Optimization of Subsidized Air Transport Networks using Electric Aircraft

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1 Extended Abstract

One of the major challenges faced by today's aviation industry is achieving its ambitious climate goals—as specified in the Net Zero Resolution approved by both airlines (IATA 2021) and airports (ACI 2021) worldwide, committing them to achieve net-zero carbon emissions from their operations by 2050. Over the past two decades, driven by escalating environmental apprehensions, the aviation industry has significantly intensified its efforts in researching and developing strategies to curtail its carbon footprint. The development of sustainable aircraft technologies, particularly in the realm of hydrogen- and electric-powered aircraft, constitutes a fundamental pillar of instruments and initiatives to achieve this target. Specifically, electric aircraft have promising prospects to significantly reduce both atmospheric emissions (i.e., zero CO_2 during operation) and noise emissions (about 36%) (see Schefer *et al.*, 2020), while at the same time fostering air connectivity and accessibility of remote regions.

At the time of this paper, there are over 300 aviation electrification projects with the pioneering aircraft models having a target entry-to-market year as early as 2024 (IATA, 2021). However, first-generation electric aircraft face a major challenge of low battery density, leading to shorter ranges, lower seat capacities, and lower speeds than their conventional fossil-fuel counterparts, which ultimately restrain their fast penetration in dense commercial aviation markets. Nevertheless, electric aircraft present an opportunity to develop sustainable air services for thin markets in the near future. A specific example of these thin markets is regional routes serving remote regions. These routes typically encompass short ranges (i.e., between 140 and 800 km (Graham, 1997, Mueller, 2021)), and exhibit thin demand that cannot sustain profitable scheduled air services when employing conventional small/medium-body aircraft.

Subsidy schemes are widely implemented by governments or transportation authorities in several countries to financially support the provision of air services to/from remote regions (see Fageda *et al.*, 2018, for a review). The Public Service Obligation (PSO) system in Europe and the Essential Air Services (EAS) program in the United States account for the largest number of subsidized routes (320) with a combined annual subsidy spending in excess of US$590 million (Mueller, 2021). Subsidy schemes have been under constant criticism regarding the continuous increase in subsidy spending. This is partly because of the use of small/medium-body conventional aircraft with large seating capacity compared to the thin demand, which in turn results in low load factors (typically below 50%) and high operating costs. In this respect, the deployment of small electric aircraft has the potential to enable a better match of supply and demand. Additionally, the use of electric aircraft has the potential to decrease subsidy costs through the reduction of operating expenses—with estimates indicating a potential reduction of maintenance costs by 20 to 50% and energy costs by 50 to 70% (Heart Aerospace, 2021, RISE, 2021) compared to conventional aircraft. Also, the combination of electric aircraft's lower operating cost and less stringent take-off and landing infrastructure requirements will potentially improve the connectivity of remote regions by taking advantage of both existing and underutilized airports and airfields. Conversely, the constraining attributes of electric aircraft, such as the low speed and range (which affect connectivity), as well as the necessity for charging (calling for new infrastructure and possibly resulting in extended turnaround times), introduce complexities in evaluating their impact and determining their optimal deployment. Thus, adequate planning tools that capture the peculiarities of electric aircraft and thin-demand markets will be essential to suitably inform decision makers toward the set up of optimal subsidized air transport networks using electric aircraft.

In this paper, we propose a novel modeling framework to assist transportation planners in evaluating the benefits and facilitating the efficient utilization of electric aircraft for operating a network of subsidized routes. We first develop an optimization-based approach to redistribute airport demand among the neighboring areas defined as geographical units (e.g., municipalities, counties, or spatial grids of arbitrary size). Leveraging demand estimates at the granular geographical units (instead of at the airport level) is crucial for several reasons: (i) assessing passengers' utility across door-to-door journeys, (ii) comprehensively capturing competing interactions between airports with overlapping catchment areas, and (iii) evaluating the potential connectivity stemming from the utilization of new airports/airfields for extensive electric aircraft operations. Subsequently, we formulate an optimization model that allows investigation of the trade-off between subsidies and the consequent network configurations and service levels, while accounting for the specific attributes of electric aircraft. Ultimately, we validate our approach and showcase its insights through a real-world case study of Sweden.

In summary, this paper makes the following contributions:

1. It develops a quadratic optimization model—referred to as *Demand Disaggregation with Generation and Allocation Properties (DDGAP)*—to estimate the distribution of air transportation demand among geographical units within airports' catchment areas. To accomplish this, the model incorporates reasonable assumptions of air transportation flows, including demand generation and allocation, symmetry of inbound and outbound flows, and correspondence with observed airport-aggregated demand values. The model is formulated with a four-term objective function, where each term expresses the sum of squared deviations from the implied fundamental relationships. The weighting of the different objectives is discussed and validated using real-world data. Ultimately, the DDGAP provides reliable demand estimates at the granularity of geographical units. These estimates stand independent of historical or observed airport choices, serving as a key input for the subsequent optimization model

2. It develops a novel bi-objective optimization model to support the design of subsidized routes using electric aircraft. From a technical standpoint, the model is formulated as an integrated flight scheduling and fleet assignment model for electric aircraft—referred to as *Three-dimensional Flight Scheduling and Fleet Assignment (3DFSFA)*. To accurately account for energy consumption and charging of electric aircraft, we propose the use of a time-space-energy multi-commodity network flow formulation in the context of air transportation, with endogenous aircraft fleet and charging infrastructure. The 3DFSFA optimizes scheduling and fleeting decisions and tracks the allocation of passenger demand to travel itineraries to maximize passenger surplus while minimizing the cost of subsidization. The model outcome is a well-defined air transport network, including its commodities—i.e., the fleet composition and size, and number and location of charging stations—and their deployment across flights or charging activities through an average daily operation. This level of (dis)aggregation allows the accurate estimation of the system costs (including aircraft ownership costs, operating costs, energy/fuel costs, and charger installation costs), which is essential to investigate the trade-off between passenger surplus and subsidy levels, and ultimately guide the design of a network of subsidized routes.

3. It proposes a relaxation approach to efficiently scale the model to real-world instances. The aforementioned 3DFSFA model is a large-scale Mixed-Integer Linear Program, which is hard to solve via direct implementation of off-the-shelf Branch-and-Cut algorithms. We thus propose a relaxation scheme and reformulation of key constraints to obtain close-to-optimal solutions to real-world sized problems in reasonable times. Notably, the proposed approach can be generally applied to time-space-energy multi-commodity network flow formulations with linearly additive cost functions, thus also offering a valid solution approach to a general class of transportation problems involving electric vehicles.

4. It demonstrates the application of the proposed optimization framework using a case study of Sweden's subsidized route network—one of the most expensive in Europe and currently operated by conventional aircraft. We consider three fleet scenarios and investigate different levels of subsidization. Results demonstrate that efficient services require a heterogeneous mix of aircraft. In particular, a hybrid fleet proves capable to synergically exploit the advantages of conventional aircraft—i.e., higher speed and capacity, which impact lower travel times and entail efficient consolidation of passenger flows—and electric aircraft—characterized by

smaller size, lower operating costs and reduced emissions, leading to higher frequencies (hence reduced schedule delays), cost-effective services on very thin routes, and more sustainable services. This, in turn, results in incentive compatible *win-win-win—social, environmental and economic*—outcomes, entailing higher passenger surplus (encompassing a higher coverage and a per-capita reduction in generalized travel cost by -1–5.3%) and reduced direct emissions (-18.2–19%) for the same subsidy spending. In practical terms, our experiments ultimately highlight the capability of the proposed approach to offer valuable decision support to transportation authorities in the strategic planning of subsidized air transport networks.

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