AerospaceEurope Conference2020
BORDEAUX, FRANCE | 25 - 28 FEBRUARY 2020
CEAS
HOSTED BY:
3AF

OPTIMAL DEFINITION OF A SHORT-HAUL AIR TRANSPORTATION NETWORK FOR DOOR-TO-DOOR MOBILITY

Lorenzo Trainelli(1), Maurizio Bruglieri(2), Carlo E.D. Riboldi(3), Francesco Salucci(4), Davide Gabrielli(5)

(1)(3)(4)(5) Department of Aerospace Science and Technology, Politecnico di Milano,
Via G. La Masa 34, 20156 Milano, Italy. Email: lorenzo.trainelli@polimi.it
(2) Department of Design, Politecnico di Milano,
Via G. Durando 38/a, 20156 Milano, Italy

KEYWORDS: regional air transport, short-haul route network, micro-feeder, hybrid-electric, optimal approach, location and routing problem

ABSTRACT:

A possible key component in the future development of a more connected transportation network is enhanced regional air travel. A novel class of short-haul airliners may connect smaller cities and open country territories with inefficient ground transportation services to major airports, enabling Europe's Flightpath 2050 vision, which envisages that virtually all EU citizens shall reach any continental destination in less than four hours, door to door, by the year 2050. An ideal candidate is an environmentally-friendly hybrid-electric micro-feeder (HE-MF) aircraft. Therefore, an innovative HE-MF-based transport service is proposed and a framework for maximizing its socio-economic effectiveness is formulated. A computational-intensive, two-stage method for the sizing of the air transport network is proposed. Preliminary results with a focus on the Italian scenario are presented, showing the potential of the proposed approach.

1. INTRODUCTION

A key-element in understanding the applicability and profitability of novel hybrid-electric aircraft is the quantitative analysis of the air transport network they can support [1]. Thanks to the stark reduction in noise and pollution emissions during terminal maneuvers [2], this new type of propulsion system allows operations from secondary airports and smaller airfields 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 the micro-feeder airliner concept [3]. The idea would be for passengers living in larger urban areas or at a distance from major cities and traveling to distant destinations currently reachable from larger hub airports, to start their journey from a local airport, making use of a connection operated by means of a smaller aircraft. This should replace the trip from home to the hub airport, today usually covered by car, train or bus.

As said, the low-emission hybrid-electric technology would play an enabling role for the spreading of this concept. Yet the need to recharge onboard batteries or to stock them on ground, as implied by the adoption of such type of propulsion, has to be coped with through the development of existing ground facilities [4]. On secondary airports, this produces a delicate trade-off scenario, where profitability from air traffic revenues should be sufficiently high to justify the procurement cost of an upgrade of the local airport facility, needed to operate with hybrid-electric aircraft.

In this sense, the quantification of the potential traffic demand in terms of seats traveling from a secondary airport or airfield to a hub airport is of paramount importance to forecast the potential profitability of a given micro-feeding route.

Another relevant aspect in the network sizing problem, with an impact on aircraft design [5], is the effect of aircraft capacity. Clearly, the larger (i.e. higher-capacity) the aircraft, the heavier the batteries and the longer the duration of the battery recharging process. The latter has an impact on time efficiency of the micro-feeder service. In other words, a less frequent service with a larger aircraft may be apparently more efficient from the airline standpoint, but would have a detrimental effect on the flexibility of the micro-feeding transport system from the passenger's perspective – if sufficiently frequent connections to the hub are not offered, the whole micro-feeding system may easily turn time-inefficient for passengers.

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 micro-feeding operators (airlines).

In this research a two-stage hybrid-electric micro-feeder (HE-MF) network sizing method is presented. At this level, this is primarily aimed at better understanding the effects of the many involved variables. The methodology will be described in Section 2, whereas example applications will be shown in Section 3.

2. NETWORK SIZING METHODOLOGY

2.1. Preliminary Analyses and Problem Structure

The starting point for the proposed network sizing algorithm is the definition of the existing and potential airport infrastructures in a geographical area of interest.

Typically, three types of airports can be defined, based on regulations. Major airports, which are most typically adopted as hubs, support a volume above 10,000 passengers per year. Secondary airports are below this volume threshold. Airfields, by far the majority of airport infrastructures in any European Country, are currently distinguished by their inability to support scheduled transport services – a definition likely to change in case they are going to be included in a novel micro-feeding transport network.

Aircraft operating on airfields are subject to weight and capacity restrictions (5,700 kg MTOW and nine seats maximum). Runway specifications and the quality of emergency services also have an impact on the chance of an airfield to carry out public services altogether.

Once the existing (i.e. already in use for public service) and potential infrastructures have been identified, the two-stage network definition procedure, termed HE-MF Location and Routing Problem (HE-MFLRP) and pictorially shown in Fig. 1, is based on the following approach, inspired by the classical four-stage traffic assignment [5].

In the first stage, called MF-PDA (micro-feeder potential demand algorithm), the demand corresponding to each of the secondary airports and airfields is quantified. In this preliminary phase, traffic data for larger airports are used to quantify their capacity in terms of passengers to be fed to the airport, as well as passengers arriving to the hub and traveling to their final destination by means of the micro-feeder network. Furthermore, for secondary airports and airfields the potential capture area needs to be assessed by taking into account local societal characteristics, as well as HEMF aircraft performance and current alternative networks (car, bus or train).

In the second stage, an optimization algorithm is deployed, aimed at maximizing the captured demand by the micro-feeding route network, while minimizing the number of airports active in the network itself. This optimization problem translates in mathematical terms the idea of balancing out the risk associated to the setting up of a new micro-feeding network, by simultaneously making it the most significant for the population and avoiding an excessively high number of secondary airports/airfields to be prepared for public flight operations based on hybrid-electric technology. At this stage, significant parameters are the size of the fleet and the capacity of each aircraft.

As it will be shown in the following sections, the inherent features of the optimization problem require the use of a Mixed Integer Linear Programming (MILP) algorithm.

The output of the HE-MFLRP will be primarily a matching set of active hubs, secondary airports/airfields, micro-feeding routes, aircraft capacity and fleet size.

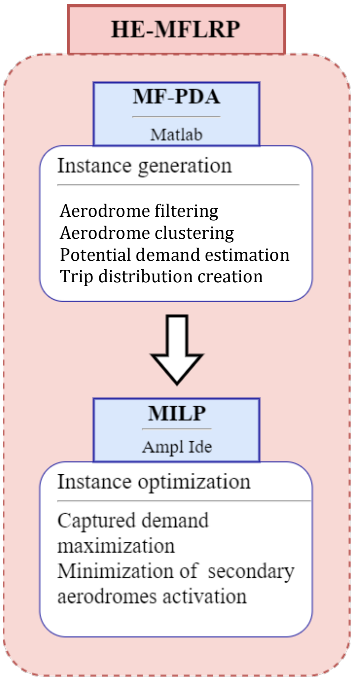


Figure 1. Conceptual scheme of the HE-MFLRP.

1.1. Micro-Feeder Potential Demand Algorithm

In order to preliminarily assess the potential demand for each connection between a hub and a secondary airport, 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 hub airport from a municipal area using the current links and that corresponding to the sum of the time needed to reach a secondary airport/airfield from the considered municipal area using land-based means and the travel time of an airline flight from the nearest secondary airport/airfield (base) to the hub [1].

In quantitative terms, for each municipality on a territory of interest, time t^{T-H} to reach the hub airport using normal means of transportation is obtained by interrogating a public database, as those offered by various internet mapping and navigation services. Similarly, time t^{T-S} for reaching a secondary airport/airfield from the municipal area is computed in the same manner. Time t^{T-S} is then added to the time needed for the micro-feeder to reach the hub airport from the secondary base, t^{mf}. The latter is clearly a function of the flight performance characteristics of an assumed HE-MF, and is composed of a set of components as

$$t^{mf} = t^{c-in} + t^{ta} + t^{to-lnd} + t^{t-in} + t^{t-out} + t^{c} \quad (1)$$

where the variables on the right-hand side are (from left to right): the time durations for check-in, aircraft turnaround, take-off and landing, taxi-in, taxi-out and cruise.

Now, the catchment area for a secondary airport is defined based on the positive evaluation of the following time constraints,

$$t^{mf} + t^{T-S} \leq \frac{t^{T-H}}{2}, \quad (2)$$

$$\left| t^{T-H} - (t^{mf} + t^{T-S}) \right| \geq 600\, s. \quad (3)$$

Eq. 2 represents an imposed, significative time advantage of the novel HE-MF-based transport solution with respect to the usual, purely ground-based one. The constraint in Eq.3 further stresses this advantage, imposing a minimum difference of an hour. This can be explained for instance by considering a possibly higher fare of the micro-feeder solution with respect to a purely ground-based one. Adding a more significant time difference between the two services in favour of the micro-feeder may balance out a possible slight economical shortcoming of this solution.

It should be noted that the comparison between the two mentioned travel solutions to reach a hub airport, even though not involving any optimization, is a computationally intensive problem by itself. For this reason, and for easing the optimization problem to follow by reducing the number of candidate secondary bases (and consequently of the connection routes between secondary bases and hubs), it is recommendable to pre-process the database as follows.

A first simplification is represented by neglecting the municipal areas with a population not reaching a given threshold. Especially in regions where towns are geographically scattered, the demand not computed (lost) due to smaller towns far from secondary airports should not be significant. A second simplification is obtained by clustering secondary airports/airfields together. This can be carried out based on a criterion of geographical proximity, and besides easing the optimization phase, it avoids the unrealistic scenario where two secondary bases very close to each other are both included in the network, feeding the same hub from origins that are just too close to one another (parallel routes).

The application of Eq. 2 and 3 to all considered municipal areas, airport clusters and hubs allows defining a number of connections between hubs and secondary clusters, representing a potential traffic demand. This can be expressed in terms of the total number of passengers P_i with an advantage in reaching the i-th hub via the HE-MF service. However, this datum, based only on demography, may be too little sensitive to the potential interest to travel of the local population. A second factor is thus considered besides demography (population distribution), namely the local distribution of the national gross domestic product (GDP). Therefore, considering the pair represented by the i-th hub and the j-th secondary cluster, the corresponding route is associated to a demographic level D_{ij}, bound to the population size, and to an economic index GDP_{ij}, representing the will/need to travel of the population associated to the route. Based on these parameters, it is possible to define the route value function $F_S(i,j)$ as

$$F_S(i,j) = \alpha \frac{D_{ij} - \min_{j\in H} D_{ij}}{\max_{j\in H} D_{ij} - \min_{j\in H} D_{ij}} + (1-\alpha) \frac{GDP_{ij} - \min_{j\in H} GDP_{ij}}{\max_{j\in H} GDP_{ij} - \min_{j\in H} GDP_{ij}} \quad (4)$$

where H represents the group of all secondary clusters, and α is a tuning parameter defining the relative relevance of the economical or travel need aspect, with respect to a purely demographic datum.

The analysis of the traffic potential of the connection routes need to match with the actual feeding needs of hub airports. This can be quantified easily through the variables P_i^{arr} and P_i^{dep}, retrieved from publicly available databases and representing the number of passengers arriving and departing respectively from the i-th hub hourly.

In order to obtain a match between the actual airport need and the potential traffic quota pertaining to each route connecting the i-th hub with secondary clusters, the following algorithm is proposed.

The values P_i^{arr} and P_i^{dep} are normalized by the population corresponding of the area connected with the considered hub, N, generating the following indices:

$$O_i = \frac{P_i^{arr}}{N}, \quad (5)$$

$$D_i = \frac{P_i^{dep}}{N}, \quad (6)$$

where the values of O_i and D_i represent the hourly number of passengers generated and attracted by the i-th hub, respectively.

Next, the route value functions for all hub-secondary cluster pairs are normalized with respect the sum over the number of secondary clusters, yielding

$$\varphi(i,j) = \frac{F_S(i,j)}{\sum_{j\in S} F_S(i,j)} \quad (7)$$

where S represents the group of secondary clusters.

Finally, the hourly rate of generated (input) traffic on the routes from all hubs to a secondary cluster is defined as

$$o_j = \sum_{i\in H} \varphi(j,i)\, D_i, \tag{8}$$

whereas the hourly traffic rate input on the route from the j-th secondary cluster to the hubs is defined as

$$d_j = \sum_{i\in H} \varphi(i,j)\, O_i. \tag{9}$$

For clarity, the potential hourly demand of the route from the i-th hub to the j-th cluster appears in Eq. 8 as $G_{ji} = \varphi(j,i)\, D_i$, whereas the dual value is $g_{ij} = \varphi(i,j)\, O_i$, appearing in Eq. 9.

Both g_{ij} and G_{ji} are potential traffic demand parameters. Based on airport records, these are usually a function of the time in the day, as airport passenger flow in hubs typically features traffic peaks.

1.2. Optimal Micro-Feeder Network Sizing

In order to obtain the definition of the best possible micro-feeding network, an optimal approach is envisaged, where a suitable algorithm seizes the best solution in terms of the highest percentage of the actual (as opposed to potential) global demand of HE-MF traffic, while at the same time minimizing the number of secondary clusters included in the network.

The mathematical formulation of the problem, and in particular the formulation of the constraints, has been presented in [6]. The parameters included in the optimization as constants are the fleet size, aircraft capacity, the values of G_{ji} and g_{ij} introduced in Section 2.2, the distance between each hub and secondary clusters and the number of hourly movements on each hub.

Furthermore, technology parameters are related to the features pertaining to the hybrid-electric propulsion technology. Concerning energy aspects, the considered scenario is based on the assumption that only the taxi, take-off and initial climb phases are carried out in purely electric mode, hence allowing to associate roughly the same electric energy consumption to all flights (with only slight changes due to the actual weight of the aircraft including payload). Furthermore, the recharging process will take place linearly in time, up to 100% state of charge, and only on hub or secondary airports.

The constant parameters which need to be specified to allow the analytical formulation of constraints related to the energy management of the power-train are the time needed to recharge the batteries (as said, up to a state of charge of 100%), and their discharging rate [7] [8].

The optimization variables included considered in the formulation of the optimal problem include the number of passenger transported between each node of the network (i.e. for each hub-secondary cluster pair) in a given time slot over the day, plus a set of Boolean decision variables, defined for each route, and defining the activation of a secondary cluster and of a route, the need to recharge of an aircraft and the need to arrest an aircraft – the latter happens typically when facing a problem over a large time frame, implying peak traffic requirements are possibly met by a larger number of aircraft, whereas after the peak some aircraft can be momentarily left on ground.

3. CASE STUDIES

3.1. Preliminary Study On Northern Italy Scenario

The network definition algorithm has been tested in the Italian scenario. Due to the high computational intensity of the proposed solution algorithm (for both the potential demand assessment and optimization phases), practical validation results have been obtained at first only for Northern Italy. In Tab. 1 estimated demand parameters for this specific case are reported. The five hubs considered are Milano-Malpensa (MXP), Milano-Linate (LIN), Bergamo-Orio al Serio (BGY), Torino-Caselle (TRN) and Venezia-Tessera (VCE). For the potential demand assessment (Sections 2.1 and 2.2) only municipalities with more than 20,000 inhabitants have been considered.

Table 1. Configuration and demand analysis for Northern Italy.

Number of hubs					5
Number of secondary airports					45
Number of airfields					54
Number of clusters					28
	MXP	LIN	BGY	TRN	VCE
Potential demand (10^3 people)	1,008	1,044	2,243	4,690	3,475
Secondary airports share	52%	44%	45%	53%	49%
Airfields share	48%	56%	55%	47%	51%

In a first stage, results have been obtained without adopting clusters. Due the ensuing high burden in terms of required computational resources, the optimal network configuration was computed separately over increasingly longer time frames over the day, as shown in Tab. 2. The size of the fleet has been kept as a parameter, constant for each optimization run. Similarly, in this example the aircraft capacity has been kept fixed at 19 seats.

As shown in Tab.2, several values of fleet size have been tried, and in Scenario #1, also different values of the route value tuning parameter α, instrumental in the definition of the potential demand (see Eq. 4).

Table 2. Scheme of optimization runs for Northern Italy (no clusters).

Scenario ID	Time frame	Fleet size (min-max)	α	CPU time limit
1	4 h (8-12)	10-120	0.0 0.5 1.0	2h
2	6 h (8-14)	10-50	0.5	3h
3	12 h (8-20)	10-30	0.5	3h
4	24 h	10-30	0.5	3h

The last column in Tab. 2 refers to the maximum allowable computational time for a scenario. This can be set based on experience, since the adopted MILP solver, CPLEX Studio 12.8 implemented in Ampl, should successfully come to a solution rather quickly (clearly, with respect to the size of the problem and computational resources), or rather fail to reach a solution at all. The computation for the scenario presented in Tab. 2 were carried out on a 1.1 GHz Intel Core processor with 8 GB RAM.

The results of several optimization runs performed in Scenario #1 for different sizes of the fleet and values of α, as per Tab. 1 are presented in Fig. 2.

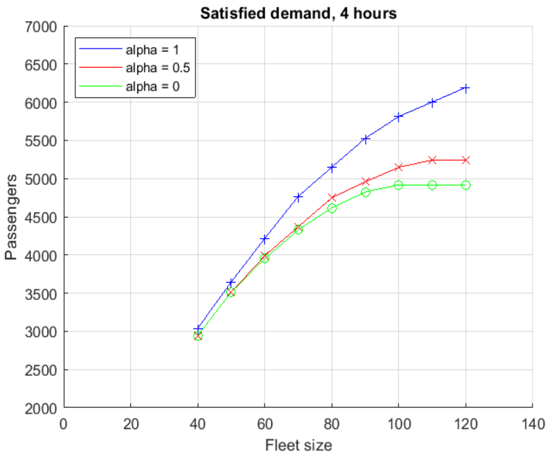
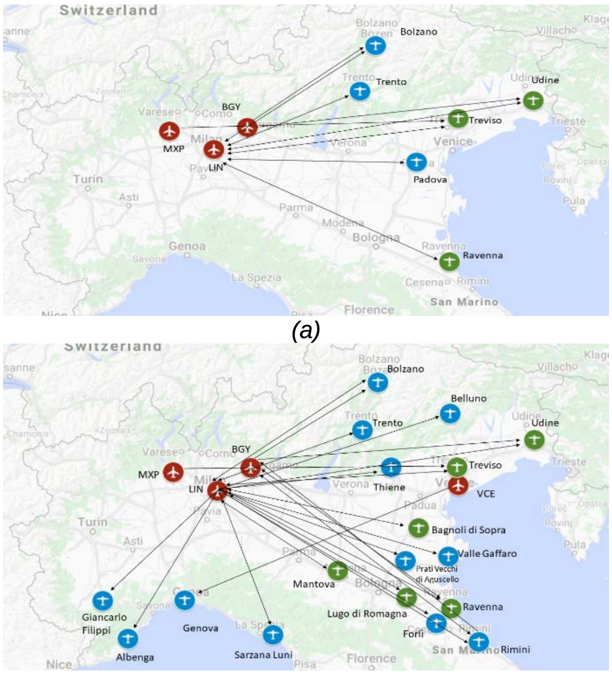


Figure 2. Optimal captured demand for Scenario #1 as a function of fleet size and tuning parameter α.

The saturation effect which can be noticed for larger fleet sizes is due to the saturation of the capacity of hubs in terms of hourly movements (take-off/landing). The effect of the weighting parameter α is felt more for larger fleet sizes, where the GDP factor has a significant lowering effect on the potential demand. For smaller fleets, this effect is less pronounced, and the solutions tends to be more similar to each other, irrespective of the value of the tuning parameter α.

The plot in Fig. 3 complements the previous one, showing the number of airports activated in the HE-MF network depending on the fleet size. This parameter does not show a dependence on α for the specific case analysed.

A synoptic view of the network during the first hour (8-9 a.m.) of operation in Scenario #1 (Tab. 2) for two different fleet sizes is shown in Fig. 3. The number of activated airports corresponds to the data in Fig. 4, depending on the fleet size: 20 aircraft for plot (a) and 80 for plot (b), respectively.



(a)

(b)

Figure 3. HE-MF optimal network between 8-9 a.m. for Scenario #1: (a) fleet of 20 a/c, (b) 80 a/c.

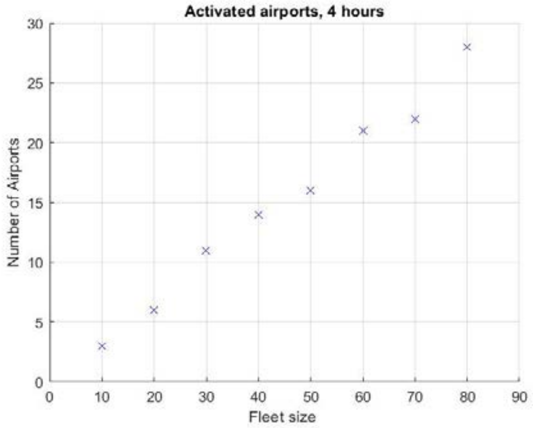


Figure 4. Activated airports in the HE-MF network for Scenario #1.

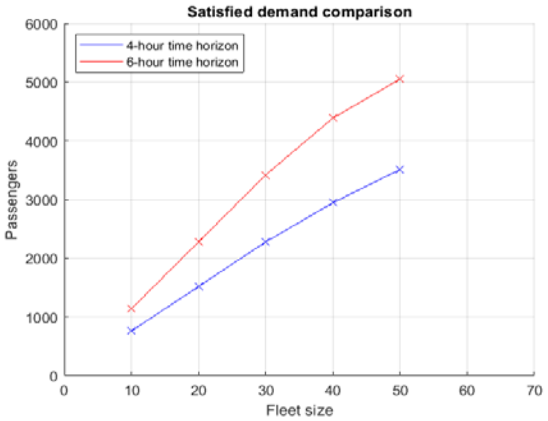


Figure 5. Optimal captured demand for Scenarios #2 and #3, as a function of the fleet size, for $\alpha = 0.5$.

Results for longer time frames (scenarios beyond #1 in Tab. 2) show a progressively higher difficulty of the solver in successfully finding a solution for larger fleet sizes. Fig. 5 reports the only cases where the MILP algorithm successfully produces a solution, considering cases #2 and #3, and for a value of $\alpha = 0.5$.

It can be noticed that no solutions are found for a fleet size over 50 aircraft, as a result of the time constraint imposed on computational time.

3.2. Advanced Studies For The National Italian Scenario

The limitations encountered in Section 3.1 suggest deploying appropriate measures to ease the computation and allow extending the analysis to larger scenarios.

Firstly, as explained in Section 2.2, available secondary bases are collected in clusters, so as to reduce the number of nodes in the network. As an example, a map of the clusters obtained for Northern Italy is reported in Fig. 6.

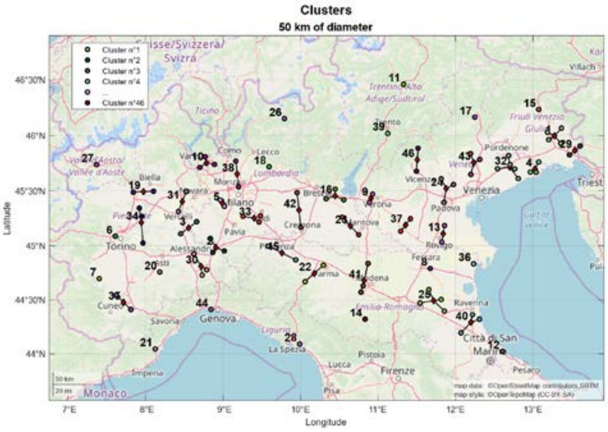


Figure 6. Map of clusters based on secondary bases, Northern Italy.

The size of the clusters for the three main areas of Italy (North, Centre, South) are reported in Tab. 3, together with the corresponding potential demand.

Table 3. Data of clusters for Northern, Central and Southern regions of Italy.

Area	Clusters	Potential demand [pax]	Fleet share
North	28	18,137	25%
Centre	9	39,768	60%
South	11	9,270	15%
Total	48	67,176	100%

Secondarily, the optimization problem is solved separately over shorter time frames, differently from the scenarios introduced in Tab. 2. The adopted maximum time span for the optimization is 6 hours, on account of the limitations noticed in producing the results of Fig. 5.

With these methods, the computation of the optimal network can be carried out on a more extensive territory. Therefore, the whole Italian national territory can be considered. Example results similar in quality to those presented in Fig. 2 are reported in Fig. 7, for a time frame of 6 hours, between 12 p.m. and 6 p.m. for a 19-seater.

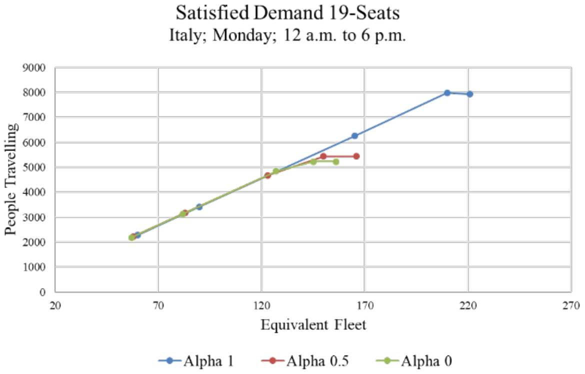


Figure 7. Optimal captured demand for Italy, as a function of the fleet size and for different values of α.

Another effect is that produced by aircraft capacity. Fig. 8 displays the difference for $\alpha = 0.5$ between a solution with nine seats and another with 19 seats. It can be noticed that the same top demand captured by the 19-seater can be meet by the 9-seater, provided the size of the fleet is increased.

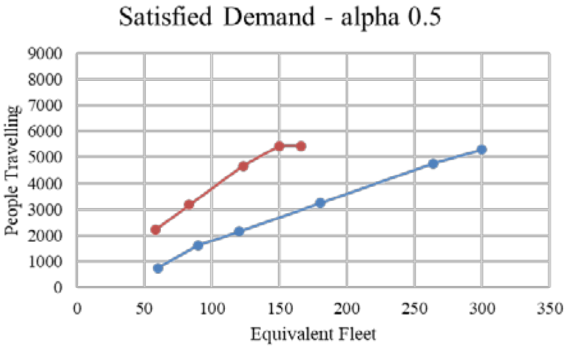


Figure 8. Optimal captured demand for Italy, comparison of a 9-seater and 19-seater fleet, for $\alpha = 0.5$.

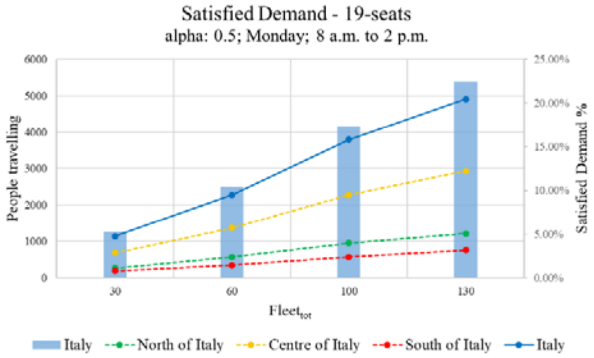
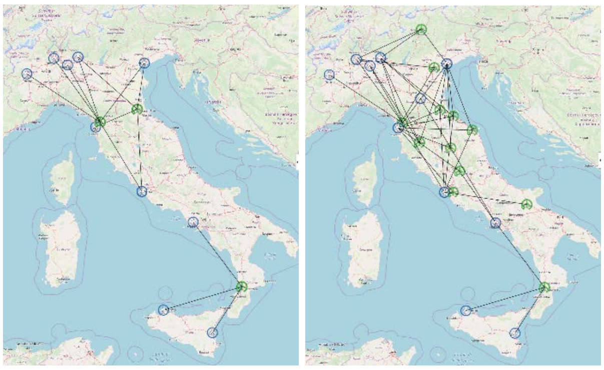


Figure 9. Optimal captured demand for Italy as a function of the fleet size, for $\alpha = 0.5$.

Considering the three regions of Italy separately and the case of the 19-seater, the results in Fig. 9 are obtained, similar in quality to Fig. 7. Besides confirming the same trend with respect to the size of the fleet, it can be noticed that the contribution of Central Italy, where a large part of the population may take advantage of a HE-MF service, in view of the local orography and availability of land-based high-speed transportation means (Tab. 3), makes for the majority of the captured demand.

Finally, a synoptic view of the optimal solutions for the national HE-MF network for two different fleet sizes (30 and 130 a/c) is presented in Fig. 10, again for a 19-seater and $\alpha = 0.5$.



(a) (b)

Figure 10. Optimal captured demand for all regions of Italy as a function of the fleet size, considering a 19-seater and $\alpha = 0.5$

In Fig. 10 blue circles are used for hubs, whereas green ones represent secondary bases (clusters). For the case of 30 aircraft in the fleet, the active hubs are 10 and the secondary bases are three (plot (a)), whereas for the larger 130 aircraft fleet, there are 11 active hubs and 13 secondary bases.

4. CONCLUSION

In this paper the problem of the optimal sizing of a future micro-feeder network based on a hybrid-electric commuter aircraft is considered. A two-stage algorithm is proposed.

In a first step the potential demand is estimated, based on the existing airport infrastructure. This is composed of hubs, secondary airports (nowadays already active), and airfields, which might be upgraded to the role of nodes in the new network, provided this turned out to be profitable. To ease computations performed by the optimization algorithm, secondary bases are collected in clusters. The output of this phase is a potential demand for each connection between a hub and all clusters, based on demography and economics data, and accounting for the actual traffic currently supported by the considered hub airports.

The second stage is centred on the solution of an optimization problem. At the current stage, the number of aircraft in the network and their capacity have been left out of the optimization, and considered as fixed parameters, whereas the number and identity of network nodes and connections have been considered among the optimization variables. Due to the nature of the optimal problem, a Mixed Integer Linear Programming solver was deployed, leading to significant computational performance issues. These can be solved by a proper discretization of the time domain (in terms of hour slots over the day) and by recurring to airport clustering.

The case studies have highlighted the ability of the proposed algorithm to produce interesting results for the scenario of Northern Italy, and for the wider Italian national scenario.

Future steps will include a standardization of the algorithm and the employment of larger computation resources to carry out more complete computations in a timely manner.

5. FUNDING

This research was partially funded by the EU Horizon 2020 research and innovation program, under project MAHEPA, GA N. 723368.

REFERENCES

[1] R. Ibrahim, “Market and cost analysis for hybrid-electric aircraft,” Politecnico di Milano, Milan, Italy, 2018.

[2] C. E. D. Riboldi, L. Mariani, L. Trainelli, A. Rolando and F. Salucci, “Assessing the effect of hybrid-electric power-trains on acoustic and chemical pollution,” in *Aerospace Europe Conference (AEC2020)*, Bordeaux, France, 2020.

[3] A. Rolando, F. Salucci, L. Trainelli, C. E. D. Riboldi and Y. M. Khan, “On the Design of an Electric-Powered Micro-Feeder Aircraft,” in *Aerospace Europe Conference 2020 (AEC2020)*, Bordeaux, France, 2020.

[4] F. Salucci, C. E. D. Riboldi, L. Trainelli and A. Rolando, “Optimal Sizing and Operations of a Battery Recharging Infrastructure for a Regional Airport,” in *Aerospace Europe Conference (AEC 2020)*, Bordeaux, France, 2020.

[5] L. Trainelli, C. E. D. Riboldi, F. Salucci and A. Rolando, “A General Preliminary Sizing Procedure for Pure-Electric and Hybrid-Electric Airplanes,” in *Aerospace Europe Conference (AEC 2020)*, Bordeaux, France, 2020.

[6] C. Papacostas and P. Prevedouros, Transportation engineering and planning, 3rd Ed., Upper Saddle River, NJ: Prentice Hall, 2001.

[7] M. Bruglieri, A. Marchionni and L. Trainelli, “Optimization of the demand satisfied by a micro-feeder hybrid-electric air transport service,” in *25th AIDAA International Conference*, Rome, Italy, 2019.

[8] O. Worley and D. Klabjan, “Optimization of battery charging and purchasing at electric vehicle battery swap stations,” in *IEEE Vehicle Power and Propulsion Conference (VPPC)*, 2011.

[9] Y. Zheng, Y. Dong, Y. Xu, K. Meng, J. H. Zhao and J. Qiu, “Electric vehicle battery charging/swap stations in distribution systems: comparison study and optimal planning,” *IEEE Transactions on Power Systems,* vol. 29, pp. 221-229, 2014.