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Capturing the Demand for an Electric-Powered Short-Haul Air Transportation Network

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A procedure for the assessment of the capability of a regional network system based on electric-powered commuter aircraft, christened SHARONA (Short-Haul Air Route Optimal Network Assessment), is illustrated. The environmentally-friendly and efficient alternative to road travel represented by this service, especially for longer distance commuting, generates a potential demand for a given territory that takes into account the competition with ground-based transportation means. Subsequently, an optimization algorithm defines a complete air transportation network for the territory at hand, being capable to capture the highest possible share of the potential demand, based on the availability of a given aircraft fleet. The methodology is applied to define the potential demand and to capture the maximum number of daily commuters in Italy.

I. Introduction

A key-element in understanding the applicability and profitability of novel electric-powered aircraft [1–4] is the quantitative analysis of the air transport network they can support. Thanks to the stark reduction in noise and chemical emissions, especially during terminal maneuvers [5, 6], airliners endowed with this new type of propulsion system may operate from secondary airports and smaller airfields, collectively referred to as Secondary Aerodromes (SAs), often built very close to towns or in densely populated city areas, which are nowadays constrained by traffic limitations to reduce social cost and public annoyance. The upgrade of these overlooked assets to the role of nodes in a new air transportation infrastructure would be possible especially when coupled with a fleet of pure-electric or hybrid-electric commuter airplanes capable to take off and land from small SAs [7]. Such a miniliner, specifically designed for passenger transportation on short and very-short haul routes, may be used in two flavors.

The first, here referred as "microfeeder", is intended as a hub-and-spoke service, used to feed major airports from smaller cities and open country territories, in an effort to ease the accessibility of medium- and long-range flights. The second, here termed "intercity liner", is intended as a point-to-point service, used to connect smaller cities and open country territories, mainly for daily commuting journeys. Both services may reveal as key components in the future development of a more connected continental transportation network through enhanced, environmentally sustainable regional air travel, especially in territories with inefficient ground transportation services to major airports or between towns. In particular, they may decisively contribute to the European Flightpath 2050 vision of a transportation system offering virtually any EU citizen the possibility to complete any intra-continental journey in no more than 4 hours, door-to-door.

However, profitability from air traffic revenues should be sufficiently high to justify the procurement cost of an upgrade of SA facilities needed to operate with the new aircraft. Moreover, in Europe such a market segment is currently underdeveloped at best and thorough market studies for the prediction of the potential passenger demand are called for. This motivates developing the methodology proposed in this paper, christened Short-Haul Air Route Optimal Network Assessment (SHARONA). This is being applied in the context of the EU-funded projects MAHEPA (Modular Approach to Hybrid Electric Propulsion Architecture) project and UNIFIER19 (Community Friendly Miniliner). In the MAHEPA project, market studies are carried out to predict scenario elements for the scalability of Hybrid-Electric (HE) propulsive technologies from General Aviation (GA) applications to regional air transportation. This, starting from HE design

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and analysis [3, 8], includes also studies related to infrastructural sizing and scheduling [9, 10] and to environmental impact [5, 6]. In the UNIFIER19 project, a near-zero emission 19-passenger aircraft is being designed [11] and market studies for short-haul air transportation networks are carried out to derive fundamental top-level aircraft requirements such as cruising speed, range, and take-off/landing field length that may provide the best solution in terms of the capability to capture the highest possible traveling demand [12].

The SHARONA methodology implies two phases: first, the potential travel demand is estimated for a given territory, which in principle may range from a relatively small region (for example, in the neighborhood of a single hub) to a large continental area (a cluster of countries, such as the EU); second, a complete route network is defined to capture the highest possible share of the potential demand, based on the availability of a given aircraft fleet. In this work, the demand estimation and optimal network definition are studied with reference to the intercity liner service for regular passengers, i.e. job and study commuters (the microfeeder case is discussed in [13]). The intercity miniliner is a near-zero-emission 19-seater hybrid-electric aircraft that can be operated from small SAs. It is considered as an environmentally-friendly and efficient alternative to road travel, the current main choice for long distance commuting in many cases. The scenario presented is the Italian market. The starting point is an origin-destination matrix of commuters, representing the number of commuters that live in a town and work or study in another town, for each possible town pair. In order to determine for which routes the intercity miniliner is competitive, its travel time is compared to road travel for the same trip and a definite time advantage is defined. Afterwards, the demand is introduced in the mathematical model that allows obtaining the optimal route network.

II. Aerodrome clustering and selection

The starting point for the estimation of the potential demand for a miniliner service is the definition of the existing and potential airport infrastructures in a geographical area of interest. One of the main advantages of the miniliner concept as considered in the UNIFIER19 project is its ability to be operated without needing a fully-developed infrastructure, being capable to operate a grassy airfield. As a consequence, the possible nodes of the network greatly multiply. According to the OpenAIP database [14], there are 602 potential aerodromes in Italy that could be serviced by the miniliner. In contrast, the Italian Aeronautical Information Publication (AIP) [15], indicates that only 44 aerodromes are certified for schedule air transport operations. Other than regulatory issues, there is no reason to stick to this subset of aerodromes, as it is technically feasible to operate from other, less equipped, facilities. In fact, the only design constraint considered here is the minimum runway length required for take-off and landing.

However, these facilities are not necessarily uniformly distributed across the territory. Sometimes, two or more aerodromes can be close together and their simultaneous operation could result in unnecessary redundancy. This motivates a clustering of the SAs, aimed at grouping aerodromes together attending to the distance between them and choosing a representative member of each group. In this way, a more spatially uniform SA network is obtained. This is not a trivial task and there are different methods to accomplish it. The hierarchical agglomerative method is used here, which merges airports in an iterative way [16]. The process followed is:

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

This process results in a dendogram like the one depicted in Figure 1. The next step is to define a cut distance (i.e. a minimum distance between clusters) and cut the dendogram at that distance. For the present studies, a 50 km distance is used. This distance is not a great-circle distance, but a road distance, which is obtained using the HereMaps Application Programming Interface (API). Using the aforementioned 50 km road distance cut in the Italian case, 109 candidate SA result. These shall be further filtered by applying the runway requirement constraint.

The clustering result can be seen in Figure 2, where a total of 108 aerodromes are found with a minimum runway length of 600 m (a), 75 with 800 m (b), and 54 with 1,000 m (c). The 600 m minimum runway length requirement does not really pose a limitation in the number of usable aerodromes (only one, Vercelli airport, has a runway shorter than 600 meters) so Fig. 2a is basically the map of all the potential nodes for the miniliner network problem.

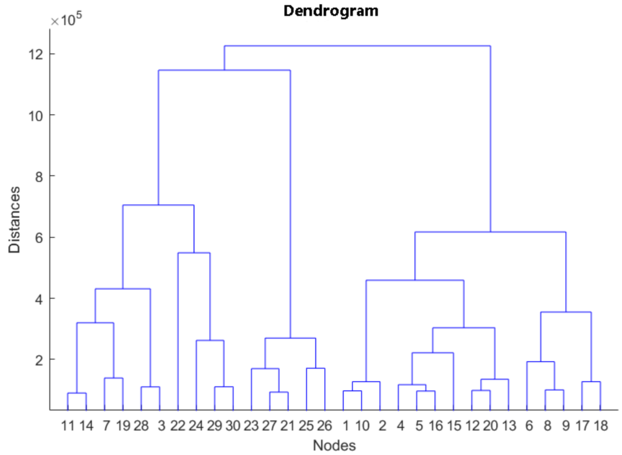
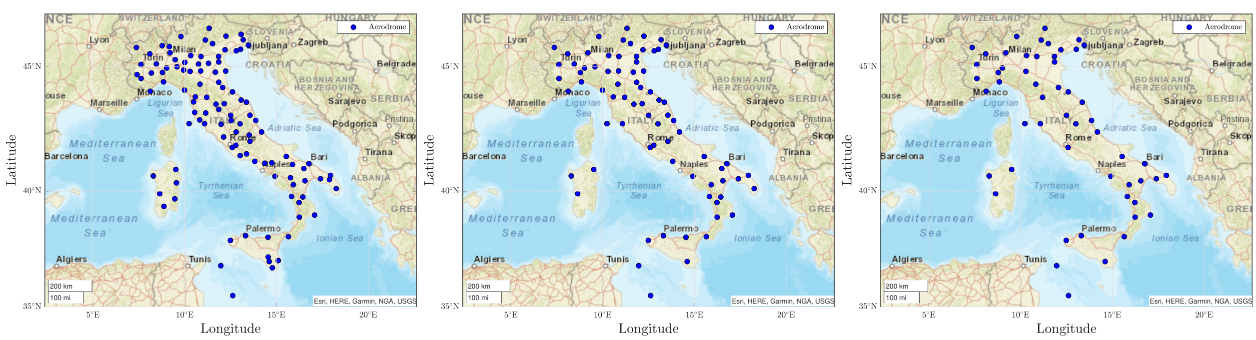


Fig. 1 Example of the dendogram resulting from a clustering process.



(a) Minimum runway length of 600 m. **(b) Minimum runway length of 800 m.** **(c) Minimum runway length of 1,000 m.**

Fig. 2 Italian candidate secondary aerodrome after clustering.

III. Potential demand estimation methodology

Once the aerodrome infrastructure is known, a vast number of routes may be traced connecting all locations. It is clearly crucial to be able to down-select possibly interesting routes from these large sets in an appropriate way. For this market study, a selection is enforced according to time-saving criterion: the air route which guarantees a minimum time advantage with respect to the alternatives provided by the ground transportation network are considered, while the others are discarded. Of course, in a subsequent phase, further important functions of merit in addition to travel time, such as ticket cost and passenger comfort, should be included in the analysis.

The data used for the travel time estimations have been retrieved from publicly available databases, such as those offered by various internet mapping and navigation services. Air route distances have been calculated by referring to orthodromic distances, while ground travel distance and times have been gathered through HERE Maps APIs. In order to preliminarly assess the potential demand for each connection between SAs, the number of passengers that may find this type of connection more convenient than others can be computed by comparing the time needed to reach the destination from a municipal area using the current land-based links and that corresponding to the use of a miniliner service from a location close to the origin to a location close to or at the destination.

A. Identification of route catchment areas

For an intercity service, the travel time t_{ic}^{T1-T2} is given by

$$t_{ic}^{T1-T2} = t^{T1-SA1} + t^{f} + t^{SA2-T2}, \tag{1}$$

where t^{T1-SA1} i the time needed to reach the nearest SA, SA1, from the departure town T1 using land-based means, t^f is the miniliner flight duration, and t^{SA2-T2} is the time to go by car/train/bus from the arrival SA, SA2, to the destination town T2. The miniliner flight duration t^f is clearly a function of the flight performance characteristics of an assumed aircraft, and is obtained from a set of components:

$$t^{f} = t^{c-in} + t^{ta} + t^{to-lnd} + t^{t-in} + t^{t-out} + t^{c} \tag{2}$$

where t^{c-in} is the time necessary for check-in operations, t^{ta} is aircraft turnaround time, t^{to-lnd} stands or take-off and landing duration, t^{t-in} for taxi-in time, t^{t-out} for taxi-out time, and t^c for block cruise duration (including climb, cruise, and descent flight phases). It is remarked that only the last term actually depends on the trip distance, while the other terms are constant.

Given the previous travel time definitions, the catchment area for a route traced between two SAs is defined based on the positive evaluation of the following time constraints:

$$\frac{t^{T1-T2}}{t_{ic}^{T1-T2}} \geq k \tag{3}$$

$$t^{T1-T2} - t_{ic}^{T1-T2} \geq t_{ref}. \tag{4}$$

Eq. (3) represents an imposed time advantage of the novel miniliner-based transport solution with respect to the usual, purely ground-based one, where k is a parameter that can be freely defined by the user. Eq. (4) further stresses this advantage, imposing a minimum difference of a duration t_{ref}. This can be explained for instance by considering a possibly higher fare of the miniliner solution with respect to a purely ground-based one. Adding a more significant time difference between the two services in favor of the miniliner may balance out a possible slight economical shortcoming of this solution. Eventually, the catchment area for a given route is obtained gathering all towns for which the above time constraints are satisfied.

B. Intercity potential demand estimation algorithm

In order to estimate the number of people interested in traveling between any two towns using the miniliner service, data about commuting habits from the Italian National Institute of Statistics were used. In particular, periodical censuses usually provide *matrices of commuting habits* estimating the number of people that commute daily for work or study reasons. The total traffic flow can be arranged in the form of a typical Origin-Destination (OD) matrix G such that

$$G = \begin{bmatrix} g_{11} & g_{12} & \cdots & g_{1n} \\ g_{21} & g_{22} & \cdots & g_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ g_{n1} & \cdots & \cdots & g_{nn} \end{bmatrix} \tag{5}$$

where g_{ij} represents the commuter flow from the i-th town origin to the j-th destination. It is interesting to note that commuter traffic flow is bidirectional: those who travel in the morning will travel back in the afternoon/evening. Therefore, the "afternoon" OD matrix is simply the transpose of the "morning" OD matrix:

$$G_{\text{afternoon}} = G^T_{\text{morning}} \tag{6}$$

By evaluating of all route catchment areas relative to each entry of the OD matrix, the total potential demand can be estimated.

IV. Network sizing methodology

The potential demand estimation phase described above represents the fundamental input for the second phase in the SHARONA methodology, which applies a dedicated optimization algorithm to the determination of the network capable to capture the highest travel demand while minimizing the number of SA to be activated, for a given miniliner fleet. This is stated as a Mixed Integer Linear Programming (MILP) location and routing problem, according to a fully parametric approach, just as the process described for the potential demand estimation. The solution to the MILP problem provides a complete description of the sought network, including the time scheduling of the miniliner flights, the number of passenger transported in each flight, and the need to recharge and/or refuel [13].

A relevant aspect in the network sizing problem is the effect of aircraft passenger capacity. Clearly, the higher the capacity the aircraft, the heavier the batteries and/or the larger the tanks and the longer the duration of the battery-recharging/tank-refueling process. This clearly has an impact on the time efficiency of the miniliner service. Furthermore, the risk of flying with a reduced passenger load factor most of the time, more typical to a larger aircraft designed to cope with peak demand encountered only rarely in a day schedule, makes the definition of aircraft capacity a sensible parameter also from the standpoint of miniliner operators. Other relevant aspects in the network sizing problem are connected to fundamental miniliner performance items, particularly: maximum range, cruising speed, and take-off and landing distances. In order to build on reliable data, aircraft performance and other relevant characteristics such as battery capacity have been derived from the application of HYPERION, a dedicated hybrid-electric aircraft preliminary sizing tool [3], starting with suitable mission requirements.

A. Mathematical model

Given a time horizon, an estimation of the potential demand for the miniliner transport service and a homogeneous fleet of aircraft, the optimization problem consists in finding a subset of SAs to be activated and, for each aircraft, a route alternating between two SAs to serve as a link between two towns. The primary objective is the maximization of the total demand captured, while the secondary objective is the minimization of the total activated airports. This optimization problem, termed ‘arc-based‘ model is formulated via a MILP approach as described in [13]. The arc-based model assures an optimal solution only when applied to small instances, since it requires high computational resources. Therefore, a revised and simplified ‘string-based‘ formulation, was employed for the present work. The string-based model is a binary Integer Linear Programming (ILP) problem aimed at solving both the microfeeder and the intercity problems as different variants of the Green Vehicle Routing Problem (GVRP), which is a Vehicle Routing Problem (VRP) with the added complexity of working with electric or alternatively fueled vehicles.

In the case of the hybrid-electric miniliner, this complexity stems from the battery charging needs. The main parameter for this is the battery discharge ratio, which is assumed to be constant. A discharge ratio greater than 0.5 implies that the aircraft must be recharged after each flight. A discharge ratio greater than 0.25 implies that the aircraft should be recharged after every two flights, and so on. Battery charging time also plays an important role.

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

For a string to be created, its demand has to be over a threshold. It is not profitable to dispatch an aircraft without a minimum number of passengers on board. The ratio of passengers over the aircraft capacity is the passenger load factor and is another important parameter in the network. With respect to time, the model works with dimensionless time slots. Therefore, it is possible to work with different time resolutions without needing to change the model. However, the input data should be re-scaled appropriately.

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

- String compatibility. Consecutive strings have to meet two conditions. A string destination has to be equal to the next string origin. Also, a string departure time slot has to be smaller or equal to the previous string arrival time plus the charging time.
- Airport blockage. There is a limit on the number of operations an airport can hold per unit time. In the case of the microfeeder, accurate data of the available movements at hubs are available. As there are no relevant data for SAs, a limit of 30 operations per hour is assumed here.

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

B. Optimization software

The intercity miniliner network is optimized using the string-based model. This is done using the software AMPL, and the state-of-the-art solver CPLEX. The only two parameters set to start the optimization are the gap and the time limit. If the time limit is reached, the iterations are stopped and the result assigned is the last one achieved, although sub-optimal. The gap refers to the difference between each iteration potential optimum and the upper bound assigned at each iteration step. When the relative difference between the potential optimum and the upper bound is less than the minimum gap specified, the iterations stop and the result is considered optimal. The time limit used is 3,600 seconds and the minimum gap is 0.01.

V. Estimating the potential traveling demand

A. General setup

In order to derive useful information on the effect of some of the UNIFIER19 miniliner design top-level requirements (TLAR) on the demand-capturing capability of an intercity service, parametric studies have been performed, considering suitable ranges in the main design-driving values. Relevant aspects in the potential demand estimation are connected to fundamental miniliner performance items: maximum range, cruising speed, and take-off and landing distances.

Cruising altitude is set to 4,000 ft. This is possibly reduced in case the trip is so short that the climb phase ends before reaching cruise altitude. Other mission profile parameters include optimal climb at a rate of climb of 500 ft/min and descent at cruising airspeed at a rate of descent of 250 ft/min. The size threshold for towns to be considered in the analysis is 20,000 inhabitants. The constant part of the total travel time is set to 40 min. Finally, the parameters defining the time advantage in Eqs. (3) and (4) are set as $k = 1.3$ and $t_{ref} = 30$ min.

The full Italian territory is considered in the analysis and the commuters OD matrix G from the 15$^{\text{th}}$ population and housing census from 2011 [17] is adopted.

B. Aircraft performance sensitivity analysis

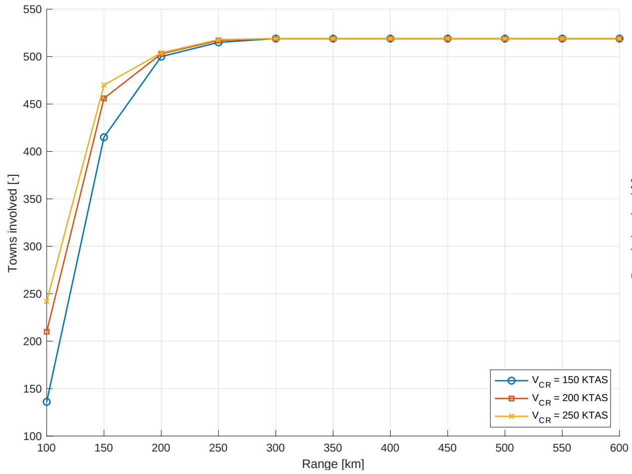
As anticipated, among the main performance items that shall drive the design of the UNIFIER19 miniliner appear:

- Range: greater values make the miniliner able to connect more distant communities, for which it is likely to be more convenient than land-based transportation means.
- Cruising speed: as time is the key parameter that makes the service competitive, the fastest communities can be connected, the greatest will be the advantage.
- Minimum runway length: as the starting point for a network definition process is selecting its nodes, a larger set of candidate aerodromes is obtained with lower runway lengths.

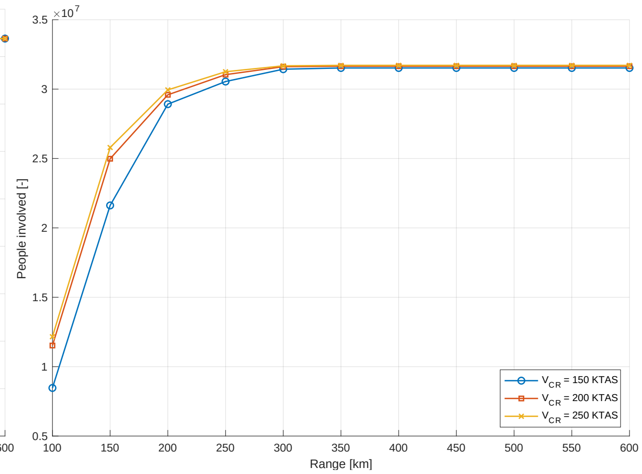
Thus, a sensitivity analysis on the potential demand is carried out by varying these parameters. The indicator for the potential demand is the number of travelers that could benefit from the miniliner. In addition, other elements characterizing the network are also obtained:

- The number of towns participating in the network, providing or receiving commuters.
- The number of aerodromes participating in the network, acting as nodes.
- The total population of the towns involved.

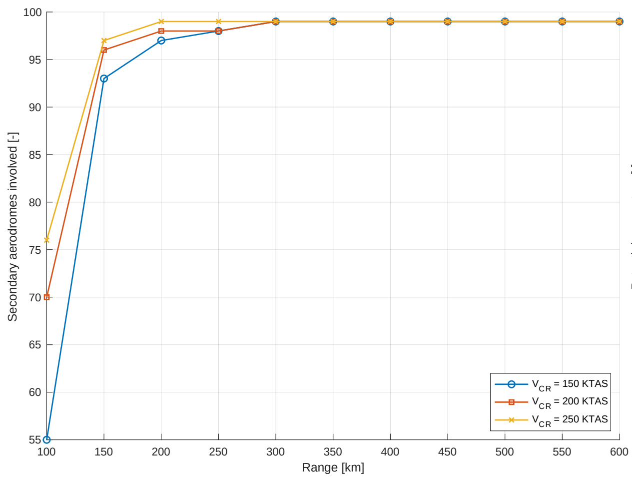
In Figures 3, 4, and 5, the result of this analysis is presented for minimum runway lengths of 600, 800 and 1,000 meters, respectively. As seen, the number of towns (and consequently the total population) involved are not very



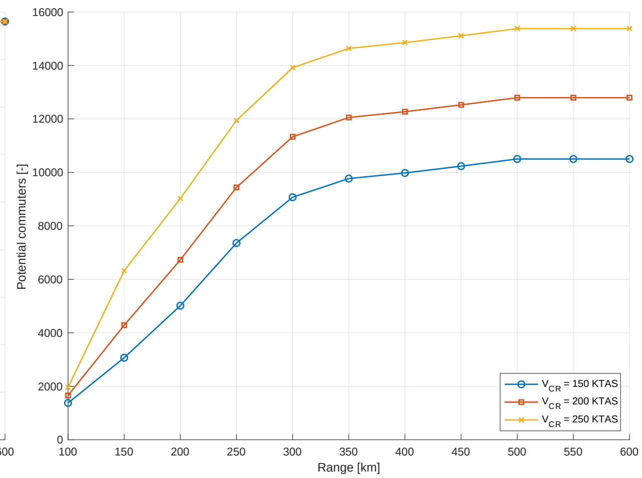
(a) Towns involved.



(b) Total population of the towns involved.



(c) Number of secondary aerodromes involved.



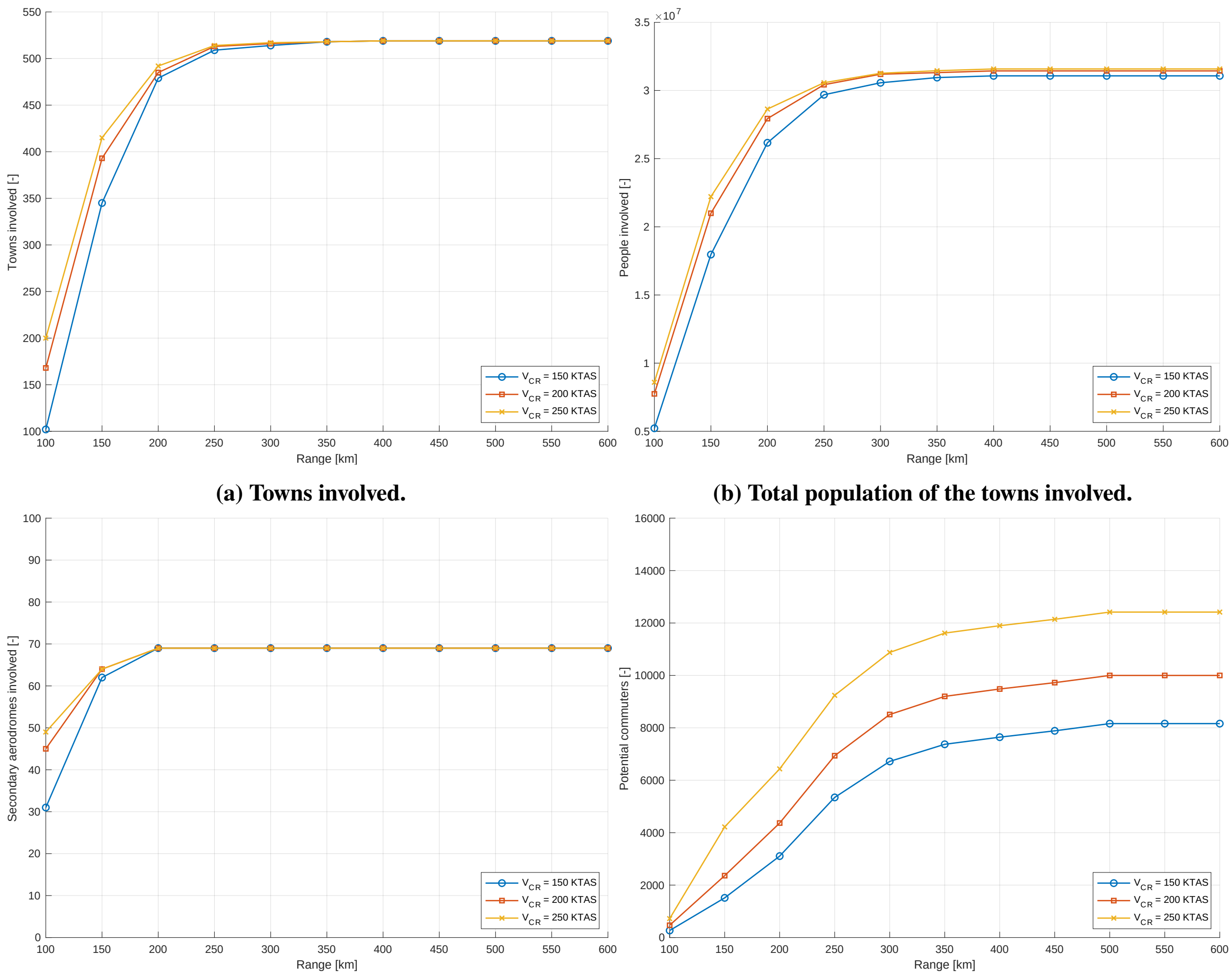
(d) Potential passenger demand.

Fig. 3 Potential demand estimation results for an intercity service in Italy in the case of 600 m long runways for secondary aerodromes.

sensitive to cruising speed and runway length. With respect to range, a saturation is reached for values around 200÷250 km. The behavior of the involved aerodromes is similar, but with the obvious restriction of the runway length, which limits the saturation to the maximum number of aerodromes that meet the requirement.

At first sight, this may seem incompatible with the behavior of the potential passenger demand, which does vary progressively way with range and presents significant variations with cruising speeds and runway lengths. Nevertheless, there is a relatively simple explanation for this apparent discrepancy. Indeed, even at low range values, there is a significant potential demand that spans across the whole Italian territory. Hence, all the aerodromes, towns and population are called into play. For potential commuters, although the towns and the aerodromes they shall transit through are active, the range does not allow for a connection to their destination. Initially, a number of smaller 'isolated' networks are present which, as range is increased, become more interconnected, being able to absorb more demand. Figure 6 shows some examples of this phenomenon by depicting the geographic distribution of towns (yellow marks) and SAs (blue marks) for three cases of 200 KTAS cruising speed, 300 km range and runway length ranging between 600 m and 1,000 m.

Table 1 reports the ten routes with the highest potential demand. The parameters for this study are range of 300 km, cruising speed of 200 KTAS, and runway longer than 800 m.



(a) Towns involved.

(b) Total population of the towns involved.

(c) Number of secondary aerodromes involved.

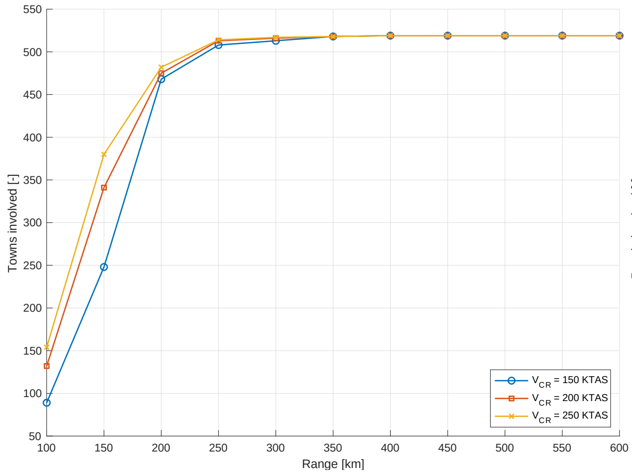
(d) Potential passenger demand.

Fig. 4 Potential demand estimation results for an intercity service in Italy in the case of 800 m long runways for secondary aerodromes.

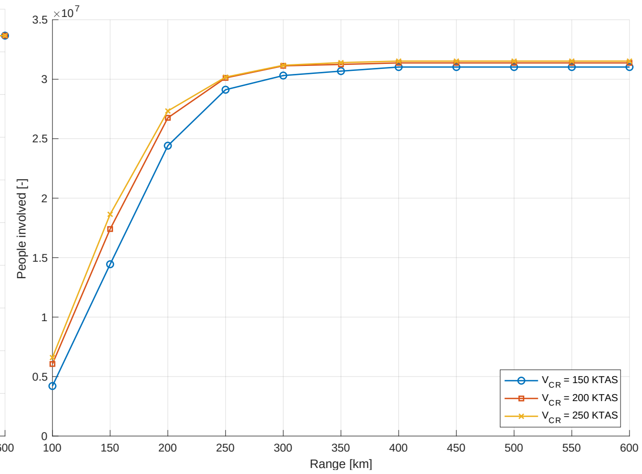
C. Airport times and time gain sensitivity analysis

The effect of the parameters k and t_{ref} are visible in Figure 7, which shows the distribution of the pairs t^{T1-T2} (x-axis) and t_{ic}^{T1-T2} (y-axis). As seen, increasing or decreasing t_{ref} moves up and down the time difference constraint boundary (Eq. 4), represented by the solid black line. However, this constraint has a limited effect, if any, in the current configuration. Modifying k rotates around the origin the time gain constraint boundary (Eq. 3), represented by the dashed black line. In particular, decreasing k makes the boundary steeper and hence, less restrictive. Also, increasing the aircraft performance or reducing the airport times (the latter amounting to 40 minutes), moves down the point cloud introducing more potential town pairs.

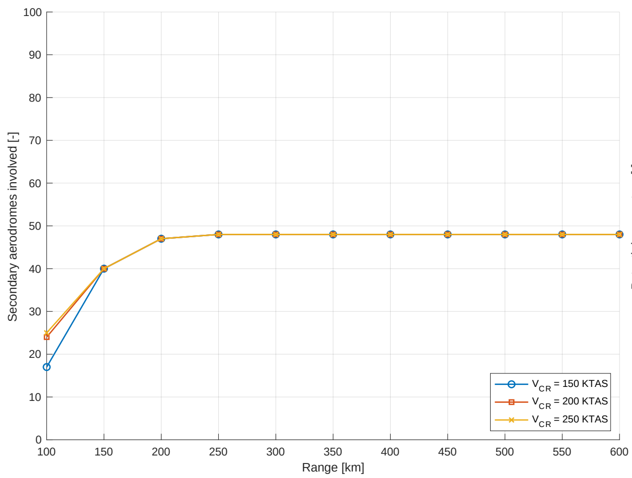
The influence of the airport times (except charging time) and the time gain parameter k has a deep effect on the number of potential travelers. This is presented in 8, where the absolute time difference t_{ref} is not considered due to its lower effect. The rationale behind this study is that nominal airport times were selected with the microfeeder service in mind, in which the passenger continue the trip after disembarking from the miniliner, to take an international flight. In the intercity liner, this is no longer the case. The commuters are expected to be light travelers, so shorter check-in, turnaround and, in general airport associated times could be achieved. Also, time gain expectations may be different for commuters. In the figure, a range of 200 km, a cruising speed of 200 KTAS and a minimum runway length required of 800 m are considered. Airport times are added up and treated as a block. This exposes the considerable impact airport times have on the potential demand. In the trivial case of vanishing airport times, more than 22,000 commuters are



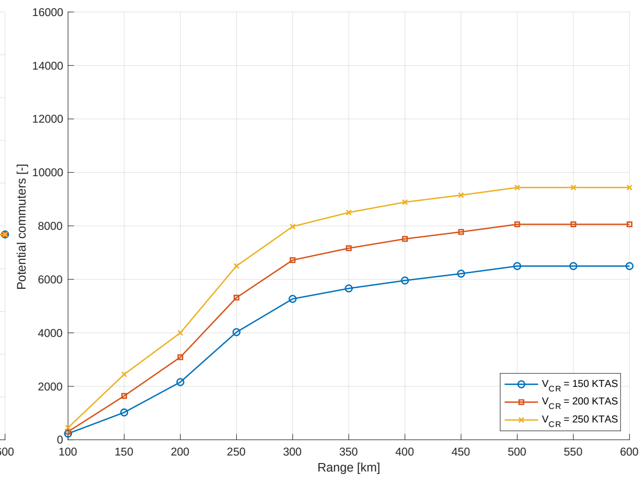
(a) Towns involved.



(b) Total population of the towns involved.



(c) Number of secondary aerodromes involved.



(d) Potential passenger demand.

Fig. 5 Potential demand estimation results for an intercity service in Italy in the case of 1000 m long runways for secondary aerodromes.

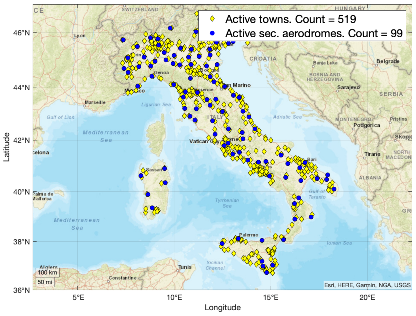
potentially willing to use the service. On the other hand, with airport times between 40 minutes (the nominal value) and one hour, this number is reduced by one order of magnitude, to 1,000÷4,000 commuters. The effect of increasing the time gain parameter k is less relevant and provides an increase in the potential demand that quickly reduces with increasing airport time.

VI. Optimal network definition

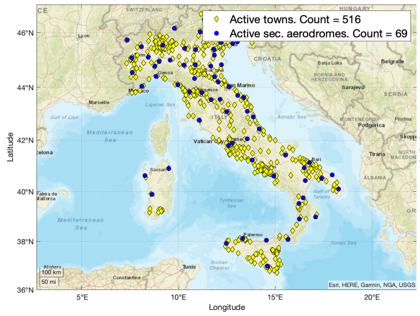
A. Potential demand scheduling

The results obtained above for the potential demand estimation constitute the necessary input for the definition of an optimal route network. To do so, the estimated potential demand must be distributed within the desired time domain, according to the adopted time steps. This implies that the OD matrix introduced above must be completed with information regarding the departure time of commuters. Commuting is a periodic phenomenon within the day. Specifically, a working day can be divided in three parts:

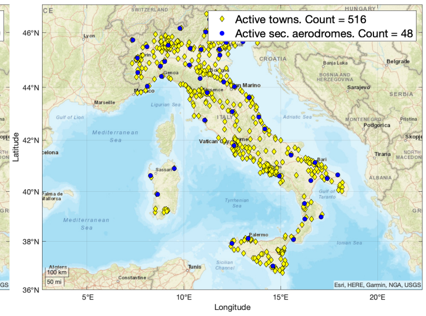
- A morning peak time in which people go to their work/study places.
- A valley time in which no significant traveling is observed.
- An afternoon peak time in which people return home.



(a) **Minimum runway length of 600 m.**



(b) **Minimum runway length of 800 m.**



(c) **Minimum runway length of 1,000 m.**

Fig. 6 Distribution of towns and secondary aerodromes involved in an intercity service in Italy in the case of 200 KTAS cruising speed and 300 km range.

Table 1 Ten intercity routes with the highest potential demand in Italy.

Route	Potential demand
Sessa Aurunca ↔ Roma Ciampino	323
Salerno ↔ Roma Ciampino	236
Firenze Peretola ↔ Roma Ciampino	199
Perugia S.Francesco ↔ Roma Ciampino	162
Lucca Tassignano ↔ Milano Bresso	155
Roma Ciampino ↔ Firenze Peretola	151
Milano Bresso ↔ Firenze Peretola	150
Roma Ciampino ↔ Perugia S. Francesco	130
Firenze Peretola ↔ Aero Club Piacenza	129
Grosseto ↔ Firenze Peretola	124

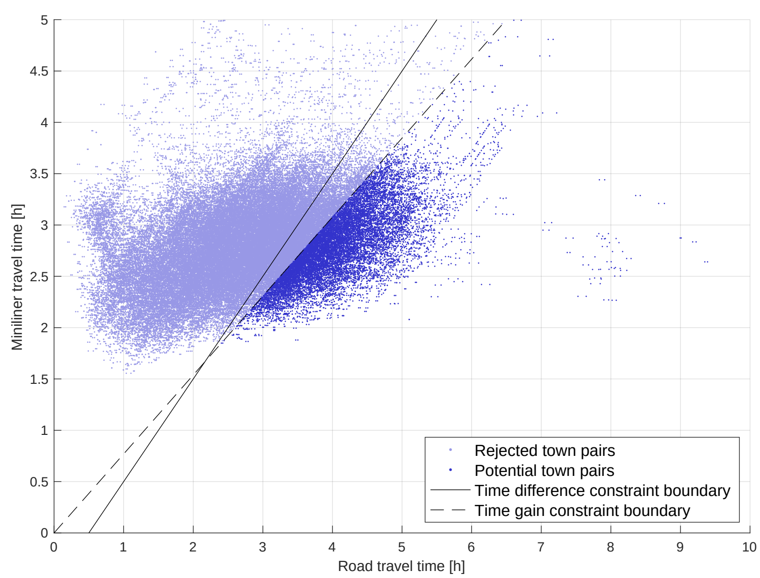


Fig. 7 Miniliner travel time and road time for all the town pairs, including trip constraints.

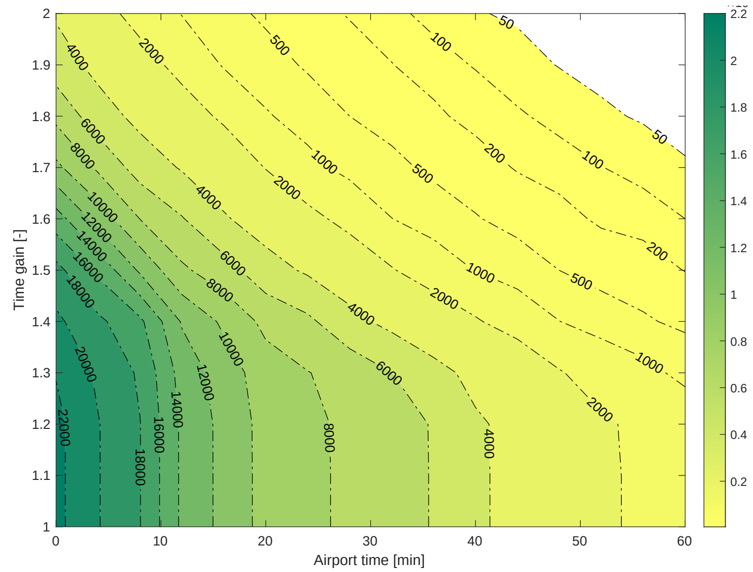


Fig. 8   Potential commuters with respect to overall airport time and time gain parameter.

The Italian commuting pattern is represented in Figure 9. In order to assume that the whole commuting population in Italy is homogeneous with regards to their departure time, an analysis was carried out for a set of Italian regions. To avoid biased results, these regions are selected spanning all of Italy's geographical area, from North to South. Specifically:

- Lombardia, Northern Italy (mainland).
- Lazio, Central Italy (mainland).
- Puglia, Southern Italy (mainland).
- Sicilia, a major island at the Southernmost location.

As seen, commuting can be considered spatially homogeneous across the country, with the following characteristics:

- 27% of commuters leave between 6 a.m. and 7 a.m.
- 50.5% of commuters leave between 7 a.m. and 8 a.m.

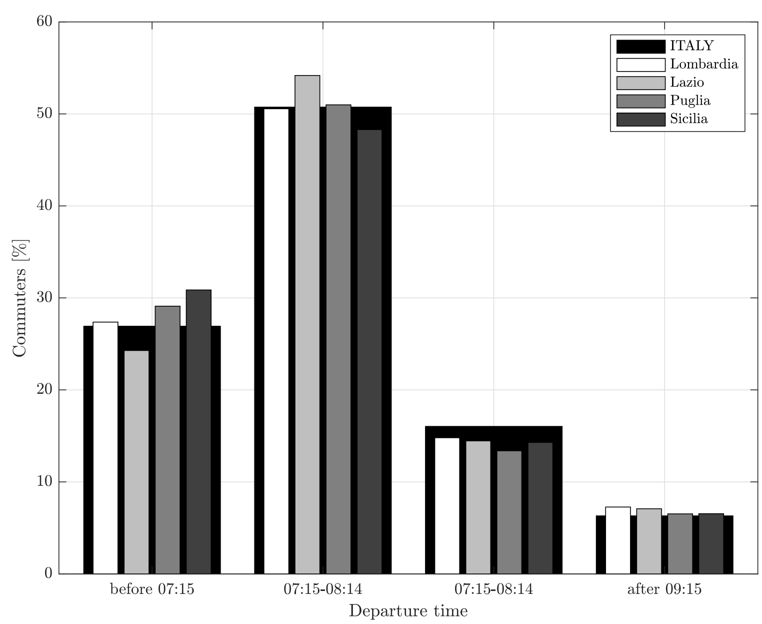


Fig. 9   Distribution of commuters in Italy according to departure time.

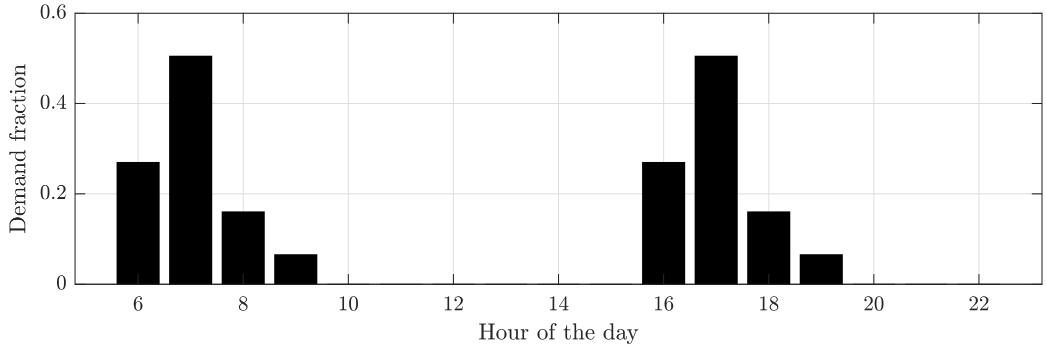


Fig. 10 Distribution of intercity network demand along the day.

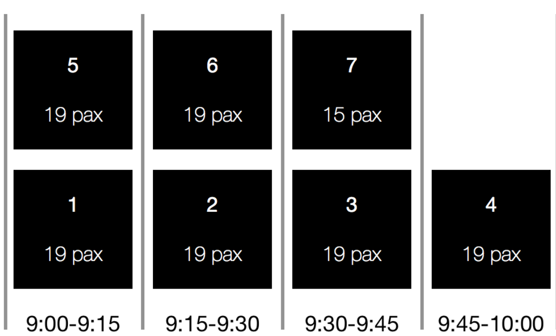
- 16% of commuters leave between 8 a.m. and 9 a.m.
- 6.5% of commuters leave between 9 a.m. and 10 a.m.

The commuting matrix lacks of information about the return time. This forces to make some assumptions about the afternoon rush hour: supposing the first ones to leave in the morning are also the first ones to return in the afternoon seems reasonable. Figure 10 depicts the time distribution of the potential demand along the day according to the discussed assumptions.

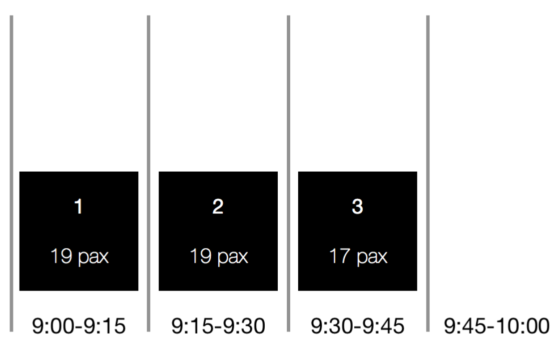
In order to fit the demand data into the set of strings for the string-based MILP model, the demand data must be split according to the different time slots. As these may vary from run to run in both extension and resolution, a flexible way for the splitting has been implemented. If the time slot resolution is one hour or lower, the solution is straightforward as the demand distribution by time is also hourly. However, if the time slot has a finer resolution, which is the usual case, the demand is assigned in packages ordered from the first to the last time slot. These packages have the same capacity as the aircraft. In this way, in the case of only having demand for a single flight, it will be assigned to the first time slot and the rest of the time slot will not have any demand assigned at all. If the demand is enough to fill more than one flight per time slot, the procedure cycles back to the first time slot. As a result, all packages will be full except the last one, which may not be full, provided the minimum load factor is satisfied. In Figure 11, two examples on the functioning of this splitting are shown for the interval between 09:00 and 10:00 a.m.

B. Capturing the traveling demand

This section illustrates an instance of application of the specialized SHARONA location and routing problem, aimed at the definition of an optimal air transportation network system for the Italian short-haul intercity commuting market. The parameters assumed for this exercise are gathered in Table 2. The airplane data (passenger capacity, range, cruising speed) are shown together with other assumptions such ad the minimum trip distance (below such value, land travel is



(a) Case with 129 passengers.



(b) Case with 55 passengers.

Fig. 11 Examples of the splitting of the demand distribution in 15-minute time slots for two values of the potential passenger demand.

Table 2 Input parameters for the network definition exercise.

Parameter	Nominal value
Aircraft capacity	19 passengers
Aircraft range	300 km
Aircraft cruising airspeed	200 KTAS
Minimum trip distance	40 km
Airport times (without battery charging)	2,400 s
Minimum passenger load factor	0.8
Maximum battery discharge per flight	80%
Time frame	06:00 a.m. – 08:00 p.m.
Time slot	30 min

considered more convenient *a priori*), airport time, minimum passenger load factor (at least 16 passengers to allow a flight). The time frame is a full working day, from 06:00 to 20:00, subdivided in half-hour slots. Every airplane can perform only one flight before being recharged, since at the end of each flight only 20% of the battery state of charge is assumed. Two variable parameters are considered: fleet size and battery charging time. The former is considered to vary up to 200 aircraft. The latter is selected to be 0, 30 or 60 minutes. A null charging time is representative of a conventionally-powered aircraft fleet, while 60 and 30 minutes reproduce, in a conservative way, the charging time of current electric land vehicles.

The final results of the network sizing, in terms of captured potential demand are shown in Figure 12. It clearly appears that the fleet size has the most important effect in increasing the captured demand. It is interesting to see that a saturation is reached with a fleet of 150 aircraft. The corresponding value for the captured demand is about 6,000 passengers. The battery charging time appears to have a scaling effect on the number of passengers, in particular with fleets from 20 to 150 aircraft. On the other hand, a smaller influence is observed on the saturation limit. This is around

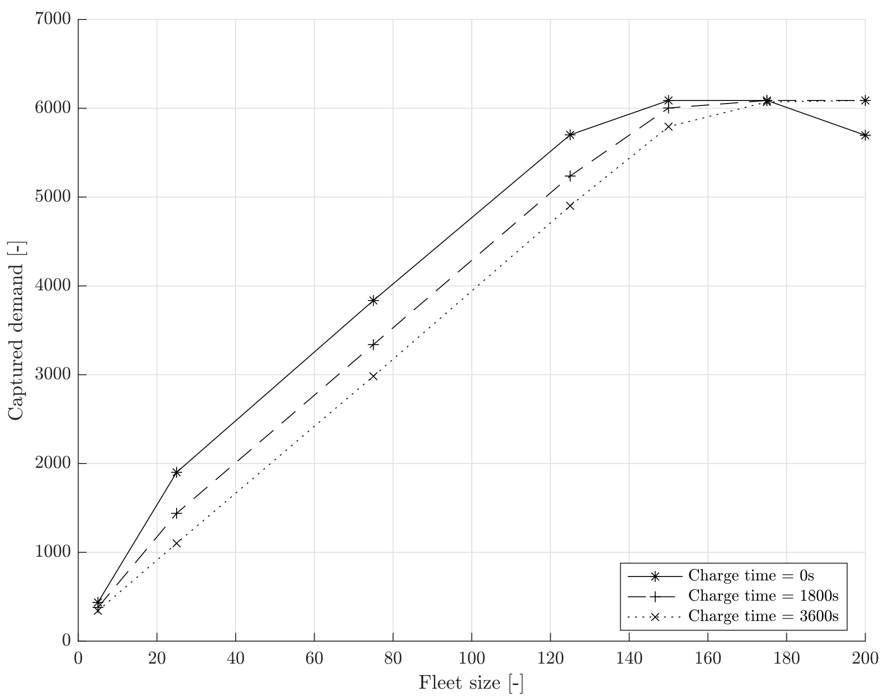


Fig. 12 Captured demand of the optimized network in the full day case for different fleet sizes and charging times.

37% of the maximum theoretically achievable, which is twice the potential demand in Figure 4 (due to the full day simulation and, hence, the addition of the potential commuters in the morning and afternoon OD matrices).

The reason for this relatively low capture is not immediately clear and is assumed to be related to the limited number of available time slots and to the overall size of the time domain. An important role is played by the minimum load factor: since much of the potential demand appears to be distributed in small portions, there are numerous instances of flights that cannot be allowed due to too few passengers. Further investigations are necessary to provide more insight on this phenomenon, aiming to suggest possible strategies to enhance the capturing ability of the network.

VII. Conclusion

A novel methodology to predict the potential traveling demand and define an optimal route network for a future short-haul air transportation system based on hybrid-electric miniliners has been presented. Miniliners may be used in a microfeeder service, as discussed in [13], or in an intercity service for commuting travelers, as illustrated here.

The present discussion is representative of the potential contribution of the SHARONA methodology in the scenario studies for innovative, environmentally friendly, regional air transportation services capable to greatly enhance the citizens mobility, providing an alternative to the development of high-speed land transportation by using the existing, diffuse network of smaller airports and airfields in many regions of the world. These studies are currently carried out in the frame of projects MAHEPA and UNIFIER19, to derive valuable information such as appropriate mission requirements for the design of electric-powered passenger aircraft. In particular, the UNIFIER19 project is devoted to the design of a zero emission 19-passenger aircraft, a community-friendly miniliner, aiming at providing European travelers with a radically new mobility opportunity, towards the 4-hour-door-to-door goal stated in the FlightPath 2050 initiative.

The presented results concerning the potential demand estimation show good prospects for such a miniliner-based transport system. For Italy, up to 15,000 potential users could benefit from such a diffuse point-to-point service. That is obtained assuming relatively conservative aircraft parameters, allowing some degree of adjustment. The optimal network definition provides interesting results, although further studies are needed to deepen the analysis and, possibly, increase the captured demand. In this regard, it is worth noting that the potential users for the intercity miniliner service go beyond commuters, as defined in the national statistics employed. In fact, in this study, commuters are defined as travelers that perform a certain route every single working day. However, many more frequent travelers, who do not commute every day, should be added to the potential customers. For instance, the route Firenze – Roma has a potential demand of 199 commuters based on the OD matrix, but there are currently four daily flights and more than 15 high speed trains only during the morning shift on that route (data for the year 2020 before the COVID-19 outbreak). Including this additional quota of potential travelers will translate into a much larger passenger flow, providing further customers to the miniliner service.

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