated by the runway length under analysis. However, a complete superposition can be seen with respect to previous studies.

The only aspect varying is potential demand, which increases with respect to when the original OD matrix is used. This increment is higher with growing runways, ranges, and speeds. Saturation appears to be at about 500 km of range, thus an higher value with respect to [19]. Results are shown in Figure 6.1 and Figure 6.2.

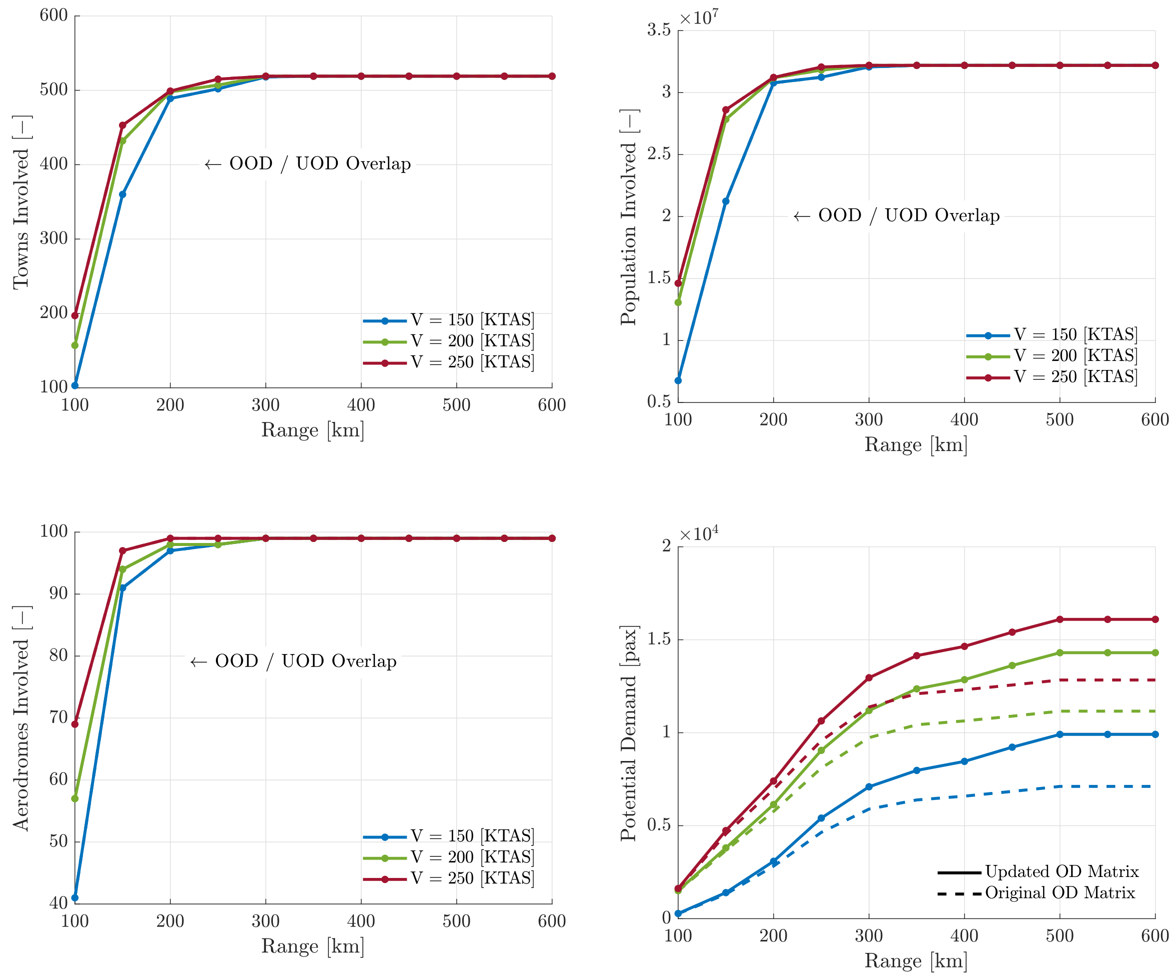
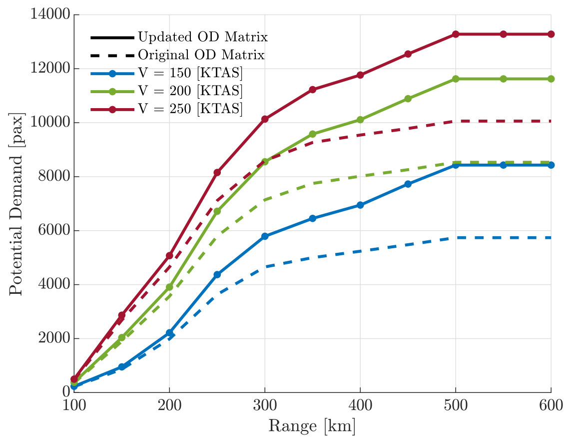


Figure 6.1: Potential Demand Sensitivity for Minimum Runway Length of 600 meters.

(a) Runway of 800 meters.



(b) Runway of 1000 meters.

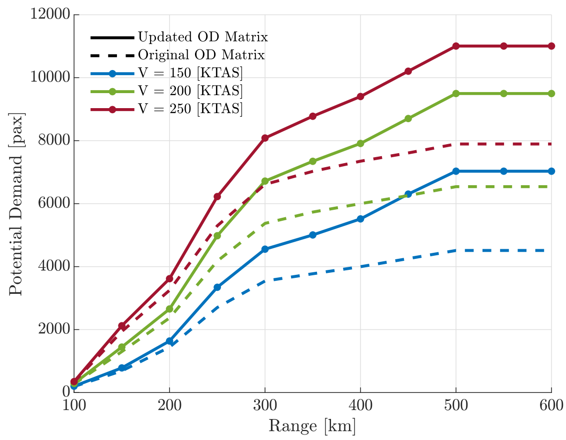


Figure 6.2: Potential Demand Sensitivity for Minimum Runway of 800 and 1000 meters.

In all cases, potential demand varies slightly at low values of the range, while the increment becomes maximum at saturation. For the intermediate runway value, namely 800 meters, which is also the case for configuration C7A of UNIFIER19 [11], percentage increments are shown in Table 6.2. Finally, increments become less marked as velocity increases.

Table 6.2: Potential Demand Percentage Increment for Minimum Runway of 800 meters.

SPEED [knots]	**RANGE** [m]					
	100	**200**	**300**	**400**	**500**	**600**
150	5.9	11.5	24.4	32.6	46.9	46.9
200	6.1	9.5	19.8	26.1	36.2	36.2
250	5.1	9.0	17.9	23.3	32.0	32.0

Potential demand also shows an approximately linear dependency on minimum runway required. Solid lines in Figure 6.3 represent updated demand, which is higher for any value of range with respect to [19]. Furthermore, this increment becomes larger and larger as the range itself increases. The packing at higher vales of range observed in previous studies is here less marked, but anyway present. Notice that results shown are referred to just one value of cruise speed, namely 250 knots, but same considerations apply for other values.

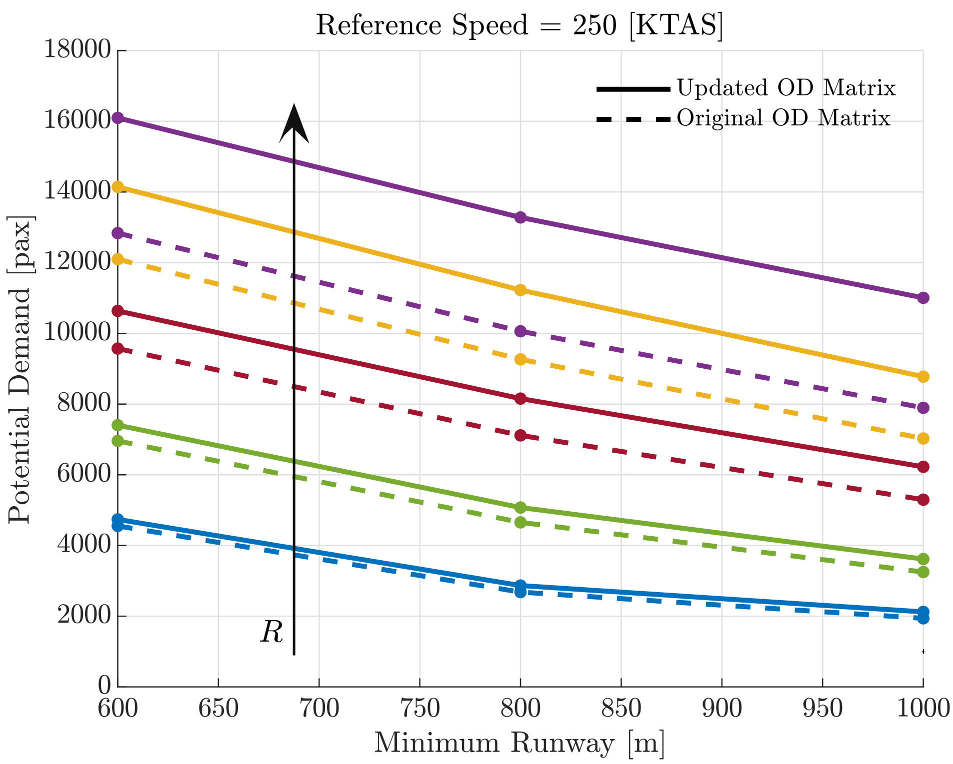


Figure 6.3: Potential Commuters varying with Minimum Runway Required and Range.

6.2 Time and Cost Implementation Logic

As anticipated in Chapter 4, the cost constraint can be implemented in two flavours with respect to the time constraint, namely with and AND or OR logic. The scope of this section is to investigate how the network changes when the implementation changes. For the sake of simplicity, results for UPA will be shown, but same results apply for U19. All analyses have been executed with the CAR2 value of fuel consumption.

With reference to Figure 6.4, it can be seen that the OR logic does not seem to bring strong benefits to none of the involved parameters: aerodromes, towns, and population involved are nearly superposed with respect to the TIME ONLY logic. Furthermore, potential demand shows an increment which in no cases of range, speed, and runway, is higher than 1%. This said, to avoid an unnecessary overloading of figures, the only logic to be discussed henceforward is the AND.

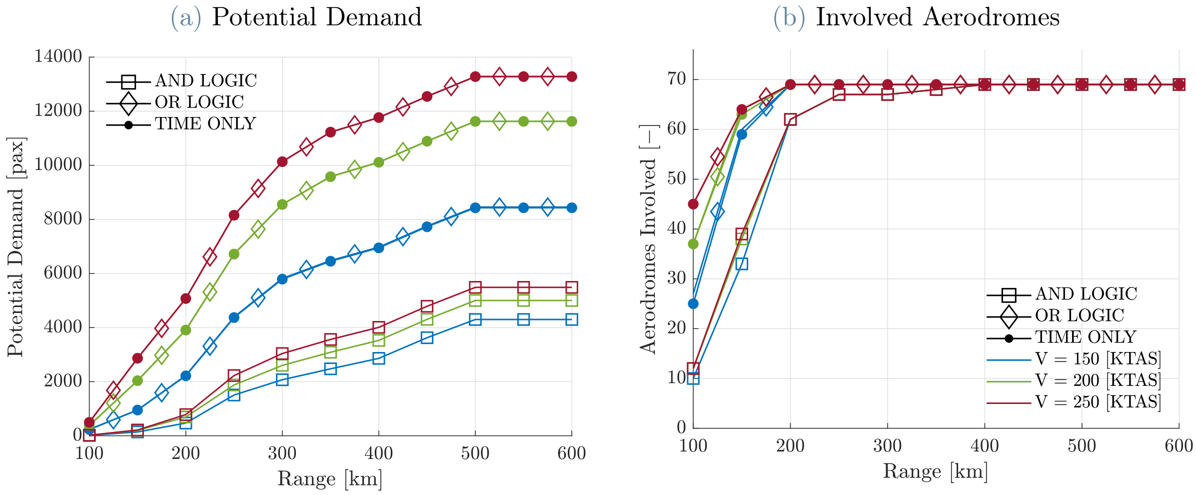


Figure 6.4: Commuters and Aerodromes varying with Cost Logic (RWY = 800 meters).

Concerning the AND logic, a visible reduction of potential commuters is shown. This reduction exhibits a little dependence on flight speed with respect to the TIME ONLY logic alone, for which the difference is more marked. Quantitative data will be discussed in the next sections. Moreover, the cost logic does not change the saturation range for any of the cruise speeds, which keeps staying at about 500 kilometers.

Involved aerodromes also decrease in number, but their value goes back to the same as TIME ONLY logic after a range of about 250 kilometers. The same behaviour has been seen for the other two runway lengths, therefore same considerations apply.

6.3 Fluctuations of Ground Travel Costs

A first set of quantitative data can be established when considering the two cost models and letting ground price parameters vary, namely fuel consumption, fuel price, and value of time of people travelling. Nominal speed, runway, and range will be heron considered. Fuel price for car travels will vary from 1 to 2 €, while VoT will change of ± 10%.

Refer to Figure 6.5. Higher car fuel consumptions, as one would imagine, let potential demand increase. The behaviour of potential demand appears in any case approximately linear with fuel cost and with variations of value of time. Furthermore, according to the updated Piaggio Aerospace model, its slope varies with fuel consumption, and it increases if fuel consumption increases: this does not happen for UNIFIER19, for which only a translation along the y axis takes place.

However, apart from considering very low fuel prices, which do not apply to most of the conventional vehicles, a consistent potential demand is present, even if a clear evidence of the impact of the cost constraint is highlighted.

(a) UPA (b) U19

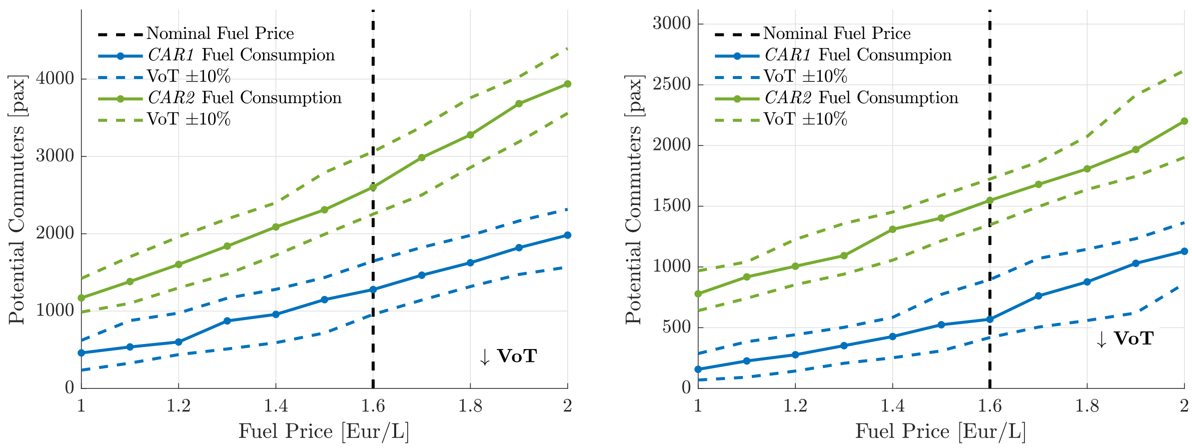


Figure 6.5: Potential Demand varying with Ground Fuel Price.

Piaggio Aerospace model, which is a TOC model, surprisingly brings to higher demands with respect to UNIFIER19, which is only based on DOC. With reference to Figure 4.2, this could be due to the higher ticket prices involved for U19 at low values of range.

Perhaps, this could show the benefits of using a cost model which spreads costs on a whole year and on flight hours, as UPA does, rather than on single flights. U19 cost approach could be modified, in order to obtain low values of ticket prices for short journeys.

For the UPA cost model and for step variations of fuel price of 0.1 €/L, the mean difference in potential demand is 152 and 277, respectively for the two values of low and high fuel consumptions. This stands in a percentage variation of 8 and 14% with respect to the maximum value of potential demand (namely, at $P_{carFuel} = 2$ €/L).

When instead considering U19 model, mean differences are 97 and 142, resulting in a percentage variation with respect to maximum potential demand of 9 and 13%. This values are comparable with the ones found for UPA: therefore, even if absolute potential demand is different for the two approaches, variations due to fuel price are similar.

In Table 6.3 and Table 6.4, percentage variations for varying fuel prices are shown, in comparison both with respect to the nominal price and to the TIME ONLY logic. For simplicity, results are listed only for the CAR2 value of fuel consumption.

Table 6.3: Potential Demand Percentage Reduction with UPA Model and CAR2.

	FUEL PRICE [€/L]						
	1.3	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**
POTENTIAL DEMAND	1840	2088	2310	2603	2985	3279	3683
% wrt $P_{carFuel} = 1.6$ €/L	-29%	-20%	-11%	0%	15%	26%	41%
% wrt TIME ONLY	-78%	-76%	-73%	-70%	-65%	-62%	-60%

Table 6.4: Potential Demand Percentage Reduction with U19 Model and CAR2.

	FUEL PRICE [€/L]						
	1.3	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**
POTENTIAL DEMAND	1093	1310	1403	1548	1680	1808	1967
% wrt $P_{carFuel} = 1.6$ €/L	-29%	-15%	-9%	0%	9%	17%	27%
% wrt TIME ONLY	-87%	-85%	-84%	-82%	-80%	-79%	-77%

Concerning activated aerodromes, they vary in a non-liner way with respect to fuel price. For the high fuel consumption case, variation is low and the number of aerodromes stays at a nominal value for all fuel prices, as can be seen in Figure 6.6.

When it comes to the lower fuel consumption instead, variation is more marked. For the two cost models under analysis, the minimum number of activated aerodromes is 62 and 56. Namely, 57% and 51% of all possible infrastructures are used.

(a) UPA (b) U19

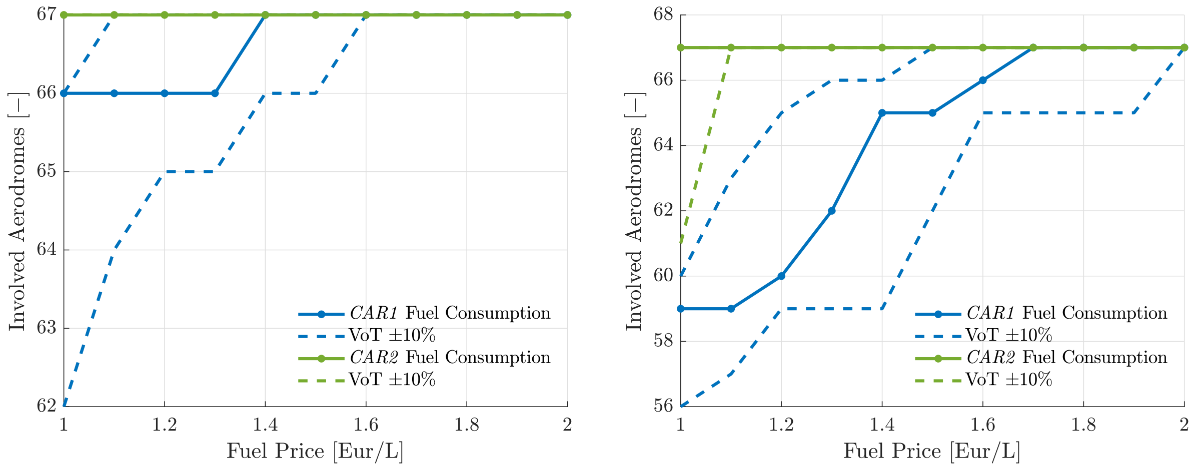


Figure 6.6: Involved Aerodromes varying with Ground Fuel Price.

6.4 Fluctuations of Liquid Hydrogen Price

Costs for air travels have also been left vary in order to asses potential demand sensitivity. Apart from the two ground fuel consumptions, fluctuations to be considered stand in the price of the liquid hydrogen to be used to feed the hybrid-electric powertrain. Battery energy has a significantly lower impact on costs, since it is only used during terminal maneuvers, which is why it will not be further questioned.

Potential demand variations with liquid hydrogen price follow a non-linear behaviour, which is why graphs shown in Figure 6.7 are constructed considering a logarithmic scale on the x axis. A fast drop in potential demand starts when hydrogen price raises above the value of 2 €/L. This behaviour is more clear-cut for the UNIFIER19 cost model. Results are shown in Tables 6.5 and 6.6, where potential demand is again compared with the cases of nominal liquid hydrogen price, and with respect to the TIME ONLY logic.

For UPA cost model, the mean difference in potential demand with respect to its maximum value is 5 and 10%, respectively for the two values of low and high fuel consumptions. When instead considering U19 model, mean percentage variations are 5 and 9%. Therefore, mean variations due to hydrogen price are similar between the two cost models.

Involved aerodromes are heavily impacted by increases in hydrogen price. For the high fuel consumption case, the value keeps constant until a price of liquid hydrogen of about 10 €/kg, then starts dropping significantly. This is of course due to the reduction in potential demand. The maximum value does not vary depending on the used cost models, and is about 64% of all possible infrastructures. Results are shown in Figure 6.8.

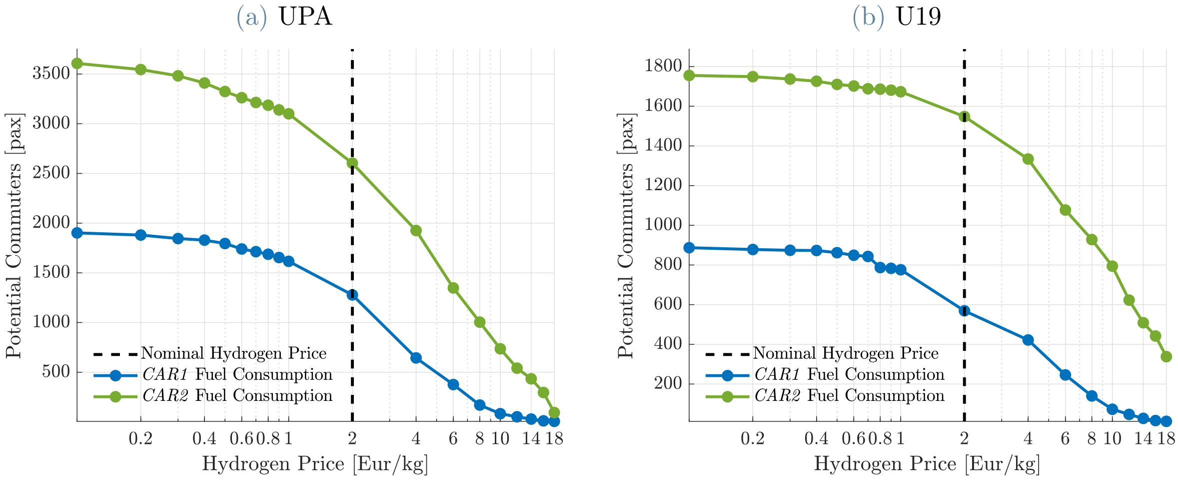


Figure 6.7: Potential Demand varying with Liquid Hydrogen Price.

Table 6.5: Potential Demand for UPA Model and CAR2.

	LIQUID HYDROGEN PRICE [€/kg]						
	0	**0.5**	**1**	**2**	**4**	**6**	**8**
POTENTIAL DEMAND	3651	3324	3100	2603	1926	1348	1004
% wrt $C_{hydrogen}$ **= 2** €/kg	40%	28%	19%	0%	-26%	-48%	-61%
% wrt TIME ONLY	-57%	-61%	-64%	-70%	-77%	-84%	-88%

Table 6.6: Potential Demand for U19 Model and CAR2.

	LIQUID HYDROGEN PRICE [€/kg]						
	0	**0.5**	**1**	**2**	**4**	**6**	**8**
POTENTIAL DEMAND	1788	1710	1673	1548	1334	1077	928
% wrt $C_{hydrogen}$ **= 2** €/kg	16%	10%	8%	0%	-14%	-30%	-40%
% wrt TIME ONLY	-79%	-80%	-80%	-82%	-84%	-87%	-89%

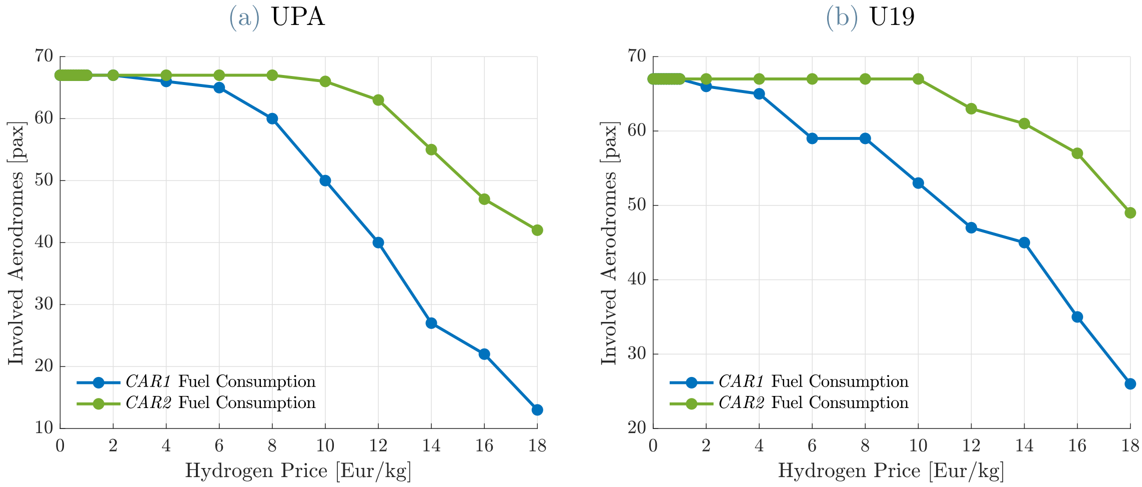


Figure 6.8: Involved Aerodromes varying with Liquid Hydrogen Price.

SHARONA-PDE busiest routes are shown in Table 6.7 at the end of this chapter. Nominal values have been considered for runway, time activation thresholds, fuel price, liquid hydrogen price, and VoT. Results are listed for three values of speed and for a range of 350 kilometers, as equal to C7A configuration cruise range. The AND logic has been considered. Descending order of potential passengers, for the case of UNIFIER19 cost model and 200 knots, is highlighted in bold. Flows are displayed in Figure 6.9: Rome has the greatest number of incoming travellers, while Firenze the greatest outgoing flow.

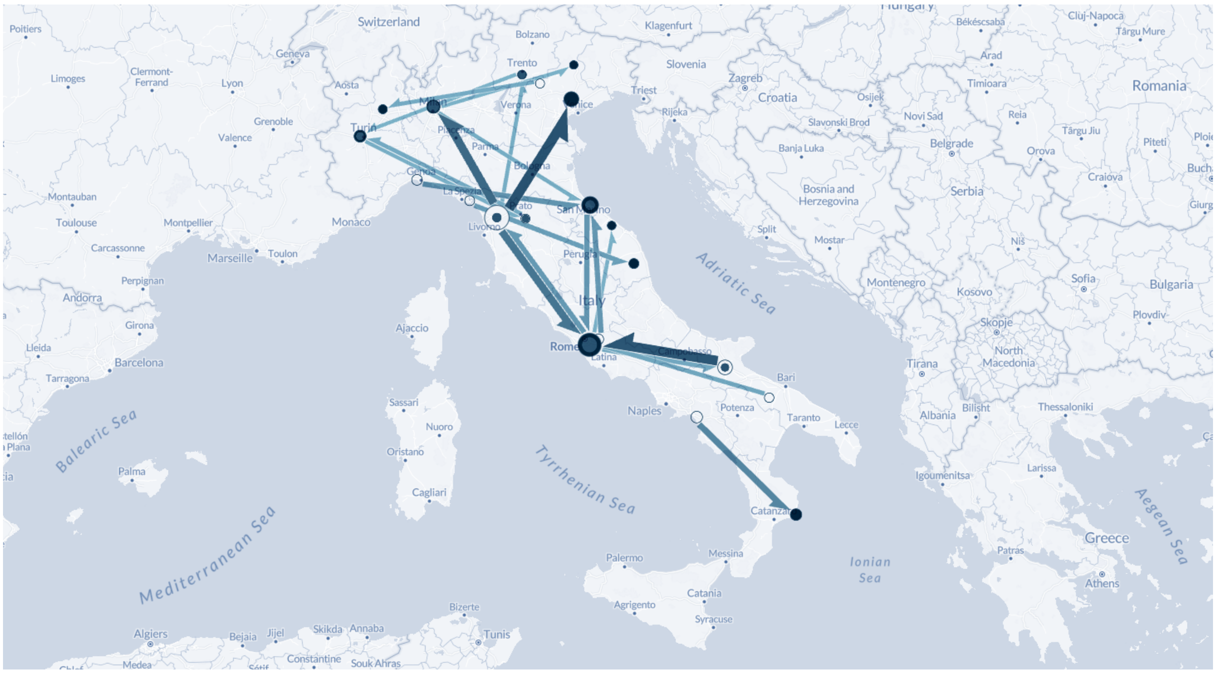


Figure 6.9: Flowmap.blue [71] Scheme of the Busiest Routes resulting from S-PDE.

6.5 Reformulation of the Time Constraint

Finally, a further analysis was carried out by setting $k = 1$. This has been done since in the original idea of SHARONA-PDE no cost constraint was introduced, and the relative time activation threshold of 1.3 was needed in order to penalize travel time savings. It comes out that the implementation of the cost model overshadows the action of parameter k. Results are shown in Figure 6.10, where the case of $k = 1$ has been compared with the nominal case, in terms of potential demand difference.

The increment in potential demand is in the order of units of passengers, and therefore negligible. Updated Piaggio Aerospace cost model has relatively higher deviations, while UNIFIER19 method leads to an almost complete overlap between the two cases.

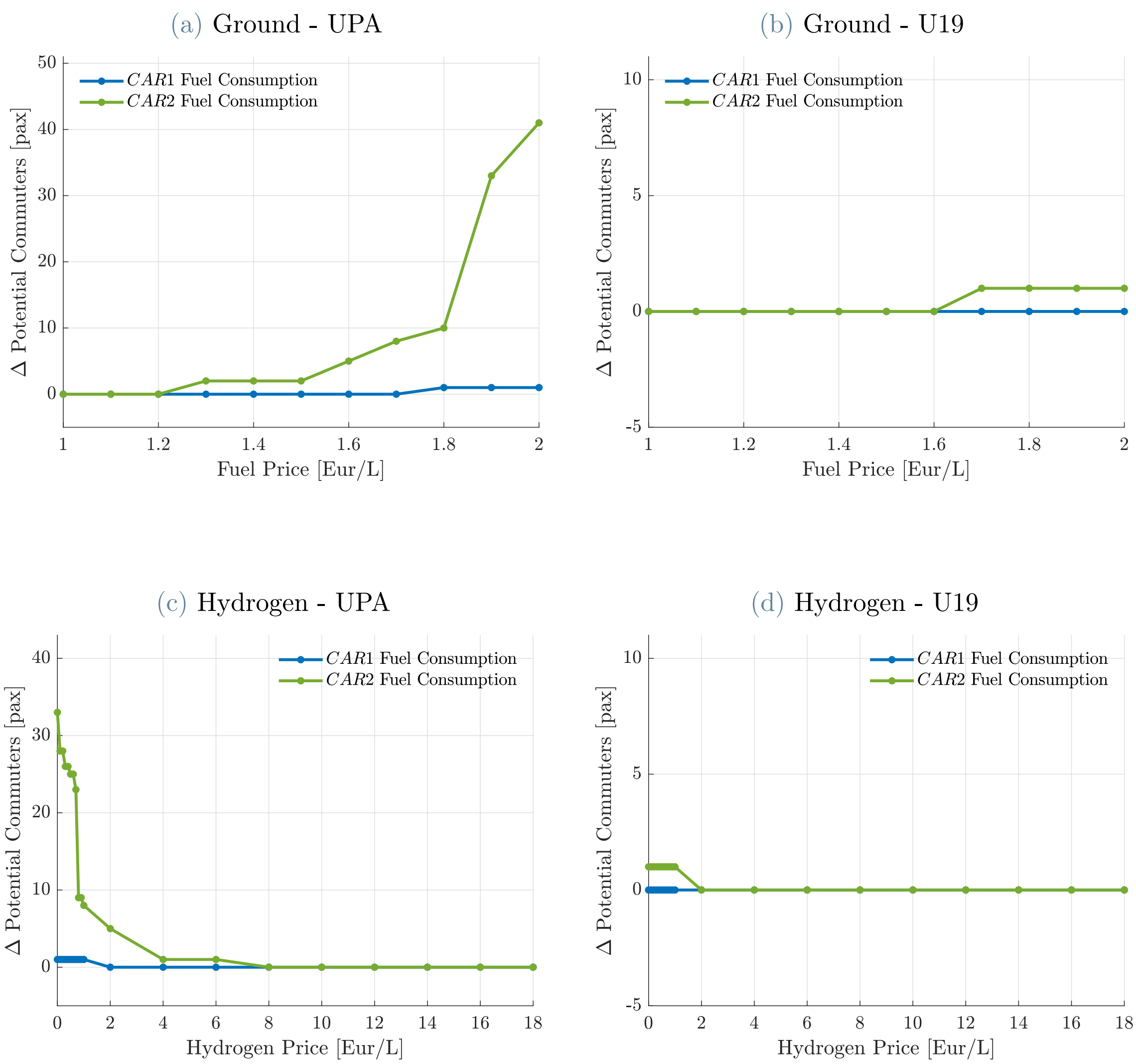


Figure 6.10: Fluctuations of Ground and Air Travel Prices with respect to $k = 1$.

Table 6.7: Main Routes for UPA and U19 and three Nominal Cruise Speeds [knots].

ROUTE	**UPA**			**U19**		
	150	**200**	**250**	**150**	**200**	**250**
Aeroporto di Lucca - Tassignano / Aeroporto di Treviso - S. Angelo	57	**63**	64	64	64	64
Aeroporto di Foggia - Gino Lisa / Aeroporto di Roma - Ciampino	61	**61**	61	61	61	61
Aeroporto di Lucca - Tassignano / Aeroporto di Milano Bresso	41	**51**	59	77	80	92
Aeroporto di Lucca - Tassignano / Aeroporto di Roma - Ciampino	14	**45**	45	45	45	45
Aeroporto di Salerno - Pontecagnano / Aeroporto di Crotone - Sant'Anna	37	**37**	37	37	37	37
Aeroporto di Genova - Sestri / Aeroporto di Rimini - Miramare	31	**31**	31	31	31	31
Aeroporto di Rimini - Miramare / Aeroporto di Roma - Ciampino	30	**30**	30	30	30	30
Aviosuperficie Aviocaipoli - Gallicano / Aeroporto di Rimini - Miramare	14	**30**	31	31	31	31
Aeroporto di Roma - Ciampino / Aeroporto di Lucca - Tassignano	9	**29**	33	26	33	41
Aeroporto di Sarzana - Luni / Aviosuperficie Guido Paci - Montegiorgio	2	**27**	27	2	27	29
Aviosuperficie Ceraso - Altamura / Aeroporto di Roma - Ciampino	24	**24**	24	24	24	24
Aeroporto di Roma - Ciampino / Aeroporto di Foggia - Gino Lisa	21	**23**	23	23	23	23
Aeroporto di Asiago - Romeo Sartori / Aeroporto di Biella - Cerrione	0	**22**	22	0	23	23
Aeroporto di Firenze - Peretola / Aeroporto di Torino - Aeritalia	22	**22**	22	22	22	22
Aeroporto di Lucca - Tassignano / Aeroporto di Trento - Mattarello	20	**21**	21	21	21	21
Aeroporto di Milano Bresso / Aeroporto di Rimini - Miramare	5	**21**	35	6	23	37
Aeroporto di Torino - Aeritalia / Aeroporto di Firenze - Peretola	20	**20**	20	20	20	20
Aeroporto di Roma - Ciampino / Aviosuperficie Valcesano - Monte Porzio	20	**20**	20	20	20	20
Aeroporto di Milano Bresso / Aeroporto Arturo dell'Oro - Belluno	18	**19**	19	19	19	19
Aeroporto di Trento - Mattarello / Aeroporto di Torino - Aeritalia	19	**19**	19	19	19	19

7 | Conclusion

In addition to usual commuting flows, a preliminary study on potential demand brought also to the incorporation of occasional business travellers in SHARONA-PDE. This led to a significant increase in potential passengers with respect to previous works, with values up to 50% and more. Nevertheless, the process did not raise the number of activated aerodromes, thus not leading to higher operating costs.

Piaggio Aerospace and UNIFIER19 cost models were then implemented. The first lays on the evaluation of total operating costs spread on a whole year, while the second follows the path of establishing direct operating costs per flight. The first approach led to lower ticket prices for very short-haul flights, namely until a range of about 300 kilometers.

Before analyzing the application of the cost models to SHARONA-PDE, Piaggio Aerospace network was examined, composed by two main hubs and nine minor aerodromes. Conclusions arising from SHARONA-PDE have shown to be comparable with results coming from Piaggio Aerospace analyses, thus confirming the right functioning of the implementation. Moreover, the potential demand algorithm brought to an increment in the number of activated routes, showing the benefits of demand gathering among municipalities, with respect to methods based on single origin to destination fluxes.

When cost models were applied to S-PDE, considering a cost OR a time saving did not lead to a significant increase in potential demand (in no case the increment overcame the value of 1%). On the contrary, for a cost AND a time saving, potential demand reduced.

Parametric studies showed that variations in potential passengers are approximately linear with respect to fuel price for ground vehicles. Furthermore, potential demand resulted also very sensitive to variations in liquid hydrogen prices, this time in a higher-than-linear way: significant reductions appeared after a price of two euros per kilogram. The number of activated aerodromes shows in this case less dependence with respect to car fuel prices.

7.1 Further Developments

The reduction in potential demand was predictable, since the model went from having a single constraint to a double constraint. However, it has to be taken into account that feeding SHARONA-PDE is not the overall demand, since the used origin-destination matrix contains just 519 Italian municipalities. This accounts for only 47% of total commuters and for only 8% of total occasional business travellers. Therefore, a comprehensive study could be executed including all Italian municipalities, leading to more realistic results.

Piaggio Aerospace and UNIFIER19 cost models could be merged in a single one, unifying the positive characteristics of both approaches. Moreover, the model could be implemented in an iterative way with respect to network optimization, leading to a maximization of the demand and to an optimal network definition.

VoT implementation could be enhanced in order to consider different values, based on the importance of the route under analysis. Finally, road traffic has never been considered an issue until now, but taking it into account would surely lead to more realistic scenarios, as ground times and prices would raise, benefiting the use of Miniliner.

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A | List of Selected Clusters

ID	NAME	ICAO	ϕ [deg]	λ [deg]	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	09.0158	1120
5	Aeroporto di Vercelli - Carlo del Prete	LILI	45.3117	08.4228	0560
6	Aviosuperficie Cosenza - Bisignano	-	39.5261	16.2300	1000
7	Aeroporto Cassaliggio - Piacenza	-	44.9978	09.5814	0860
8	Aviosuperficie Toniatti - Bibione	-	45.6694	13.0392	1000
9	Aviosuperficie Massalengo	-	45.2731	09.4825	0700
10	Aviosuperficie Marina di Modica	-	36.7231	14.7750	0600
11	Aeroporto di Brindisi - Casale	LIBR	40.6567	17.9453	3048
12	Aviosuperficie Cascina Valentino - Envie	-	44.6975	07.4019	0630
13	Aviosuperficie Grumentum - Nova	-	40.2694	15.9178	1110
14	Aviosuperficie Umberto Nobile - Minturno	-	41.2353	13.8211	0800
15	Aeroporto di Lucca - Tassignano	LIQL	43.8253	10.5789	0910
16	Aeroporto di Verona - Villafranca	LIPX	45.3953	10.8875	3068
17	Aviosuperficie Guido Paci - Montegiorgio	-	43.1014	13.5553	0800
18	Aeroporto di Bolzano - Dolomiti	LIPB	46.4625	11.3297	1294
19	Aviosuperficie Esperti - Cellino San Marco	-	40.4789	17.8844	0600
20	Aeroporto di Rimini - Miramare	LIPR	44.0219	12.6053	3300
21	Aeroporto di Prati Vecchi di Aguscello	LIDV	44.7903	11.6731	0800
22	Aviosuperficie Bolgheri - Castagneto Carducci	-	43.2114	10.5442	0750
23	Aviosuperficie Valle Gaffaro - Codigoro	-	44.8333	12.2333	0900
24	Aviosuperficie Divinangelo Primo - Sezze	-	41.4719	13.0236	0600
25	Aeroporto di Pavullo nel Frignano	LIDP	44.3225	10.8322	1190
26	Aviosuperficie Alituscia - Vejano	-	42.2278	12.1197	0700
27	Aeroporto di Torino - Aeritalia	LIMA	45.0867	07.6092	1074
28	Aviosuperficie Aretusa Fly - Canicattini Bagni	-	37.0372	15.0953	0630
29	Aviosuperficie Pittini A.V.R.O.	-	46.2358	13.0736	0600
30	Aviosuperficie Il Borro	-	43.5375	11.7061	0920
31	Aviosuperficie San Giorgio di Cascia	-	42.7561	13.0164	1050

32	Aeroporto Arturo dell'Oro - Belluno	LIDB	46.1667	12.2492	0812
33	Aeroporto di Scalea	LICK	39.7772	15.8208	1450
34	Aeroporto di Brescia - Montichiari	LIPO	45.4289	10.3306	2990
35	Aeroporto di Alzate - Brianza	LILB	45.7717	09.1644	0600
36	Aviosuperficie di Dorgali	-	40.3478	09.5481	0650
37	Aviosuperficie Valcesano - Monte Porzio	-	43.7006	13.0739	0820
38	Centro Volo Serristori - Castiglion Fiorentino	-	43.3325	11.8581	0600
39	Aeroporto di Crotone - Sant'Anna	LIBC	38.9947	17.0772	2000
40	Aeroporto di Albenga - Riviera	LIMG	44.0450	08.1244	1432
41	Aeroporto di Parma	LIMP	44.8208	10.2950	2124
42	Campo Volo Xptz - Decimoputzu	-	39.3631	08.8678	0790
43	Aeroporto di Pescara - Pasquale Liberi	LIBP	42.4300	14.1881	2419
44	Aviosuperficie Falcone - Lavello	-	41.1042	15.8761	0750
45	Aeroporto dell'Elba - Marina Di Campo	LIRJ	42.7633	10.2369	1197
46	Aero Club Benevento - Olivola	-	41.1775	14.7472	0650
47	Aviosuperficie Boglietto - Costigliole d'Asti	-	44.7586	08.1833	0645
48	Aeroporto di Legnago	LIDL	45.1325	11.2925	0610
49	Aeroporto di Varese - Calcinate del Pesce	LILC	45.8100	08.7708	0600
50	Aeroporto di Sarzana - Luni	LIQW	44.0903	09.9892	0905
51	Aeroporto di Trapani - Birgi	LICT	37.9125	12.4892	2695
52	Aeroporto di Padova - Gino Allegri	LIPU	45.3953	11.8492	1122
53	Pegaso Flying Club - Ceccano	-	41.5417	13.3694	0600
54	Aviosuperficie Enrico Mattei - Pisticci	-	40.4325	16.5544	1440
55	Aeroporto di Salerno - Pontecagnano	LIRI	40.6203	14.9203	1654
56	Aviosuperficie Massarotti - Caltagirone	-	37.1917	14.5511	0700
57	Avio Club di Chiusdino	-	43.1903	11.1458	0700
58	Aviosuperficie Corte - Melpignano	-	40.1067	18.2583	0985
59	Aviosuperficie l'Aquila - Poggio Picenze	-	42.3008	13.5172	0650
60	Aviosuperficie Minotaurus e Medusa	-	38.0481	14.5406	0800
61	Aeroporto di Asiago - Romeo Sartori	LIDA	45.8869	11.5167	1120
62	Aviosuperficie Aviocaipoli - Gallicano	-	41.8903	12.7847	0810
63	Aeroporto di Firenze - Peretola	LIRQ	43.8086	11.2011	1750
64	Aviosuperficie di Sondrio - Caiolo	LILO	46.1542	09.7925	1050
65	Aviosuperficie Aliquirra - Perdasdefogu	-	39.6786	09.4619	0650
66	Aeroporto di Alghero - Fertilia	LIEA	40.6331	08.2894	3000
67	Aeroporto di Foggia - Gino Lisa	LIBF	41.4339	15.5358	1438
68	Aeroporto di Aosta - Corrado Gex	LIMW	45.7386	07.3681	1499
69	Aeroporto di Pantelleria	LICG	36.8150	11.9669	2030
70	Aeroporto di Lampedusa	LICD	35.4992	12.6156	1800
71	Aviosuperficie Ceraso - Altamura	-	40.9389	16.4944	0890

72	Aviosuperficie del Sagrantino	-	42.8900	12.5328	0720
73	Aeroporto di Trieste - Ronchi dei Legionari	LIPQ	45.8272	13.4703	3000
74	Aeroporto di Novi Ligure - E. Mossi	LIMR	44.7781	08.7889	1050
75	Aeroporto di Casale Monferrato	LILM	45.1089	08.4528	0880
76	Aeroclub Sibari Fly - Cassano allo Ionio	-	39.7569	16.4381	0800
77	Aviosuperficie Cortina di Alseno	-	44.8700	09.9378	0720
78	Aviosuperficie del Litorale di Caorle	-	45.6125	12.8103	0833
79	Aeroporto di Milano Bresso	LIMB	45.5372	09.1997	1080
80	Aeroporto di Comiso - Pio la Torre	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	07.6208	2100
83	Aviosuperficie Pantano - Pignola	-	40.5614	15.7592	0600
84	Aeroclub Volturno Fly - Limatola	-	41.1575	14.3669	0630
85	Aviosuperficie Grecciano - Collesalvetti	-	43.6286	10.4828	0700
86	Aeroclub Mantova - Curtatone	-	45.1011	10.7506	0750
87	Aviosuperficie Tronto - Monteprandone	-	42.8894	13.8689	1499
88	Aeroporto di Trento - Mattarello	LIDT	46.0214	11.1253	1130
89	Aeroporto di Forlì - Luigi Ridolfi	LIPK	44.1950	12.0697	2540
90	Aeroporto di Lugo - Francesco Baracca	LIDG	44.3983	11.8556	0800
91	Aviosuperficie Aliscarlino - Podere le Cascine	-	42.9122	10.8167	0670
92	Aviosuperficie di Bagnoli di Sopra	-	45.1844	11.8575	1180
93	Aeroporto di Roma - Ciampino	LIRA	41.8000	12.5933	2200
94	Aeroporto di Carpi - Budrione	LIDU	44.8367	10.8711	0850
95	Aviosuperficie Alfina - Castel Viscardo	-	42.7375	11.9831	0750
96	Aeroporto di Biella - Cerrione	LILE	45.4975	08.1022	1320
97	Aviosuperficie di San Sepolcro	-	43.5583	12.1556	0875
98	Aviosuperficie Vallesanta - Rieti	-	42.4272	12.8053	0785
99	Aeroporto di Treviso - S. Angelo	LIPH	45.6508	12.1978	2459
100	Aeroporto di Cremona - Migliaro	LILR	45.1675	10.0042	0650
101	Aeroporto d'Olbia - Costa Smeralda	LIEO	40.8997	09.5158	2445
102	Aeroporto di Ancona - Falconara	LIPY	43.6156	13.3619	2965
103	Aeroporto di Lamezia Terme - Sant'Eufemia	LICA	38.9064	16.2433	3017
104	Aeroporto di Genova - Sestri	LIMJ	44.4131	08.8444	2916
105	Aeroporto di Oristano - Fenosu	LIER	39.8969	08.6406	1199
106	Aeroclub dei Marsi - Celano	-	42.0514	13.5572	0830
107	Aeroporto di Palermo - Boccadifalco	LICP	38.1144	13.3128	1224
108	Aeroporto di Grosseto - Corrado Baccarini	LIRS	42.7633	11.0828	3007
109	Aeroporto di Reggio Calabria - dello Stretto	LICR	38.0733	15.6525	2061

B | Main Routes for Travellers

ORIGIN	DESTINATION	PAX_{year}	$PAX_{day}^{business}$
Roma	Rimini	256556	77
Roma	Milano	214334	64
Milano	Roma	205841	62
Roma	Riccione	149259	45
Torino	Roma	148718	45
Roma	Firenze	145418	44
Roma	Cervia	144833	43
Roma	Cesenatico	138515	41
Napoli	Roma	129235	39
Roma	Torino	122289	37
Milano	Rimini	115479	34
Roma	Jesolo	111517	33
Roma	Ravenna	101132	30
Roma	Venezia	94106	28
Genova	Roma	84019	25
Torino	Rimini	83432	25
Roma	Napoli	80049	24
Roma	Vieste	77392	23
Roma	Cattolica	75226	22
Roma	Bologna	75028	22
Bologna	Roma	73456	22
Napoli	Rimini	72502	21
Torino	Milano	69702	21
Roma	Caorle	67620	20
Milano	Riccione	67183	20
Milano	Firenze	65454	19
Milano	Cervia	65191	19
Roma	Lignano Sabbiadoro	63584	19

Milano	Cesenatico	62347	18
Firenze	Roma	61442	18
Napoli	Milano	60570	18
Roma	Abano Terme	59537	18
Roma	Comacchio	58903	17
Milano	Torino	55044	16
Verona	Roma	53887	16
Venezia	Roma	53803	16
Palermo	Roma	53566	16
Roma	Verona	52645	15
Milano	Jesolo	50195	15
Roma	Orbetello	49706	15
Torino	Riccione	48539	14
Roma	Genova	47417	14
Torino	Firenze	47290	14
Genova	Rimini	47135	14
Torino	Cervia	47100	14
Roma	Pisa	46951	14
Roma	Padova	46749	14
Roma	Ischia	46630	14
Milano	Ravenna	45520	13
Roma	Grosseto	45408	13
Torino	Cesenatico	45045	13
Padova	Roma	43693	13
Roma	Chioggia	42920	12
Milano	Venezia	42358	12
Napoli	Riccione	42180	12
Bologna	Rimini	41209	12
Napoli	Firenze	41094	12
Napoli	Cervia	40929	12
Roma	Senigallia	40492	12
Torino	Torino	39768	12
Genova	Milano	39378	11
Napoli	Cesenatico	39144	11
Roma	Forio	38852	11
Roma	Fondi	37583	11

Parma	Roma	37238	11
Roma	Andalo	36972	11
Trieste	Roma	36852	11
Roma	Trento	36433	11
Bari	Roma	36279	10
Torino	Jesolo	36265	10
Milano	Napoli	36031	10
Roma	Palermo	35442	10
Modena	Roma	35112	10
Roma	Assisi	35093	10
Milano	Vieste	34835	10
Roma	Camerota	34795	10
Napoli	Torino	34558	10
Roma	Pinzolo	34498	10
Roma	Piombino	34478	10
Firenze	Rimini	34469	10
Bologna	Milano	34427	10
Perugia	Roma	33945	10
Milano	Cattolica	33860	10
Milano	Bologna	33771	10
Roma	Alassio	33661	10
Roma	Bibbona	33643	10
Roma	Misano Adriatico	33221	10
Torino	Ravenna	32888	9
Prato	Roma	32522	9
Roma	Massa	32396	9
Roma	Perugia	32060	9
Reggio nell'Emilia	Roma	31782	9
Roma	Ugento	31628	9
Napoli	Jesolo	31514	9
Roma	Viareggio	31483	9
Torino	Venezia	30603	9
Milano	Caorle	30436	9
Roma	Badia	30249	9
Verona	Rimini	30231	9
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List of Figures

List of Tables

List of Symbols

SYMBOL	UNIT	DESCRIPTION
$\alpha_{GAL/H-L/H}$	[L/gal]	Conversion Factor from Gallons to Liters
α_{MIN-H}	[h/min]	Conversion Factor from Minutes to Hours
α_{NM-KM}	[km/NM]	Conversion Factor from Nautical Miles to Kilometers
α_{TON-LB}	[lb/TON]	Conversion Factor from Tons to Pounds
$\alpha_{USD-EUR}$	[€/USD]	Conversion Factor from Dollars to Euros
α_{W}	[%]	Percentage of Yearly Travellers for Working Reason
γ_{L-KG}	[kg/L]	Conversion Factor from Liters to Kilograms (for JET - A1)
$\eta_{electricMotor}$	[%]	Electric Motor Efficiency
$\eta_{fuelCell}$	[%]	Fuel Cell Efficiency
$\eta_{jetEngine}$	[%]	Jet Engine Efficiency
λ	[−]	Scaling Factor for Car Fuel Costs
$\chi_{battery}$	[%]	Percentage of Battery Capacity used per Flight
A_{OM_i}	[−]	Sum of Italian Residents in Origin Municipality i
A_{OR_k}	[−]	Sum of Italian Residents in Origin Region k
AOC	[€]	Annual Total Operating Costs per Aircraft
B_{cycles}	[−]	Battery Cycles before Replacement
B_{energy}	[kWh]	Total Energy Capacity of the Batteries
$C_{attendants}$	[€/h]	Average Hourly Flight Attendant Wage
$C_{battery}$	[€]	Single Battery Cost (from C7A Data)
$C_{boarding}$	[€/pax]	Boarding Costs per Passenger
$C_{checkin}$	[€]	Check-In Costs per Single Departure
$C_{electric}$	[€/kWh]	Electric Energy Price (non-Household)
$C_{freelancePilot}$	[€]	Yearly Freelance Pilot Costs per Aircraft
C_{fuel}	[€/gal]	Conventional Fuel Price
$C_{fuelCell}$	[€]	Single Fuel Cell Cost (from C7A Data)

$C_{hydrogen}$	[€/kg]	Hydrogen Cost per Kilogram
C_{LND}	[€]	Landing Fees per Flight per Aircraft
$C_{LND\&TO}$	[€/TON]	Takeoff and Landing Fees per TON
$C_{maintenanceLabor}$	[€/h]	Maintenance Labor Cost per Flight Hour
$C_{maintenanceParts}$	[€/h]	Maintenance Parts Cost per Flight Hour
C_{motor}	[€]	Single Motor Cost (from C7A Data)
$C_{parking}$	[€/TON h]	Parking Cost per Ton and Hour
C_{pilot}	[€] or [€/h]	Average Hourly Pilot Wage
$C_{refurbishing}$	[€/h]	Refurbishing Cost per Hour
C_{sales}	[€]	Sales and Promotion Costs per Ticket
D_{day}	[–]	Number of Departures per Day (Round-Trip)
D_{week}	[–]	Number of Departures per Week (Round-Trip)
D_{year}	[–]	Number of Departures per Year (Round-Trip)
$\bar{D}_{year}$	[–]	Number of Completed Departures per Year (Round-Trip)
DOC	[€]	Sum of all Direct Operating Costs
$DOC_{airport}$	[€]	Landing and Ground Handling Fees per Flight
DOC_{crew}	[€]	Crew Direct Operating Costs
$DOC_{depreciation}$	[€]	Depreciation Direct Operating Costs
DOC_{fees}	[€]	Fees Direct Operating Costs
DOC_{fuel}	[€]	Fuel Direct Operating Costs
$DOC_{insurance}$	[€]	Insurance Direct Operating Costs
$DOC_{interest}$	[€]	Interest Direct Operating Costs
$DOC_{maintenance}$	[€]	Maintenance Direct Operating Costs
$DOC_{navigation}$	[€]	Navigation Fees Direct Operating Costs (Eurocontrol)
$DOC_{ownership}$	[€]	Ownership Direct Operating Costs
$DOC_{terminal}$	[€]	Terminal Fees Direct Operating Costs (Eurocontrol)
DP	[years]	Depreciation Period of the Aircraft
E_{block}	[kWh]	Electric Energy Consumption during Block Time
ED_{H_2}	[kWh/kg]	Liquid Hydrogen Energy Density
$ED_{jetFuel}$	[kWh/kg]	Jet Fuel Energy Density
F_{block}	[kg]	Conventional Block Fuel needed for the Mission
$F_{consumption}$	[gal/h]	Conventional Fuel Consumption
F_{cycles}	[–]	Flight Cycles per Year for Typical Mission
$F_{depreciation}$	[€]	Monthly Depreciation Fee per Aircraft

$F_{financing}$	[€]	Monthly Financing Fee per Aircraft
f_{RV}	[%]	Residual Value Factor for Depreciation
$f_{departures}$	[%]	Completion Departure Factor
f_{ease}	[MMH/FH]	Ease of Maintenance Factor
$f_{inflation}$	[%]	Inflation Factor from 2016 to 2020 for VoT
$f_{insurance}$	[%]	Insurance Factor for determining Insurance Price
$f_{profitMargin}$	[%]	Yearly Profit Margin of the Airline per Aircraft
f_{tax}	[%]	Local Sales Tax Rate for Lease Payment
$FCPAC$	[€]	Total Yearly Fixed Costs per Aircraft
$FHPY$	[h]	Flight Hours per Year for a Typical Mission
G	[pax]	Occupancy OD Matrix - 519 × 519
$\bar{G}$	[pax]	Original OD Matrix (Commuting Matrix) - 519 × 519
G_E	[pax]	Occupancy OD Matrix including Isola d'Elba - 519 × 519
G_H	[pax]	Occupancy OD Matrix including Leisure - 519 × 519
H_{block}	[kg]	Liquid Hydrogen Consumption during Block Time
$H_{parking}$	[h]	Daily Parking Hours of the Aircraft
$H_{refursbishing}$	[h]	Refurbishing Hours per Seat
IR	[%]	Interest Rate for Aircraft Financing
K_N	[€]	Navigation Fees Reference Factor
K_T	[€]	Terminal Fees Reference Factor
k	[−]	Relative Time Difference for SHARONA-PDE
$KMPY$	[km]	Flown Kilometers per Year for a Typical Mission
LF_{min}	[%]	Minimum Aircraft Load Factor
$\hat{M}$	[%]	Overall Percentage of Monthly Departures
M_p	[%]	Percentage of Monthly Departures for each Month
m_p	[−]	Monthly Departures for each Month (in Thousands)
MF	[%]	Money Factor for Financing Charges
$MTOW$	[kg] or [lb]	Maximum Takeoff Weight of the Vehicle
$N_{attendants}$	[−]	Number of Flight Attendants needed for One Flight
N_{crews}	[−]	Crew Complement (i.e. Number of Crews needed)
N_{pilots}	[−]	Number of Pilots needed for One Flight

$P_{aerodrome}$	[€/h]	Aerodrome Charges Price per Flight Hour
P_{air}	[€]	Air Cost to Travel between Municipality Pairs
$P_{aircraft}$	[€]	Aircraft Selling Price
$P_{boarding}$	[€/h]	Boarding Price per Flight Hour
P_{car}	[€]	Car Prices between Municipalities
$P_{carFuel}$	[€/L]	Car Fuel Prices (part of P_{car})
P_{CCZ}	[€]	Congestion Charge Zone Prices (part of P_{car})
P_{crew}	[€]	Yearly Crew Price per Aircraft
P_{energy}	[€/h]	Energy Price of Batteries per Flight Hour
P_{ferry}	[€]	Ferry Prices from Mainland (part of P_{car})
P_{fuel}	[€/h]	Fuel Price per Flight Hour
P_{ground}	[€]	Ground Cost to Travel between Municipality Pairs
$P_{handlingParking}$	[€/h]	Handling and Parking Price per Flight Hour
P_{hangar}	[€]	Yearly Hangar Price per Aircraft
$P_{hydrogen}$	[€/h]	Liquid Hydrogen Price per Flight Hour
$P_{insurance}$	[€]	Yearly Insurance Price per Aircraft
P_{lease}	[€]	Monthly Lease Payment per Aircraft
$P_{maintenance}$	[€/h]	Maintenance Price per Flight Hour
$P_{management}$	[€]	Yearly Airline Management Price per Aircraft
$P_{modernization}$	[€]	Modernization Price after 10 Years
$P_{navigation}$	[€]	Yearly Navigation Price per Aircraft
$P_{ownership}$	[€/h]	Ownership Price per Flight Hour
$P_{parking}$	[€]	Total Parking Price per Year of the Aircraft
$P_{refurbishing}$	[€]	Yearly Refurbishing Price per Aircraft
$P_{residual}$	[€]	Aircraft Residual Value at End of Operations
P_{sales}	[€]	Yearly Sales and Promotion Price per Aircraft
$P_{suppliesCatering}$	[€/h]	Supplies Catering Price per Flight Hour
P_{ticket}	[€]	Ticket Price for the Typical Mission
$P_{TO\&LND}$	[€/h]	Takeoff and Landing Price per Flight Hour
P_{toll}	[€]	Toll Prices for Motorways (part of P_{car})
$P_{training}$	[€]	Yearly Training Price per Aircraft
$P_{weather}$	[€]	Yearly Weather Price per Aircraft
$PAX_{IT\rightarrow DM_j}$	[pax]	Italian Travellers moving to Destination Municipality j
$PAX_{IT\rightarrow IT}$	[pax]	Sum of Italian Occasional Travellers (Business and Leisure)
PAX_{max}	[pax]	Maximum Capacity of the Aircraft (i.e. Number of Seats)
$PAX_{OM_i\rightarrow DM_j}$	[pax]	Italian Travellers moving from OM i to DM j

$PAX_{OR_k \to DM_j}$	[pax]	Italian Travellers moving from OR k to DM j
$PAX_{OR_k \to IT}$	[pax]	Italian Travellers moving from Origin Region k
PAX_{year}	[pax]	Passengers per Year for a Typical Mission
PPY	[€]	Yearly Profit of the Airline per Aircraft
R	[km] or [NM]	Mission Range for Ticket Price Estimation
RPK	[€/pax km]	Revenue Passenger Kilometer
T_{air}	[s]	Air Time to Travel between Municipality Pairs
T_{block}	[min] or [h]	Flight Block Time (Gate to Gate)
$T_{checkIn}$	[s]	Check-In Airport Time
T_{DUH}	[h]	Daily Utilization Hours of the Vehicle
T_{flight}	[s] or [min]	Flight Time to Travel between Aerodromes
T_{ground}	[s]	Ground Time to Travel between Municipality Pairs
T_{leave}	[s]	Leave Airport Time at Arrival Aerodrome
$T_{miniliner}$	[s]	Air Time to Travel between Aerodromes
T_{ref}	[s]	Absolute Time Difference for SHARONA-PDE
T_{taxi}	[min]	Taxi Time (including Taxi-In and Taxi-Out Times)
T_{taxiIn}	[s]	Taxi-In Airport Time (part of T_{taxi})
$T_{taxiOut}$	[s]	Taxi-Out Airport Time (part of T_{taxi})
$T_{TO\&LND}$	[s]	Takeoff and Landing Airport Times
$T_{turnaround}$	[min]	Turnaround Time between Flights
$TBO_{fuelCell}$	[h]	Fuel Cell Time Between Overhaul
TBO_{motor}	[h]	Motor Time Between Overhaul
U	[h]	Yearly Utilization Rate or Yearly Flight Hours
V	[knots]	Cruise Speed of the Vehicle
$VCPFH$	[€/h]	Total Variable Costs per Flight Hour
VoT	[€/h]	Value of Time for Commuters and Business Travellers
$WMPY$	[weeks]	Weeks of Maintenance per Year
WU	[days]	Weekdays Utilization of the Vehicle
$\bar{Z}$	[pax]	Occupancy Data OD Matrix - 7914 × 3288
Z	[pax]	Reduced Occupancy Data OD Matrix - 519 × 519

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Con questo lavoro di tesi si conclude un percorso importante della mia vita, forse il più importante *fino ad ora*, ma, spero, il meno importante *a partire da ora*.

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