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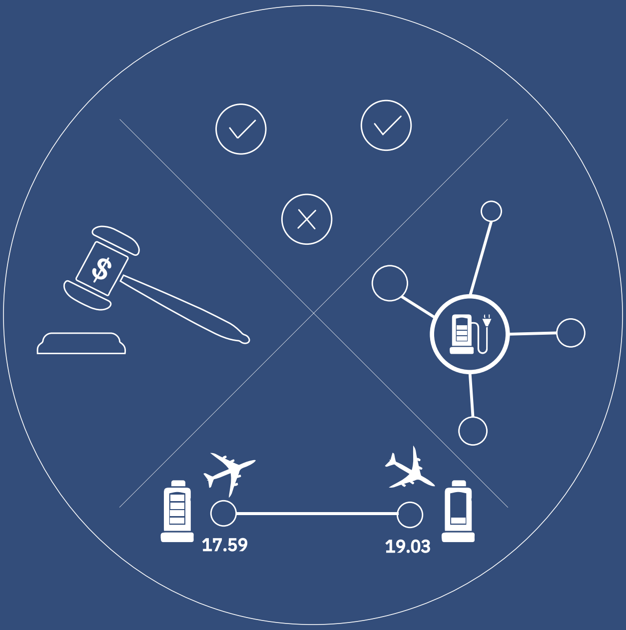
Models for the Procurement of Subsidized Air Services

Conventional Aircraft and the Adoption of Electric Aircraft

Alan Kinene



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Norrköping 2022

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Abstract

In liberalized air transportation markets, governments often adopt subsidy schemes through which they ensure air services along routes that are deemed commercially non-viable but economically and socially essential. The objective of these subsidized air service routes is to ensure a minimum level of services to outlying communities or remote regions that are difficult to access—by other modes of transportation—from the capital, other main cities or a hub airport yet can not be served commercially due to thin demand. Through these subsidy schemes, transportation authorities offer compensation—usually in form of subsidies—to airlines in exchange for air services. Subsidized air services face two main criticisms: their misuse, for example selecting routes that may sufficiently be served by other modes of transportation; and the excessive subsidies spent by transportation authorities. Addressing these criticisms is key for the planning of socially and economically efficient subsidized air service networks. However, decision support models to address these criticisms are scant in both literature and current practice. Furthermore, past studies have naturally focused on models specific to the existing aircraft technology (i.e, conventional aircraft) with no attention towards electric aircraft yet, (1) their uptake appears faster today than predicted, and (2) they are expected to be more environmentally friendly with zero CO_2 emissions during operation) and cheaper to operate than conventional aircraft.

This thesis develops decision support models using the conventional aircraft as well as electric aircraft. Specifically, the thesis contributes with optimization models that can be used by transportation authorities to select the routes to subsidize, to set appropriate level of service requirements that should be met by the airlines (while either minimizing the subsidies or total social cost), and to strategically plan for the adoption of electric aircraft on subsidized routes. The usefulness of the models is demonstrated through applications to the subsidized air service network in Sweden, and this gives three main insights. First, transportation authorities can use an optimization model to improve accessibility of outlying regions to given destinations and at lower subsidy cost. Second, having a requirement on the maximum airfare but not the minimum number of flights provides an appropriate set of service requirements that should be met by the airlines. Third, leveraging the many currently under-utilized regional airports

during the adoption of electric aircraft has accessibility and infrastructure-investment benefits; however, the isolated adoption of a homogeneous fleet of electric aircraft with limited seat capacity, slow speed and short range capabilities is not sufficient to serve remote regions. In the short run—at least until the the battery technology develops further—a hybrid network consisting of both these electric aircraft and the larger, faster and longer range conventional aircraft can be leveraged to provide a better services to the people.

Sammanfattning

På liberaliserade marknader för flygtransport, flygtjänster från och till avlägsna samhällen eller regioner anses vanligtvis vara kommersiellt olämpliga och därför ignoreras av flygbolagen eftersom de har otillräcklig efterfrågan på passagerare för att stödja lönsam verksamhet. Dessa regioner är också svåra att komma åt (t.ex. från huvudstaden eller en navflygplats) med andra transportsätt, men de är vanligtvis ekonomiskt och socialt viktiga för sina länder. Som ett resultat antar regeringar, till exempel i Europa, USA, Asien, Australien, Malaysia och Peru, ofta subventionssystem för att garantera tillgängligheten för dessa regioner till och från resten av landet. Genom dessa subventionssystem erbjuder transportmyndigheter kompensation— vanligtvis i form av subventioner—till flygbolag i utbyte mot flygtjänster.

Trots fördelarna med subventionerade flygtjänster för regional sammanhållning möter de två huvudsakliga kritiker: deras missbruk, till exempel att välja rutter som kan trafikeras tillräckligt av andra transportsätt; och de stadigt ökande totala subventionerna som spenderas av transportmyndigheter. Att bemöta denna kritik är nyckeln till planeringen av socialt och ekonomiskt effektiva subventionerade flygtrafiknät. Beslutsstödsmodeller för att bemöta denna kritik är dock knapphändiga i både litteraturen och nuvarande praxis. Dessutom har tidigare studier naturligtvis fokuserat på modeller som är specifika för den befintliga flygplansteknologin (dvs konventionella flygplan) utan uppmärksamhet på elektriska flygplan ännu (1) deras upptag verkar snabbare idag än förutspått, och (2) de förväntas vara mer miljövänliga med noll CO_2-utsläpp under drift) och 30 till 70% billigare att använda än konventionella flygplan.

Detta examensarbete utvecklar beslutsstödsmodeller som använder både konventionella flygplan och elektriska flygplan. Specifikt bidrar avhandlingen med optimeringsmodeller som kan användas av transportmyndigheter för att välja de rutter som ska subventioneras, för att fastställa lämpliga servicekrav som bör uppfyllas av flygbolagen (samtidigt som de antingen minimerar subventionerna eller den totala sociala kostnaden), och för att strategiskt plan för adoption av elektriska flygplan på subventionerade rutter. Användbarheten av modellerna demonstreras genom ansökningar till det subventionerade flygtjänstnätverket i Sverige, och det ger tre huvudsakliga insikter. För det första, när det gäller valet av rutter att

subventionera, kan transportmyndigheter använda en optimeringsmodell för att förbättra tillgängligheten för avlägsna regioner till givna destinationer (t.ex. huvudstaden och en internationell flygplats) och till lägre subventionskostnader. För det andra, att ha ett krav på högsta flygpris men inte minsta antal flygningar ger en lämplig uppsättning servicekrav som flygbolagen bör uppfylla. För det tredje, att utnyttja de många för närvarande underutnyttjade regionala flygplatserna under införandet av elektriska flygplan har fördelar för tillgänglighet och infrastrukturinvesteringar; Det isolerade antagandet av en homogen flotta av elektriska flygplan med begränsad säteskapacitet, låg hastighet och korta räckvidd är dock inte tillräckligt för att betjäna avlägsna regioner. På kort sikt—åtminstone tills batteritekniken utvecklas ytterligare—kan ett hybridnätverk bestående av både dessa elektriska flygplan och de större, snabbare och längre räckvidden konventionella flygplanen utnyttjas för att ge bättre service till folket.

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Tobias, you have exemplified the kind of mentor/boss that I would like to be. You have always been calm even through my periods of panic, allowed me to fail and learn, always full of ideas, always providing solutions, and readily available to advise. Thank you! Sebastian, thank you for helping me improve my problem formulation and writing. I am so proud of what we have done together and I hope to pass it on to someone else.

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Norrköping, June 30, 2022 Alan Kinene

Contents

Part I

Overview

CHAPTER 1

Introduction

Air transportation boosts socio-economic development through facilitation of connectivity on a national and international scale. The commercial transportation of people (passenger traffic) by airlines started in 1914, and in 1926, governments began regulating it to create market stability. The governments controlled route entry and exit of the airlines, regulated airfares, and awarded subsidies to airlines that operated unattractive routes. As the number of passengers and routes grew, the regulation became inefficient: some airlines with monopolistic practices inflated airfares and there were barriers to route entry for new airlines. Therefore, governments decided to deregulate air transportation—1978 in the United States (U.S.) and 1987 in Europe—such that the airlines could freely choose route airfares, and make route entry and exit decisions based on their profitability.

Profit orientated airlines typically ignore the routes that serve remote regions if they have insufficient passenger demand and are unprofitable (Morrison and Winston, 2010; Williams and Bråthen, 2012). This leads to lack of air connectivity to and from remote regions (Anger et al., 2016). Thus, deregulation impairs accessibility[1] of people in remote regions to and from given destinations, e.g., a major city, a hospital, and a hub or an international airport. Because of the lack of air connectivity to and from remote regions, transportation authorities in Europe, the U.S., Asia, and Australia procure air services to guarantee improved accessibility to these regions.

The procurement of air services, or simply the procurement of subsidized routes, is done within subsidy schemes where the transportation

[1] Accessibility can, for example, be measured as the ability of people from an origin to reach activities in desired destinations, usually within a specified travel time (Litman, 2020).

authorities pay subsidies to airlines that provide these air services along the routes to and from remote regions. The procurement of subsidized air services involves two major tasks: it begins with the selection of routes to subsidize, followed by the selection of airlines to serve these routes (see Trafikverket, 2017). The airlines are selected through an auction between the transportation authority and the airlines, where the latter submit sealed bids for operating a specific route or set of routes. The selected airlines receive subsidies from the transportation authority for serving the subsidized routes. Both the selection of routes to subsidize and the selection of airlines to serve these routes influence the efficient use of the subsidy schemes to improve accessibility to and from remote regions and total subsidies spent by transportation authorities.

1.1 Motivation

For the past two decades, the total subsidies spent by transportation authorities on subsidized routes have increased (Gössling et al., 2017; DoT U.S., 2009). Additionally, there is criticism regarding misuse of subsidized schemes. For example, selecting routes that may sufficiently be served by other modes of transportation such as trains leads to several redundant routes (Lian et al., 2010; Fageda et al., 2018). Designing an auction for the selection of airlines to serve subsidized routes is a crucial and hard task for two main reasons. First, the transportation authorities consider multiple service requirements, for example, the minimum level of service and the maximum airfares, which affect the subsidies paid. Second, it involves multi-agents (e.g, airlines, transportation authorities, and passengers) whose—sometimes conflicting—interests should be accounted for.

Therefore, there is need for models to assist the transportation authorities when procuring subsidized air services. For example, such models may be used to eliminate redundant routes and design an auction with appropriate service requirements, which would minimize the misuse of subsidized routes and reduce the subsidies.

1.2 Research Gaps

Despite the relevance of the route selection and auction design tasks when addressing the criticism regarding subsidized routes,—for example on minimizing the misuse of subsidized routes and reducing the subsidies,—the literature on models to carry out these tasks is scant.

Concerning the selection of routes to subsidize, previous works such as Flynn and Ratick (1988) and Matisziw et al. (2012), have proposed optimization models to assess subsidized route networks by considering multiple factors such as ground travel time to the destination and system-wide subsidy cost. However, these works are focused on the assessment of exiting subsidized route networks, particularly the Essential Air Service (EAS) program in the U.S., but are not formulated for the design of subsidized route networks from both (potential) non-existing and existing routes.

Concerning the design of an efficient auction for subsidized routes, previous literature develops optimization models that take a central planner's perspective with a focus of assessing various levels of service requirements for subsidized routes, while either minimizing the total social cost (Pita et al., 2013; Pita et al., 2014), or minimizing subsidies (e.g., Bråthen and Eriksen (2016)). These works, however, do not specifically capture a key practical aspect of tenders for subsidized routes, that is the presence of several bidding airlines with different characteristics (e.g., fleet mix). Overall, the existing literature lacks an integrated framework to support transportation authorities when designing an efficient tender for subsidized routes, e.g., one that assesses various levels of service requirements while accounting for the multi-agent nature of the procurement for subsidized routes.

The previous literature concerning both the selection of routes to subsidize and designing an efficient tender for these routes have focused on using existing aircraft technology, i.e., conventional aircraft. Although this is a natural approach towards addressing the criticisms for subsidized routes and developing models for the procurement of subsidized routes, it is indeed logical to consider expected technology aircraft technology—specifically electric aircraft.

Electric aircraft present an alternative for addressing the criticisms for subsidized routes. First, although the first generational electric aircraft are challenged by battery technology which results in short ranges on a single charge and small seat capacity, they are more appropriate for thin markets (i.e., with low demand) such as subsidized routes than conventional aircraft that typically have more seats. This difference in seat capacity between electric aircraft and conventional aircraft is further explained in Chapter 2.3. Second, electric aircraft are predicted to be 30 to 70% cheaper to operate than conventional aircraft Heart Aerospace (2021) and RISE (2021) due to lower energy and maintenance cost. Therefore, electric aircraft may open up new and profitable (old and new) business opportunities for serving subsidized routes. However, it is unknown exactly how the adoption of electric aircraft on subsidized routes would affect the procurement of subsidized routes, i.e., the strategic level selection of routes to subsidize and the determination of appropriate requirements for these routes. As existing models are specifically designed for conventional aircraft, there is need for them to be adjusted to capture the planning challenges and potential benefits of electric aircraft along subsidized routes.

1.3 Aim and Research Objectives

Based on the research gaps highlighted in Chapter 1.2, this thesis aims to design models that can be used by transportation authorities to select the routes to subsidize, to design auctions with appropriate requirements for these routes, and to plan for the adoption of electric aircraft on subsidized routes. Specifically, the thesis has the following research objectives (ROs):

RO1. To develop a model that can compare existing and non-existing subsidized schemes, and can objectively select an optimal set of subsidized routes.

RO2. To develop a model that can help transportation authorities choose appropriate tendering requirements by studying how changes in these requirements may affect the subsidies, the airlines and the passengers.

RO3. To develop a strategic planning model that can be used by transportation authorities to make decisions regarding the adoption of electric aircraft on subsidized routes.

1.4 Thesis Outline

The thesis is a compilation of five scientific papers and the remaining chapters are organized as follows. Chapter 2 has an overview of the procurement process for subsidized routes with a focus on the selection of routes to subsidize, the design of an auction for selecting airlines to serve these routes, and the planning implications of adopting electric aircraft on subsidized routes. Chapter 3 describes the key contributions of the thesis linking them to the five associated scientific papers (appended at the end of the thesis in Part II), then summarizes the aim, method, and conclusion for each of the papers. I conclude the chapter with a discussion and directions for future research.

CHAPTER 2

Procurement of Air Services in Subsidy Schemes

This chapter has an overview of the procurement of subsidized routes. It begins with Section 2.1 that describes what subsidy schemes are and gives a description of the four major categories of existing subsidy schemes. In Section 2.2, I discuss the three main stages in the procurement of air services in subsidy schemes. This thesis focuses on two of the stages—the selection of routes to subsidize and the design of an auction for selecting airlines to serve these routes—and they are further described in Section 2.2.1 and 2.2.2 using examples from Sweden. In Section 2.3, the chapter concludes with the planning implications of adopting electric aircraft in the procurement of subsidized air services.

2.1 Subsidy Schemes

A subsidy scheme is an economic intervention that extends any form of financial aid or in-kind support to virtually all sectors (Gössling et al., 2017). In air transportation, transportation authorities use subsidy schemes as a response to the lack of air connectivity to and from small communities or remote regions. The overall purpose of these subsidy schemes is to guarantee air connectivity to and from eligible communities with insufficient demand for commercial air services. Countries use various terms to describe an eligible community for subsidy schemes: remote regions, small communities, isolated communities, and non-commercially viable routes (Fageda et al., 2018; Williams and Bråthen, 2012). In this work, I use these interchangeably because all the subsidy schemes aim to guarantee air connectivity to and from small communities or remote regions with insufficient demand for commercial air services.

Generally, the existing subsidy schemes can be divided into four categories: route-based, passenger-based, airline-based, and airport-based schemes—see Table 2.1 for details. Some countries may have a combination of these schemes. For example, the U.S. and some European Economic Area (EEA) countries, such as Sweden and Norway, have both route-based schemes and airport-based schemes (Fageda et al., 2018).

Table 2.1: A description of the four categories of existing subsidy schemes and examples of implementing countries

Subsidy scheme	Description	Example of implementing countries
Route-based policies	This is the most widely used subsidy scheme and it has been implemented in countries where air transportation is fully deregulated. It imposes a service obligation (e.g. a number of daily flights, maximum airfare and monopoly rights) on specific routes.	Australia, Chile, European Union, Norway, Malaysia, Peru, the United States, India
Passenger-based policies	Governments give discounts to residents, which may be included in route-based policies. These discounts may either be an absolute value or a percentage of the market airfare.	Ecuador, Portugal, Scotland, Spain
Airline-based policies	Governments give financial assistance to airlines—usually state-owned—to support air services to remote regions.	Bolivia, Canada, Colombia, Ecuador, Malaysia
Airport-based policies	Airports receive subsidies for airport programs such as expanding and improving infrastructure capacity. These policies also include incentives (e.g., airport-fees discounts) that are channelled through airports to airlines, to launch new routes.	Australia, Brazil, Canada, European Union, the United States

Source: Adapted from Fageda et al. (2018)

This chapter focuses on the most studied category of subsidy schemes in the literature—the route-based subsidy schemes (Fageda et al., 2018). These subsidy schemes are implemented as short-term contracts of 2 to 5 years between governments and airlines. The contracts may specify the service levels/requirements such as flight frequencies, aircraft type, flight schedules, and route airfares. The governments pay a subsidy (per route) to the airlines for meeting these service requirements. Furthermore, the two major route-based subsidy schemes in terms of the number of routes and the amount of subsidies spent are the Public Service Obligations (PSOs) in the EEA and the Essential Air Services (EAS) in the U.S.

In the EEA, a member state autonomously decides how to impose a PSO on routes that are crucial for economic-social development of a (peripheral) region (EU Regulation, 2008). The PSO is intended to ensure that the provided air services satisfy fixed standards of continuity, regularity, pricing, and minimum capacity that would not be realized if airlines were to commercially assess the routes. In the U.S., the Office of the Secretary of the U.S. Department of Transportation (U.S. DoT) administers the EAS: it aims to guarantee that small communities that had air services before deregulation, maintain a link to the national airport network with a minimum level of scheduled air services (DoT U.S., 2009). Although the decisions of how to impose a PSO on routes or how to administer the EAS to small communities may somewhat differ, the PSO, the EAS, and other subsidy schemes aim to achieve two main objectives: (1) to guarantee air services to/from regions with low accessibility, and (2) to guarantee a connection of all regions to the national air transportation system.

2.2 The Stages in the Procurement of Air Services

Procurement is the act of buying goods and services: it consists of all the activities necessary to acquire goods and services that are consistent with defined requirements (Novack and Simco, 1991). Each country's transportation authority is in charge of the procurement for subsidy schemes with a target to guarantee sufficient and satisfactory provision of transport services to all regions in a country. The procurement of air services in subsidy schemes can be summarized in three stages as shown in Figure 2.1.

The procurement of air services in subsidy schemes begins with an investigation, where the transportation authority identifies regions to benefit from the subsidy scheme, and consequently, selects routes to subsidize. Typically, the transportation authority assesses the need for subsidized routes by regions based on defined accessibility criteria to certain destinations, for example, a major city, advanced hospital, a hub or an international airport, a university, or a tourist site. The criteria are also defined by specific time-related targets. For example, it should be possible to access a capital city within four hours. The regions that lack access to these destinations would be considered as candidates for the subsidy scheme. There are

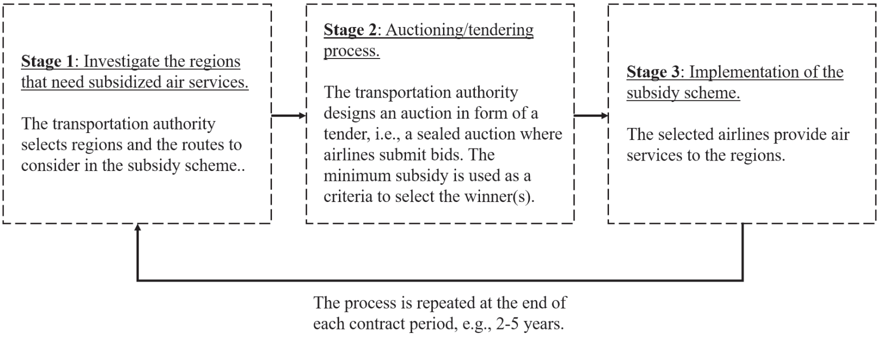


Figure 2.1: The stages in the procurement of air services in subsidy schemes

variations in how the transportation authorities in different countries define these accessibility criteria but they all aim to assess economic, social and territorial cohesion. Table 2.2 gives an example of the eight accessibility criteria used by the Swedish Transport Authority (Trafikverket) to assesses the need for subsidized routes to and from 290 municipalities (Trafikverket, 2017).

Table 2.2: The eight criteria used in Sweden. Each criterion is further described by specific targets a (good) or b (acceptable).

Criteria	Description	Target
1. To Stockholm	Reach Stockholm during the day	(a) Within 4 hours; (b) Within 5 hours
2. From Stockholm	Travel from Stockholm to the municipality	(a) Within 4 hours; (b) Within 5 hours
3. International travel	Accessibility to Stockholm-Arlanda, Gothenburg-Landvetter, Copenhagen-Kastrup, Oslo-Gardermoen and Trondheim-Vaernes airports on weekdays	Travel time is not specified
4. Major cities	Accessibility to Stockholm, Gothenburg, Malmö, Sundsvall, Umeå, Luleå, Linköping, Copenhagen, Oslo or Trondheim	(a) Within 4 hours to at least 1 city; (b) Within 5 hours to at least 1 city
5. Regional/University hospital	Accessibilty to a university or a regional hospital in Umeå, Stockholm, Uppsala, Örebro, Linköping, Gothenburg, Malmö and Lund	(a) Within 3 hours; (b) Within 4 hours
6. University and higher education	Accessibility to higher education in 23 municipalities	(a) Within 5 hours to at least 10 target municipalities; (b) Within 5 hours to at least 5 target municipalities
7. Other major cities	Accessibility to a municipality with at least 50,000 inhabitants	(a) Within 3 hours to at least 3 target municipalities; (b) Within 4 hours to at least 2 target municipalities
8. Tourism	The possibility for at least 50% of the country to reach an essential population center in the municipality	(b) Within 5 hours; (b) Within 7 hours

Source: Trafikverket (2017)

The second stage in the procurement of air services in subsidy schemes is the design of the tendering process. In this stage, the transportation authority needs to prepare tendering agreements for the provision of air transportation services to the regions selected in the first stage. The agreements include requirements to be fulfilled by the airlines. These requirements should be determined by the transportation authority such that they harmonize the interests of all stakeholders (i.e., the transportation authority, the airlines, and the passengers). Commonly used requirements in the tendering process are: (1) minimum number of round trips per day; (2) minimum seat capacity per day; (3) maximum number of stops; (4) time table requirements, for example, a maximum number of days per year with no service; (5) size of aircraft; (6) air emissions of specified substances; and (7) maximum one-way ticket fares (Williams and Bråthen, 2012). Airlines respond to the call for tenders by submitting sealed bids for bundles of combinations of routes from which the transportation authority chooses the best bid for each subsidized route. This stage concludes with the signing of a tendering agreement or contract period—usually ranging from 2 to 5 years.

After the transportation authority designs the tendering process and selects airlines to serve the subsidized routes, the third stage is the implementation of the subsidy scheme. Here, the airlines provide air services to the regions based on the tendering agreements. The transportation authority monitors the essential terms of the tendering agreements, e.g, number of flights, and resolves any possible discontinuation of air services by the airlines. This stage lasts until the conclusion of the tendering agreement or contract period, after which the procurement is repeated.

Both the selection of routes to subsidize through an investigation of the need for a subsidy scheme, and the design of the tendering process for selecting airlines to serve these routes, directly affect the efficient use of subsidized schemes and the subsidies paid by the transportation authorities. These two stages are the main focus of the thesis and I further describe them in Section 2.2.1 and 2.2.2.

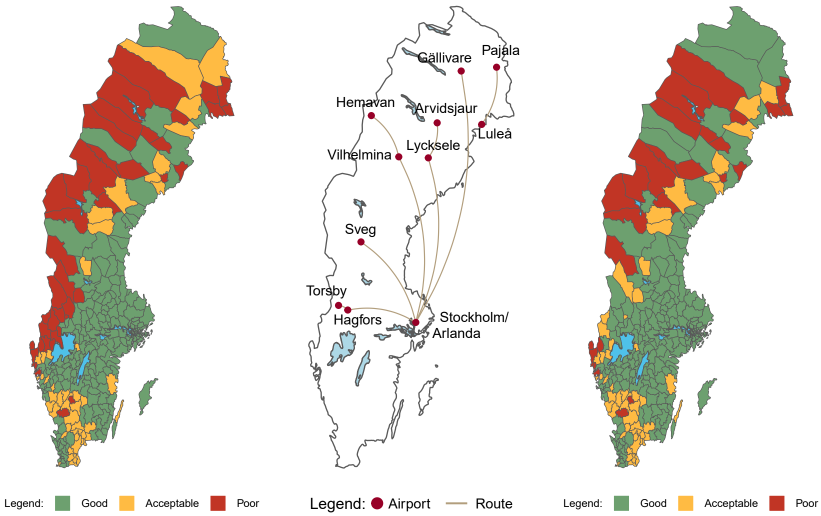
2.2.1 Selection of Routes to Subsidize

The investigation of the need for subsidized air services is done by the respective country's transportation authority through an accessibility analysis of all the country's regions based on defined criteria. The regions with a deficiency in accessibility would qualify to have subsidized routes. The selection of routes for the subsidy scheme should be within the available budget.

To further elaborate on this, I use an example from Sweden, specifically the accessibility criterion to Stockholm. The Swedish Transport Authority (Trafikverket) assesses the need for subsidized routes to and from all 290 municipalities based on the eight accessibility criteria in Table 2.2.

Trafikverket analyses the accessibility of the people in each municipality to each criterion's destination. This is done in two parts.

First, it analyses accessibility in a situation without the subsidized routes. This analysis would for example result in a map as in Figure 2.2a, which presents the accessibility using ground transportation and existing commercial flights, i.e., without any subsidized routes. The analysis is used to identify the municipalities with good (green colour) accessibility, those with acceptable (yellow colour) accessibility, and most importantly those with poor (red colour) accessibility to Stockholm.



(a) Accessibility without subsidized routes

(b) Possible subsidized routes

(c) Accessibility with subsidized routes (*a*+*b*)

Figure 2.2: Investigation of the need for a subsidy scheme based on accessibility

Secondly, Trafikverket selects possible subsidized routes both with a stop and without a stop (see Figure 2.2b) to provide scheduled air transportation services to some of the red-coloured municipalities. This is done to improve the accessibility to Stockholm for some of the municipalities with poor (red colour) accessibility, i.e., to either good (green colour) or acceptable (yellow colour) accessibility (see Figure 2.2c). As Trafikverket has a limited budget, it needs to make a trade-off between maximizing the accessibility of the municipalities for all accessibility criteria and the level of subisidies.

2.2.2 Auction for Subsidized Routes

After the selection of subsidized routes to serve remote regions, the transportation authority needs to find airlines willing to offer air services along these routes. This is done through an auction in form of a tender (sealed bid auction). A tender is a special form of auction where buyers (sellers) submit sealed bids to the seller (buyers) who then selects the winning bids. The tendering process for subsidized routes is illustrated using an example in Figure 2.3, which is based on the subsidy scheme in Sweden for the tendering period of 2015 to 2019

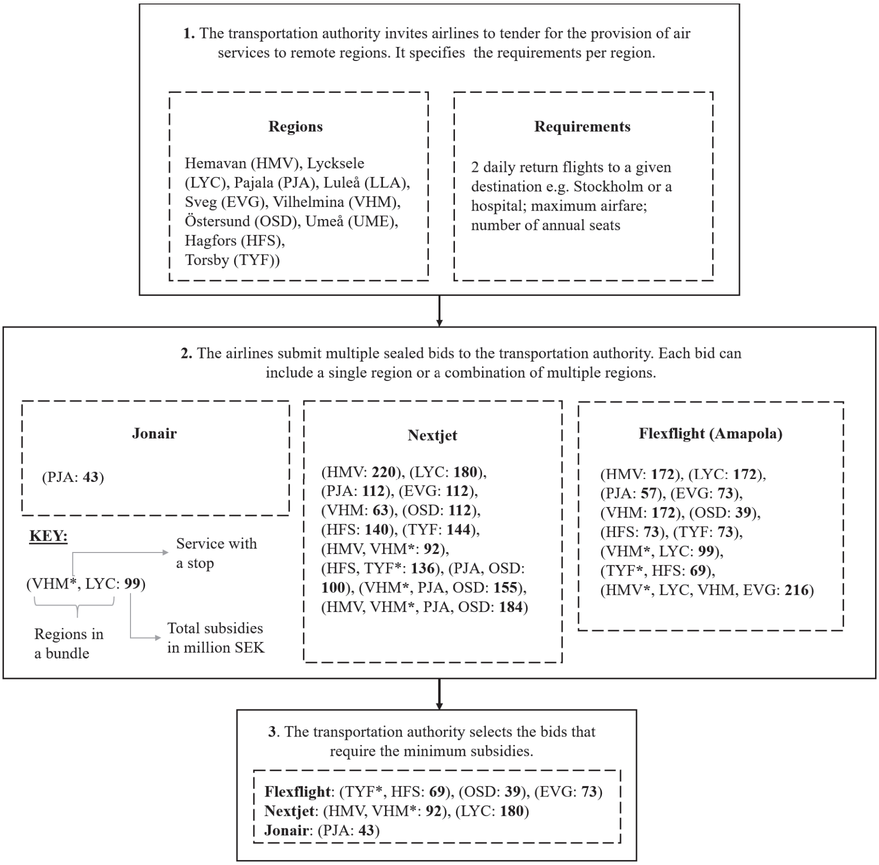


Figure 2.3: The tendering process for subsidized routes based on an example from the Swedish PSO tendering period 2015-2019

First, the tendering process begins with the transportation authority inviting airlines to tender for the provision of air services to remote regions. The invitations to tender are published on official sites, for example, the official journal of European Communities. Sometimes the tenders are defined concerning an airport serving a remote region (e.g., Vilhelmina municipality), while other times, as in Figure 2.3, it is defined in terms of airports (e.g., Vilhelmina airport (VHM)). Also, the transportation authority needs to determine the required level of service for each region. For example, in Sweden, Trafikverket states these requirements: 2 round trips per day for 6 days a week, maximum airfare, minimum number of seats per year, and the aircraft cabins should be pressurized.

Second, the airlines submit multiple sealed bids to the transportation authority. The bids are in form of bundles, i.e., a set of regions (or routes serving regions). Each bundle could include a single route to provide air services to a remote region or multiple routes to provide air services to multiple remote regions (see Step 2 in Figure 2.3). Additionally, each of the bundles is associated with an amount of subsidies required by the airline to provide air services to the associated regions.

Third, the transport authority selects one airline for each region based on an evaluation criterion, usually minimum subsidies. The airline receives a contract that states the expected subsidies—which takes into account the operation cost and revenue generated by the air services—from the transportation authority. For the example in Figure 2.3, Trafikverket selected the bids that cost 496 million SEK for the whole contract period of 2015 to 2019 (Trafikverket, 2013).

The design of the tendering process affects the airlines' participation in the tender and amount of subsidies paid by the transportation authority. For example, airlines in Europe have emphasized the strict nature of the PSO requirements as a major factor that reduces their freedom and discourages their participation in the tendering process (Williams and Bråthen, 2012). Consequently, the number of bidding airlines is worryingly declining in every successive tendering period. For example, in Sweden, the number of bids per route was 4 in the 2002-2004 contract period but reduced to 2 in the 2015-2019 contract period (Dahlström et al., 2018). Furthermore, the subsidized routes in Europe (PSO routes) have been characterized by discontinuous services: several carriers pulled out of their contracts prematurely because of underestimated operational costs for the contracted routes. In some cases, the tender-winning carrier entered into bankruptcy before the end of the contract (Williams and Pagliari, 2004). For example, Sweden's NextJet airline that won the PSO tender illustrated in Figure 2.3 went bankrupt in 2017—2 years before the end of the contract (Dahlström et al., 2018). This is also attributed to the miss-match of stakeholders' interests represented by the PSO requirements, i.e., transportation authority want to minimize subsidies, airlines want to maximize profit, and the passengers want frequent flights at cheap airfares.

2.3 Adoption of Electric Aircraft

The rapid expansion of air transportation since deregulation has generated both socio-economic benefits and long-standing negative environmental effects (e.g., atmospheric and noise pollution). The resulting climate-change pressure makes the mitigation of this environmental burden among the most critical challenges for air transportation. A promising mitigation opportunity is the adoption of Electric aircraft because of their anticipated potential to mitigate both atmospheric (i.e., zero CO_2 emissions during operation) and noise pollution (about 36% (see Schäfer et al., 2019))—compared to current best-in-class fossil-fuel conventional aircraft technology.

In this thesis, the term "Electric aircraft" refers to fixed-wing aircraft that use electric current—stored in batteries (charged by electricity) and/or fuel cells (e.g., hydrogen)—for propulsion. The term may also be used to refer to hybrids which incorporate a secondary energy source such as a conventional fossil fuel or Sustainable Aviation Fuel (SAF). However, in this thesis, I consider only pure-electric aircraft (i.e., with electricity and/or hydrogen as the energy source) because of their zero emissions during operations. I also focus on electric aircraft that are at least capable of regional routes such as subsidized routes. Thus, I exclude other electrified flying vehicles (also known as electric Vertical take-off and Landing aircraft (eVTOLs)) that are designed for urban air mobility.

The uptake of electric aircraft appears faster than predicted with more than 280 active projects (manufacturers and startups) developing electric-propelled aircraft globally (Roland Berger, 2021). Specific to regional routes, the most promising electric aircraft models have entry-in-service dates between 2020 and 2030. For example, the Alice—developed by the Israeli Eviation—and ES-19—developed by the Swedish Heart Aerospace—target certification for commercial aviation, i.e., in 2024 and 2026, respectively (Baumeister et al., 2020; Eviation, 2021).

Electric aircraft present several advantages over conventional aircraft. First, full-electric aircraft have the promise to drastically reduce both CO_2 and non-CO_2 emissions. Second, electric aircraft technology is expected to produce less noise—with a reduction of about 36%—compared to current best-in-class jet-fuel aircraft technology (see Schäfer et al., 2019). Third, a significant reduction the operating cost due to a reduction in energy cost (e.g., 50 to 70%), and lower (e.g., 20 to 50%) maintenance cost (Heart Aerospace, 2021; RISE, 2021)), specifically because of the greater simplicity of electric motors compared to combustion engines (Patterson et al., 2016).

A key challenge facing the adoption of electric aircraft is related to battery technology. Currently, the battery technology for aviation, still has only about 1/70 the energy density of jet fuel. The first generations of electric aircraft will likely be characterized by lower battery energy densities, i.e., energy per unit volume, which significantly increases their Maximum Take-off Weight (MTOW) thus limiting the size and the operating range relative to conventional aircraft. The less energy each battery can store, the more batteries an aircraft will need to reach a desired operating range, which takes up space that could be used for passengers.

According to IATA (2021), the most promising electric aircraft are capable of operating ranges of up-to 1900 km on a single charge and have seating capacity of 9 to 20 seats. Although this implies a generally lower operating range and seat capacity than conventional aircraft, electric aircraft have a higher potential to revolutionize short-haul markets (e.g. subsidized routes) than long-haul markets (Justin et al., 2020). Subsidized routes are a perfect match for the early adoption of electric aircraft. First, they are typically regional routes of range between 160 km and 800 km (Graham, 1997; Fageda et al., 2018), which is a match for the expected operating ranges of the first commercial electric aircraft, i.e., between 161 km and 1900km. Second, they are characterized by thin demand yet they are currently being served by larger conventional aircraft with higher operating cost.

The adoption of electric aircraft on subsidized routes implies fundamental changes to the two main tasks of the procurement of subsidized air services:

Selection of routes to subsidize

Generally, electric aircraft could boost regional connectivity by taking advantage of existing, underutilized airports and airfields hence encouraging the creation of new routes. For remote regions currently depending on subsidized air services to ensure their connectivity, for example to major cities, electric aircraft can improve their connectivity by encouraging the creation of profitable air service—due to lower operating costs and higher load factor[1]—thus reducing the need for public subsidy. This implies that some of the routes that currently require subsidies to be operated, may no longer do so. Hence the models for the selection of subsidized routes should account for this potential improvement in accessibility. First, transportation authorities need to answer key and complex strategic infrastructure decisions: the network of airports (including underutilized airports) to support the adoption of electric aircraft, the location of charging bases while trading off the level of investment, e.g., for revitalizing a given airport, setting-up charging stations, electric wiring on the air-side, and electric-grid upgrades.

Auction for subsidized routes

At the initial stage of the auction for subsidized routes, transportation authorities define the minimum requirements (supply) that airlines should satisfy. The setting of minimum requirements such as the minimum number of flights, the minimum number seats and the maximum airfare are strongly correlated to the tactical planning of airlines. Tactically, the

[1] Also known as passenger load factor (PLF), is an airline industry metric that measures how much of an airline's passenger carrying capacity is used. It is an indicator of how efficiently an airline fills seats and generates fare revenue.

airlines will face scheduling, routing, and fleet assignment problems. The small aircraft size may necessitate more flights (supply) to continue serving the current demand and additional generated demand. More importantly, the short ranges and battery charging times may affect the availability of aircraft thus require additional aircraft, which would increase airline operating cost. Therefore decision models for setting auction requirement for subsidized routes under electric aircraft regime need to capture the operational trade-offs between the pros and cons of adopting electric aircraft as well as the demand-supply interactions. For example, flight scheduling and fleet assignment models that are currently designed for conventional aircraft should be adjusted to capture the key operation characteristics of electric aircraft (i.e., battery energy, small seat capacity, and short operating range) and the complex demand-supply interactions when adopting electric aircraft for subsidized routes.

CHAPTER 3

Research Summary

As stated in Chapter 1, the thesis is a compilation of five scientific papers. This chapter presents a summary of the scientific papers and how they are linked to the aim and research objectives of the thesis, then summarizes the key contributions of the thesis. Finally, the chapter concludes with a discussion of the key contributions and directions for future research.

3.1 Summary of the Included Papers

The five papers in this thesis are related to the three research objectives of the thesis, stated in Section 1.3, as illustrated in Figure 3.1.

Research Objectives 1 (RO1) and 2 (RO2)

RO1 and RO2 focus on addressing the criticisms of subsidized routes using existing aircraft technology, i.e., conventional aircraft. These are addressed in Paper I and Paper II.

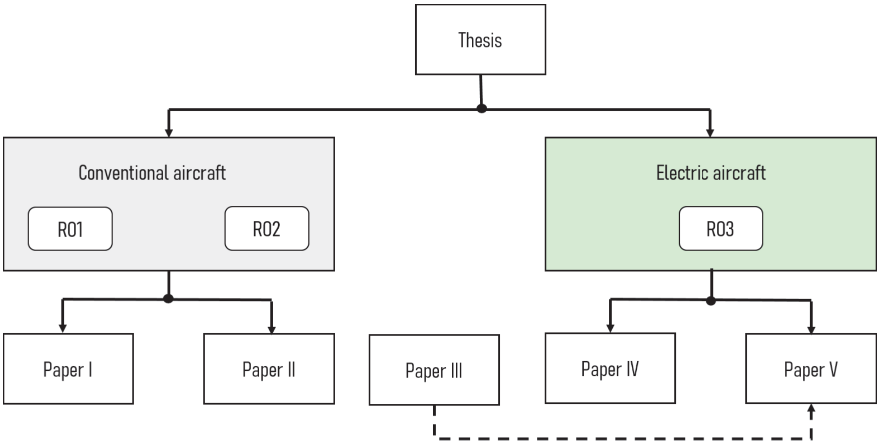


Figure 3.1: The relationship between the research objectives, aircraft technology and the scientific papers. The dashed lines indicate possible practical use of a paper's output.

Paper I: *Decision Support for an Optimal Choice of Subsidized Routes in Air Transportation*

Paper I achieves RO1, i.e., to develop a model that can compare existing and non-existing subsidized schemes, and can objectively select an optimal set of subsidized routes.

The aim of this paper is to describe a mathematical model that assists decision-makers in selecting the optimal network of subsidized routes in air transportation, subject to defined accessibility criteria (e.g., accessibility to a major city, to advanced healthcare, or to an international airport) and a budget. Specifically, we formulated the problem of selecting the routes to subsidize as a budgeted maximum coverage model that is capable of maximizing multiple objectives corresponding to different accessibility criteria. Additionally, we also presented a method to estimate the cost of subsidizing new routes because this is unknown until the auction process is carried out.

We used Sweden as a case study and explicitly modeled two of the criteria used by Trafikverket (The Swedish transport Administration), i.e., accessibility to capital city—Stockholm, and accessibility to an international airport, within 4 hours and 5 hours of total travel time. The total travel time included a combination of ground travel time and flight time (if needed). As subsidized routes aim to improve accessibility of remote regions to certain destinations, the current subsidized routes were compared to the optimal network of subsidized routes suggested by the model using the number of people with improved accessibility. We also considered a scenario where an airport is closed to further illustrate how the model also can be used to make airport location decisions.

The results showed that: (1) although most of the Swedish population already has good accessibility (i.e., either by ground transportation to the final destination or by a combination of ground transportation to the airport, a commercial flight to the final airport and possibly ground transportation from the airport to the final destination), the model can suggest new routes that could further improve accessibility without increasing the subsidization cost, and (2) the closure of an airport reduces the number of commercial routes, which would reduce the accessibility to a given destination; a subsidized route would hence be required as a replacement. The ability of the model to consider several accessibility criteria makes it useful for decision makers at transportation authorities.

This paper was co-authored with Tobias Andersson Granberg, Valentin Polishchuk, and Clas Rydergren. The author of this thesis is the lead author and has contributed to the conceiving of the original idea, to the formulation and implementation (coding) of the model, collection and processing of the data, validation of the results, and writing of the manuscript. The co-authors contributed to the conceiving of the original idea. All authors reviewed and provided critical feedback and helped shape the research, analysis and manuscript.

Paper I is published in the Journal of Air Transport Management (Kinene et al., 2020).

Paper II: *An Auction Framework for Assessing the Tendering of Subsidised Routes in Air Transportation*

Paper II achieves RO2, i.e., to develop a model that can help the transportation authorities choose appropriate tendering requirements by studying how changes in these requirements may affect the subsidies, the airlines and the passengers.

We develop an integrated auction framework—referred to as Single-round Combinatorial Auction for Subsidized routes (SCAS)—to provide decision support to transportation authorities when designing tendering processes for subsidized routes. The framework includes two main models as ingredients. First, the Airline Bid Preparation Model (ABPM), which replicates the airline's behaviour when preparing bids for subsidized routes. Second, the Winner Determination Problem (WDP), which is used to select the bids based on given evaluation criterion. We capture the responsive relationship between passenger demand and supply of air services by including passenger utility as an endogenous variable in the ABPM. Additionally, as input to the ABPM, we estimate the route operating cost for small aircraft that typically operate subsidized routes.

The usefulness of the approach is demonstrated with an application to the network of subsidized routes in Sweden, for which we provide policy guidelines. Our analysis suggests that having a restriction on the airfare but not the number of flights is the best way to design the tendering process. Additionally, we demonstrate that the transportation authorities can compensate not having a requirement on the number of daily flights through ensuring a higher number of passengers, i.e., by including maximization of the number of passengers in the bid evaluation criterion or using of passenger discounts.

This paper is co-authored with Tobias Andersson Granberg, Sebastian Birolini, Nicole Adler, Valentin Polishchuk, and Jean-Marie Skoglund. The author of this thesis is the main author and has contributed to the conceiving of the original idea, to the formulation of the model, collection and processing of the data, implementation (coding) of the model, validation of the results, and took the lead in writing the manuscript. Tobias Andersson Granberg, Sebastian Birolini, Nicole Adler, and Valentin Polishchuk contributed to the conceiving of the original idea. Sebastian Birolini provided the demand data, wrote the demand section and advised on a better model formulation. Tobias Andersson Granberg, Sebastian Birolini, and Nicole Adler verified the empirical results. All authors reviewed and provided critical feedback and helped shape the research, analysis and manuscript.

Paper II is published in Transportation Research Part A: Policy and Practice.

Research Objectives 3 (RO3)

RO3, focuses on addressing the criticisms of subsidized routes using electric aircraft. Specifically, it focuses on developing strategic planning models that (1) capture features of viable electric aircraft technology in the near- to mid-term (e.g., seating capacity, operating range), and (2) can be used used by transportation authorities to make decisions regarding the adoption of electric aircraft on subsidized routes. RO3 is presented in three papers: Paper III, Paper IV, Paper V.

Paper III: *An Optimization Based Approach for Air Transportation Demand Estimation*

Paper III makes a contribution towards achieving RO3. It focuses on airport demand modeling, which is an key input to air transportation planning models. Policy makers and airlines use airport demand estimates and forecasts for airline planning processes (e.g., Paper IV and Paper V).

To better assess how changes in the supply of air services affects the possible generation of new demand (demand generation) and the allocation of demand among existing and new airports (demand allocation), the estimates of air travel demand should be at a region level. As existing models assume or require either expensive and hardly updated stated preference data or dis-aggregated demand data at a regional level, and the available data is aggregated at the airport level. These models can not be trained if the outcome variable, i.e., the demand at the regional level is unknown. Therefore, we propose a quadratic optimization model to estimate the demand at the micro level of population areas based on available demand data that is aggregated at currently used airports. The model is based on reasonable assumptions about demand generation and allocation to better capture the demand-supply interaction.

A real-world application to Sweden demonstrated the calibration of our model when estimating micro level demand from aggregated airport data. The demand estimates are a key input for both strategic and tactical planning processes that require analysis of major changes in a region's airport use and passengers' airport choices. For example, from a regional aviation standpoint, the demand estimates from the model may be used as key input to flight scheduling and fleet assignment models for new aircraft technology such as electric aircraft; thus, fully capturing their connectivity benefits from their expected revitalization of underutilized regional airports.

This paper is co-authored with Sebastian Birolini who conceived the original idea and provided the modeling ideas. The author of this thesis is the main author, has contributed to the formulation of the model, collection and processing of the data, validation of the results, implementation (coding) of the model, and took the lead in writing the manuscript. Both authors reviewed and contributed to the final version of the manuscript.

Paper III is submitted for journal publication.

Paper IV: *Electric Aircraft Charging Network Design for Regional Routes: A Novel Mathematical Formulation and Kernel Search Heuristic*

Paper IV makes a key contribution towards achieving RO3. The uptake of electric aircraft appears faster today than predicted. Given the prominent electric aircraft technologies, short-and medium-haul routes are the ones that will benefit first, with the promise to revolutionize regional aviation at short notice. This paper aims to support the strategic planning of dedicated and enabling infrastructures (e.g., charging facilities) for the operation of electric aircraft on regional routes.

This paper proposes an optimization model to support the strategic design of charging networks for electric aircraft as a key enabling factor to prepare for and take full advantage of aviation electrification. The model, named Electric Aircraft Charging Network for Regional Routes (EACN-REG), defines a network of airports and flight paths to optimally trade-off the number of charging bases (and associated investment costs) with connectivity and population coverage targets typical for regional routes serving remote regions. Due to computational challenges in large problem instances, we propose a Kernel Search heuristic and illustrate how it can deliver high quality solutions for large cases in a shorter computational time than the branch-and-cut algorithms. A real-world application to Sweden then demonstrates the practical insights of the proposed approach; e.g., leveraging the many currently under-utilized regional airports has connectivity and investment benefits (on average +5.6% in population coverage and -8.4% reduction of travel times). Furthermore, increasing the maximum aircraft range on a single charge implies significantly fewer charging bases and more feasible travel options, thus favoring network resilience and granting higher flexibility for later planning stages.

This paper is co-authored with Sebastian Birolini, Mattia Cattaneo, and Tobias Andersson Granberg. The author of this thesis is the main author and has contributed to the conceiving of the original idea, to the formulation of the model, collection and processing of the data, implementation (coding) of the model, validation of the results, and took the lead in writing the manuscript. Tobias Andersson Granberg contributed to the conceiving of the original idea and validation of the results. Mattia Cattaneo wrote the introduction of the manuscript. Sebastian Birolini contributed to the model formulation, conceiving of the Kernel Search Heuristic idea, implementation of the model, and validation of the results. All authors reviewed and provided critical feedback and helped shape the research, analysis and manuscript.

Paper IV is submitted for journal publication.

Paper V: *Flight Scheduling of Electric Aircraft for Subsidized Routes*

Paper V makes a key contribution towards achieving RO3. It aims to assist transportation authorities in designing subsidized air transportation networks under an electric aircraft regime.

We develop a three-dimensional (time-space-energy) Flight Scheduling and Fleet Assignment (FSFA) optimization model for electric aircraft. To account for the low battery density of electric aircraft, we add an energy dimension to the typical FSFA optimization models. For a better assessment of the connectivity benefits of electric aircraft, we redistribute the demand to small areas of origin using the model presented in *Paper IV*. This demand redistribution is important for reallocating demand to currently underutilized regional airports that would be revitalized by the adoption of electric aircraft.

We applied our proposed model to a real-world case study of Sweden and provided insights. The results have revealed that the isolated adoption of a homogeneous fleet of electric aircraft with limited seat capacity, slow speed and short range capabilities is not sufficient to serve remote regions. However, in the short run—at least until the the battery technology develops further—a hybrid network consisting of both these electric aircraft and the larger, faster and longer range conventional aircraft can be leveraged to provide a better services to the people.

This paper is co-authored with Sebastian Birolini with whom the idea was conceived. The author of this thesis is the main author, has contributed to the conceiving of the original idea, to the formulation of the model, collection and processing of the data, implementation (coding) of the model, validation of the results, and took the lead in writing the manuscript. Sebastian has contributed to the formulation of the model. Both co-authors reviewed and contributed to the final version of the manuscript.

Paper V is a working paper.

3.2 Contributions

Collectively, the five scientific papers for this thesis make the following contributions:

1. Develop a budget-constrained optimization model that selects an optimal set of subsidized routes from all possible routes based on given accessibility criteria (**Paper I**).
2. Propose a method to estimate the subsidies of new routes (**Paper I**). This makes it possible to assesses all the possible subsidized routes.
3. Develop an integrated auction framework referred to as the *Single-round Combinatorial Auction for Subsidized routes (SCAS)* for the design of the tendering process of subsidized routes (**Paper II**). Such an auction can help authorities analyze the effect of different tender specifications (e.g., the tender requirements and bid evaluation criterion) on the level of subsidies requested by the airlines. The SCAS includes an Airline Bid Preparation Model (ABPM) and a winner determination model used for the determination of the winners by the authorities.
4. Develop an empirical route-operating-cost model for small aircraft that typically operate subsidized routes as input to the SCAS framework, specifically the ABPM (**Paper II**). We consider turboprops and regional jets with at most 100 seats. This calibration of the cost model provides an accurate representation of operating costs that is specific to subsidized routes.
5. Develop an optimization model to estimate demand at a region level based on aggregated airport level data. These demand estimates are key inputs to the both Strategic and tactical planning models (**Paper III**).
6. Develop a novel strategic-planning optimization model (known as the *EACN-REG*) to clearly communicate infrastructure investments and

connectivity insights, as well as which airports should have charging stations, considering the limited operational capabilities (e.g., range on a single charge) of electric aircraft (**Paper IV**).
7. Develop a tailored Kernel search solution approach that exploits the structure of the the EACN-REG—given its NP-hardness (**Paper IV**). Specifically, it develops an initialization kernel based on network centrality and extend the basic kernel search to allow for the recombination of buckets in multiple iterations to better capture the interaction among airports.
8. Develop a three-dimensional flight scheduling and fleet assignment (3DFSFA) optimization model to accurately account for the energy consumption and charging of electric aircraft and assist transportation planners in assessing the benefits from the potential use of electric aircraft for subsidized routes (**Paper V**).
9. Demonstrate the application and usefulness of the models using the Swedish subsidy scheme as a case study and suggest policy guidelines (**Paper I to V**).

3.3 Discussion and Future Research

Collectively, the papers included in this thesis contribute to the literature on the procurement of subsidized air services by developing optimization models, that consider the conventional aircraft as well as electric aircraft, and are applicable to different regions in the world. These models can provide practical insights to decision-makers during the selection of the routes to subsidize, the setting of appropriate level of service requirements that should be met by the airlines, and the strategic planning for the adoption of electric aircraft on subsidized routes. Furthermore, although presented in standalone fashion, the models provide a foundation for a comprehensive integrated decision support tool where certain model outputs are used as inputs for other models. For example, the optimal set of subsidized routes from **Paper I** could be considered as input for the auction framework in **Paper II**; the region level based demand estimates from **Paper III** can be used as input to **Paper I, II, IV, and V**; and the the flight scheduling and fleet assignment model in **Paper V** can be used to size the number of charging stations at the focal charging bases from **Paper IV**.

In regards to future research, there is two main directions—besides those identified in the papers. First, the utility models used to estimate demand in this thesis make some assumptions—regarding the alternatives—that could be relaxed. For example, in **Paper II**, the potential demand is partitioned into those who do not fly and those who fly. Although this is reasonable, these two categories would be broken down further to more accurately capture the competition between ground transportation, commercial air services and subsidized air service thus allowing a more comprehensive assessment of subsidized air services on passenger welfare. This would require the calibration of a nested logit model, which is well studied in the literature, yet no study has attempted to propose one with a focus on subsidized air services. Indeed, this would require the collection of detailed data (e.g., the frequency and ticket fare of ground transportation) and possibly administering a stated preferences survey. Second, as all the proposed models are deterministic: for example, they consider demand, airfares, cost, as well as electric aircraft characteristics to be certain. Yet, in practice, these tend to be uncertain and change throughout the contract period. Therefore, Stochastic and robust optimization models would be an ideal opportunity for future research. These models have been well studied in the literature but are yet to be applied to the procurement of subsidized air services. Indeed, this would require more comprehensive data than currently collected in several of the subsidy schemes (e.g., Sweden) and would be computationally challenging to solve. As an example benefit, such stochastic models could be used by decision makers to annually adjust service requirements rather than make contract commitments for 2 to 5 years: this would potentially lead to less subsidies.

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Part II

Papers

Papers

The papers associated with this thesis have been removed for copyright reasons. For more details about these see:

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