The Impact of Electric Aircraft Taxiing

A Probabilistic Analysis and Fleet Assignment Optimization to find Potential Cost- and Emission Reductions

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Abstract On-board electric motors can be used to drastically reduce the fuel usage during the taxiing phase of aircraft, leading to cost reductions for airlines and lower amounts of harmful emissions. This study analyses the current state of this innovation and its potential impact on aviation. On a global level, full adoption of electric aircraft taxiing is expected to cause a reduction in jet fuel usage of 846 million kg per year, equivalent to 186 million euros of reduced costs and 2.67 million tonnes of carbon dioxide emissions. This results in a reduction of 0.3% of the total global carbon dioxide emissions of the aviation sector. Locally, airports and their surroundings will benefit significantly from the reduced emissions, because a substantial fraction of airport emissions are due to the taxiing phase. Analysis of the effect of electric aircraft taxiing to key stakeholders such as airlines shows that American airlines would reap substantially larger benefits than European competitors because of consistently higher taxi times in the United States. Low-cost carriers are expected to see smaller impact than traditional hub-and-spoke airlines, due to short taxi times in the secondary airports they predominantly fly to. KLM could save 17.3 million kg of jet fuel annually, representing a cost of 3.8 million euros, which would potentially increase profits by 3%, and a carbon dioxide emission of 55 million kg. Since the road to full adoption is still long, a strategic analysis of the fleet shows the marginal yearly cost reduction per installed electric taxiing system starts at 82 thousand euros for the first product, which reduces to 10 thousand after 100 systems have been installed. Especially the flights between Amsterdam and London, Paris and Manchester should be assigned to aircraft with electric taxiing systems, because these flights would have the most impact given their relatively low flight distance and high taxi times.

Keywords

Sustainable Aviation, Electric Aircraft Taxiing, Probabilistic Distribution Modelling, Fleet Assignment Optimization

Introduction

Cost management and environmental impact are two important pillars in the aviation industry. Airlines and airports around the globe are naturally concerned with the involved costs of operations to maintain desirable profit margins. More recently, another main point of attention has been the minimization of environmental footprint as the general public has identified this sector as a relatively large contributor to global carbon emissions. The European Aviation Environmental Report 2019 (EASA et al. (2019) [1]) estimates this contribution to be 3%. Looking at this industry, the question arises in what ways reductions in emissions and costs can be accomplished. Looking at the main perpetrator, the kerosene engines, Winchester et al. (2011) [2] show that their fuel efficiency can be assumed to improve by 1% on a yearly basis. This compares meagerly to a predicted annual growth of the complete aviation sector of 5%, which is mostly due to wealth gains in highly populated Asian countries. Consequently, other areas of improvement have to be found. This thesis research does exactly that, by taking a closer look at the degree to which electrification can play a role.

More specifically, this research is concerned with aircraft taxiing. Aircraft taxiing is defined as the displacement between gate and runway, both before departure and after arrival. This is one of the flight phases to which improvements can be made in the near future through recent developments, both in terms of costs and in terms of environmental effects such as emissions of harmful substances, e.g. CO_2 or NO_x. The amount of burned fuel certainly has the attention of airlines, as on average a substantial fraction, 30%, of all airline costs in the United States in 2010 originated from it according to the research of the United States Bureau of Transportation Statistics (2011) [3]. In this area, the volatile oil price is of major importance. For that reason, this thesis work takes into account sensitivity analyses covering its effect.

The main area of interest of the proposed research is to find how aircraft taxiing can be improved in terms of costs and environmental effects, examining multiple alternatives to solve the issues at stake and including information that has not previously been used to this end. This area is likely to be the most feasible first step towards an aviation sector with lower environmental effects. Two main solutions have been proposed in the past decade to accomplish substantial reduction in fuel usage in the taxiing phase, both cutting the utilization of the main engines drastically. Aircraft can either be towed by an external vehicle or be propelled by an internal motor designated for taxiing. Both solutions are potentially feasible, but each with differing advantages and flaws. Due to these differences, future airports are likely to combine the two concepts in a balanced way for optimal results.

Out of the possible alternatives, this thesis examines the option of placing an electric motor in the aircraft to minimize emissions. Electric aircraft taxiing is one of the most promising concepts due to its economical and climate-friendly benefits. To gain a more thorough understanding of the exact impact and potential benefits of this concept on a global scale, uncertain parameters need to be estimated. The period of time that aircraft spend taxiing is of vital importance to the impact of electric aircraft taxiing, but taxi times vary greatly within and across airports. This variability should be taken into account when assessing the benefits of electric aircraft taxiing. This study will use probabilistic data on taxi times from airports around the world, both for the taxi-out and the taxi-in phase, and match this with corresponding flight schedule data featuring airline-specific commercial flights. The taxi time serves as major input to determine the amount of fuel burned during this flight phase, which in turn gives information on costs and emissions. Part of this study will be to examine the relevant parameters to determine dependencies between taxi times and its current consequences. Given the limited information provided in the taxi time data, one of the main investigations is to fit suitable taxi time distributions on this data-set. Once these distributions are completely specified, analyses can be carried out to estimate the global potential impact of electric aircraft taxiing.

Two main goals are attached to this research work. Firstly, it is desirable to achieve an accurate estimate of the global impact of implementing electric aircraft taxi systems (ETS) in aircraft. Secondly, an airline point of view is taken to find the optimal fleet adjustments to be made together with the associated impact of those adjustments. Both are accomplished by means of a probabilistic analysis using airport-specific taxi time distributions. In the bigger picture, the goal is to transform the polluting industry of aviation to become more sustainable and at the same time more cost-effective. This would benefit aviation organiza-

tions and the general public.
To design an adequate methodology and to arrive at the results to accomplish the research goals, a set of formal research questions is created. Three main questions follow from sets of sub-questions, of which the first is answered by a literature study (which this paper features a compact version of) while the other two are answered through own analyses.

1. What is the current state of electric taxiing in terms of possible concepts, industry readiness and technical performance?
   (a) What are the various industry solutions for electrifying aircraft taxiing?
   (b) For which aircraft types/models are electric taxi systems suitable and worthwhile?
   (c) How large is the reduction in fuel usage that can be achieved by electric aircraft taxiing?
2. What is the global impact in terms of costs and climate effects of electrifying ground taxiing of aircraft given the distribution of airport-specific taxi times?
   (a) Which approach is most suitable to estimate the global impact of electric taxiing?
   (b) How large is the financial component of the impact of electric taxiing?
      i. What are the most influential factors which determine the financial impact of electric taxiing?
      ii. What is the sensitivity of the impact of electric taxiing to these factors?
   (c) How large is the climate component of the impact of electric taxiing?
      i. Which emissions are harmful and can be reduced by implementing electric taxiing?
      ii. What is the reduction in harmful emissions that can be achieved by electric taxiing?
   (d) How is the global impact of electric taxiing distributed, depending on the variability of airport-specific taxi times?
3. What are the implications of electric taxi systems to key stakeholders?
   (a) For which airlines is electric taxiing worthwhile to invest in?
   (b) To what extent should airlines implement electric taxiing in terms of aircraft in their fleet?
   (c) What are the implications of electric taxiing to the future strategy of airports concerning taxi operations?

The academic relevance of the proposed research lies in the element of using probabilistic information concerning aircraft taxi times to obtain more accurate estimates of the impact of electric taxiing, as this is one of the main variables on which the profitability and feasibility of this concept depends. To achieve this, probabilistic additions and simulation techniques such as Monte Carlo methods as validation will be performed such that the outcome will provide a more thorough understanding than the current one-dimensional estimates in this field.
More practically, the results of the proposed study are targeted to indicate the probability that a certain level of cost- and emission reduction can be achieved by implementing electric aircraft taxiing systems. This is relevant on an industry level because it provides information that enables management boards of stakeholder organizations to make decisions regarding the implementation of this innovative concept. The impact will vary per airline, as it depends on which aircraft models fly from and to which airports at which frequency. This would be new information that airlines have currently no clear view on.
The structure of this paper consists of the standard scientific sections of Methodology, Results, Discussion and Conclusion, but next to that also two sections are dedicated to different topics. As a thorough 56-page literature study has preceded this thesis and serve as its theoretical groundwork, the main findings from that study are summarized directly after this introduction in a Literature section. After that, a special section is dedicated to the sets of data that are used in this research, because this makes it possible for other researchers in this field to reproduce current outcomes for validating other models or to extend this research to arrive at additional conclusions.

Literature

The projected future growth of the aviation industry has been reason for European policymakers to design the future plan termed FlightPath

2050 (European Commission (2017) [4]). One of the main strategic objectives of this plan is to reduce the environmental footprint per passenger kilometer. This calls for rigorous improvements. More specifically, for carbon dioxide, a reduction of 70% is targeted.

To accomplish the set targets, commercial aircraft manufacturers are likely to make a shift in power system dependency (Madonna et al. (2018) [5]). This is due to the widespread trend of electrification, which in the aviation industry is termed More Electric Aircraft, or indeed All Electric Aircraft. The concept of ETS could benefit from this change, as more electric power could become available for it.

Nikoleris et al. (2011) [6] and Perl et al. (1997) [7] acknowledge that aircraft taxiing represents one of the main contributors to the total emissions around airports. The study by Fuchte et al. (2011) [8], performed at Heathrow Airport in London, shows that 56% of the total nitrogen oxide emissions are caused by aircraft taxiing operations, primarily due to the fact that engines are optimized for cruise speed and therefore tremendously inefficient on the ground.

Lukic et al. (2018) [9] conclude that the most promising solution for narrow-body aircraft are on-board systems because they are not adding complexity to airport logistics. It keeps the movement of vehicles on the airport surface at a minimum. The main alternative to this is an external system, which is likely more appropriate for wide-body aircraft models. According to Vaishnav (2014) [10], it is a very difficult logistical task to make sure that aircraft are approached by the towing carts just after landing. Sillekens (2015) shows the tugs can lead to increased congestion on airport surfaces, potentially causing aircraft to be hindered by operational towing vehicles. That study ascertains congestion to be one of the main bottlenecks in a great number of modern airports.

The on-board systems generally include an electric motor, a power converter and an electrical energy source, while the location of implementation can be either in the main landing gear or in the nose landing gear. Golovanov et al. (2016) [11] and Galea et al. (2014) [12] find that the optimal position for the electric aircraft taxiing system would be the main landing gear because of the available space and better traction. Because the landing gear is altered, safety regulations must be checked thoroughly, which is a lengthy process. The research of Okuniek and Beckmann (2017) [13] shows that certification is indeed the largest obstacle.

One of the benefits of on-board systems is the fact that it enables pilots to drive away from the gate autonomously without the need for a separate pushing vehicle. Dieke-Meier and Fricke (2012) [14] estimate this cuts 64 seconds of taxi time . Furthermore, the autonomous push-back could lead to enhanced gate availability, as pilots can already leave the gate directly when boarding has completed.

There are a number of concepts currently in development for ETS, of which four initiatives focus on an on-board system while single-engine taxiing and the towing concept of TaxiBot are not on-board systems.

The four on-board ETS initiatives are the EasyJet Safran Hydrogen-Driven A-16m e-Taxi System, WheelTug, DLR Lufthansa Motor System and the Safran Airbus Electric Taxiing Program. These concepts are described in more detail in the Literature Study associated with this thesis paper, but the conclusion is that even though they are showing potential, they have to be developed further to become industry-ready.

Single-engine taxiing has been proposed as method to reduce emissions without having to change too much. However, Page et al. (2009) [15], Deonandan and Balakrishnan (2010) [16] and Kumar et al. (2008) [17] show that only few pilots embrace this type of taxiing. Moreover, Sillekens (2015) [18] mentions that slopes and requirements for acceleration make this alternative infeasible.

Another alternative to on-board ETS is the TaxiBot, which is an electric tractor with two diesel engines to perform towing operations controlled by the pilot (Lukic et al. (2018) [9]). Basu (2019) [19] shows that this system has an advantage compared to usual towing tugs due to the reduction of brake stress acting on the nose landing gear. Lukic et al. (2018) [9] points out that a driver will still be required for push-back operations, for relocation of the towing tug after each operation and in hazardous situations.

Data

The data required to perform the analyses in this study originate from two sources. Flight schedule data is retrieved from OAG Flights [20], while taxi time data is recorded by Eurocontrol [21]. The flight schedule data contains 680,446 flights that happened in 2010 between 8,357 airports all over the world, involving 824 airlines and 220 aircraft types. The information concerning these flights includes origin airport, destination airport, longitude and latitude of these airports, the associated airline, date and time of departure and arrival, aircraft type and capacity both in terms of seats and freight.

Data concerning the taxi times comes from two data-sets. The first of these is concerned with the taxi-out phase while the other features information on the taxi-in phase. Both are recorded in the summer of 2018 and involve a total of 433 airports. The taxi times are documented in minutes on the basis of five parameters, namely the mean, the standard deviation to the mean and the 10th and 90th percentiles.

Methodology

This section features a description of the steps taken to compute the results needed to answer the research questions. After introducing the assumptions of the model, an explanation is provided of the modelling of taxi times, computing the fuel savings, convolving probability distributions and finally optimizing the fleet assignment including aircraft with electric taxiing systems.

Assumptions

Several assumptions are made to make the analysis possible. Firstly, the fuel flow of the main engines during the taxi phase is assumed to have a mean level of 11.97 kg per minute, while the electric taxiing system would use 2.17 kg per minute, following the research of Wijnterp et al. (2014) [22].

Next to that, the weight of the electric taxiing system is assumed to be 400 kg at the baseline scenario, because this is the maximum design weight across the currently available concepts, namely the weight of the EGTS concept of Safran Technologies. This weight is used to compute the in-flight fuel penalty.

To translate fuel savings to cost reductions, the jet fuel price is assumed to be 0.22 euro per kg, following the Jet Fuel Price Monitor of IATA.

Finally, the warm-up and cool-down times are assumed to be 5 and 3 minutes, following the study of Vaishnav (2014) [10]. As a last assumption, the minimum turn-around time is taken to be equal for all aircraft types in this analysis.

Taxi Time Modelling

For each of the 433 airports in the study, the taxi-in and the taxi-out time is to be modelled. The data provides the necessary distributional parameters for fitting a probability curve, namely the mean, the standard deviation and the tenth and ninetieth percentiles. As found by [23], a Gumbel distribution is most suitable to the modelling of taxi times. Consequently, the initial fit is a Gumbel distribution by using the appropriate mean μ and standard deviation σ to find the right scale β and location λ parameters, as in Equations 1 and 2, in which γ represents the Euler-Mascheroni constant.

$$\beta = \sqrt{\frac{6\sigma^2}{\pi^2}} \quad (1)$$

$$\lambda = \mu - \beta\gamma \quad (2)$$

The next step involves fitting the distribution such that the lower bound of either warm-up or cool-down time are included while the tenth and ninetieth percentiles are correctly included too. This is done by generating a large number of samples from the original distribution, removing the values below the lower threshold and after that adjust the distribution in an iterative manner by removing samples until the percentiles fit, while keeping in mind the mean. The final step involves interpolating the samples histogram, yielding the correct probability distribution.

Fuel Savings and Penalties

For each unique combination of origin, destination and aircraft type, the potential fuel savings are computed by subtracting the in-flight weight penalty from the savings during the ground taxi phases. To find the latter, the taxi time distribution is scaled by the reduction in fuel flow per minute, while the penalty is found by using the empirical form of the Breguet Range equation for the B737 fleet found by Wijnterp et al. (2014) [22], see Equation 3 in which $\Delta W_{A/C}$ and S represent the additional aircraft weight and the flight distance.

$$F_{add} = \frac{\Delta W_{A/C}}{1000}(9 \cdot 10^{-6} S^2 + 0.048S + 2.34) \quad (3)$$

To adjust this to the other aircraft types in the data-set, a set of fuel data is used leading to a fuel factor that is to be multiplied by the penalty.

The penalties are subtracted from the fuel savings probability distributions, such that the final product is a probability distribution providing information about the fuel savings of each flight.

Convolution of Probability Distributions

To find the impact of electric aircraft taxiing on a large number of flights, for example all flight operated by a specific airline or all flights globally, many probability distribution have to be added. The method to accomplish this is called convolution. Mathematically, if two independent distributions X and Y, with probability densities f and g respectively, are combined to form Z ($X + Y = Z$) then the density function h of distribution Z follows Equation 4.

$$h(z) = (f \cdot g)(z) = \int_{-\infty}^{\infty} f(z-t)g(t)dt \tag{4}$$

This principle is performed in an iterative manner to combine larger numbers of probability distributions.

Fleet Assignment Optimization

Once the probabilistic distribution of fuel savings are computed for each origin-destination and aircraft type combination, it is possible to design an algorithm that choose which aircraft are assigned to each of the flights in the schedule while maximizing the fuel savings from electric aircraft taxiing. A formal overview of this assignment optimization is presented below, consisting of the sets, parameters, decision variables, objective function and the necessary constraints.

Sets

- P: Set of aircraft $(1,...,j,...,n_p)$
- A: Set of airports $(1,...,k,...,n_a)$
- F: Set of flights $(1,...,i,...,n_f)$
- ACT: Set of aircraft types $(1,...,l,...,n_{act})$
- F_k^+: Set of flights arriving at airport k
- F_k^-: Set of flights departing from airport k
- $F_k^+(\theta)$: Set of flights in F_k^+ such that $t_i^+ < \theta - \Delta t$
- $F_k^-(\theta)$: Set of flights in F_k^- such that $t_i^- < \theta$
- $F_{OT}(i)$: Set of flights operated by a different aircraft type than flight i

Parameters

- t_i^+: Arrival time of flight i
- t_i^-: Departure time of flight i
- Δt: Minimum turn-around time
- c_{ij}: Cost function (fuel savings from flight i if assigned to aircraft j
- a_j^0: Airport at which aircraft j starts its schedule

Decision Variables

- x_{ij}: Binary variable equaling 1 if flight i is assigned to aircraft j, 0 otherwise

Objective Function The objective is to maximize the fuel savings (FS) of the system:

- $Max\ FS = \Sigma_{i \in F} \Sigma_{j \in P} c_{ij} x_{ij}$

Constraints There are five constraints required for the optimization algorithm to function. The first constraint makes sure that not more than one aircraft is scheduled per flight.

The second constraint causes airport continuity for all airports except the starting one. In this way, An aircraft can only leave an airport if it has landed there at least one turn-around time earlier. The mathematical method to achieve this deserves a more extensive explanation. What the algorithm does is check for each departing flight whether the number of arrived flights minus the number of departed flights is zero or one. An aircraft can only be assigned to flights for which this number is one.

Constraint 3 is similar, but specifically targets the starting airport. The main difference being that the starting airport starts off by having one more departures than arrivals.

Constraint 4 makes sure that there is continuity in the aircraft type per aircraft with ETS. It dictates that an aircraft can only be assigned to a flight, if the designated aircraft type for that flight corresponds with the aircraft type of other flights assigned to that aircraft. To clarify the mathematical formulation: if a certain ETS aircraft is assigned to a flight, the corresponding decision variable x_{ij} will be 1. Consequently, the right-hand side of the constraint becomes 0, such that the left-hand side also must be 0 or lower. Looking at the left-hand side, this means that the summation of all flights with a different aircraft type specification cannot be assigned to the ETS aircraft in question. On the other hand, this limit

is raised to n_f if the decision variable is 0, such that the summation in that case could include all flights of other aircraft types.
Lastly, the fifth constraint causes the decision variable to be strictly binary.

1. $\Sigma_{j\in P} x_{ij} \leq 1$ for $i \in F$
2. $\Sigma_{i'\in F_k^+(t_i^-)} x_{i'j} - \Sigma_{i'\in F_k^-(t_i^-)} x_{i'j} \geq x_{ij}$ for $i \in F_k^-$, $j \in P$, $k \in A/a_j^0$
3. $\Sigma_{i'\in F_k^+(t_i^-)} x_{i'j} - \Sigma_{i'\in F_k^-(t_i^-)} x_{i'j} \geq x_{ij} - 1$ for $i \in F_k^-$, $j \in P$, $k = a_j^0$
4. $\Sigma_{i'\in ACT} x_{i'j} \leq (x_{ij} - 1) \cdot (-n_f)$ for $i \in F$, $j \in P$
5. $x_{ij} \in (0,1)$ for $i \in F$, $j \in P$

Results

This section presents the results of the performed analyses and follows the structure of the methodology above. The most crucial figures and tables resulting from the analyses are shown, but it should be noted that the created models could be used to yield more extensive results. For example, the airline KLM is chosen as main focus point, but any of the 824 airlines in the data-set can be looked at in a similar manner in more detail using the developed models.

Taxi Time Modelling

The distribution of taxi times, both at departure and at arrival, is modelled using the Gumbel distribution. For each of the 433 airports, the program computes the distribution such that it fits the input data. Figures 1 and 2 show the taxi-in and taxi-out time distribution at Amsterdam Airport Schiphol, respectively.
The curves show that taxiing times before take-off are considerable longer, with mean 13.9 minutes compared to 8.0 minutes at taxi-in, and contain more outliers causing a heavier right-side tail. The origin of this difference is likely the presence of situations in which aircraft have to wait due to delays in earlier departing aircraft, airport traffic jams so to say, while arriving aircraft spend their delayed arrivals loitering around the airport in designated airspace [24]. The lower bounds of the figures indicate the parameters used for warm-up and cool-down time.
The difference in taxi times between airports can be substantial. Table 1 shows an overview of the difference between the three most and the three

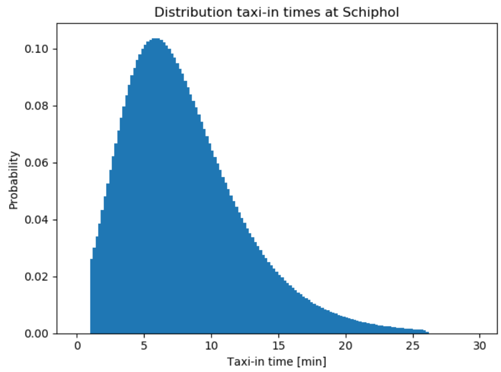

Figure 1. Distribution of taxi-in times at Schiphol.

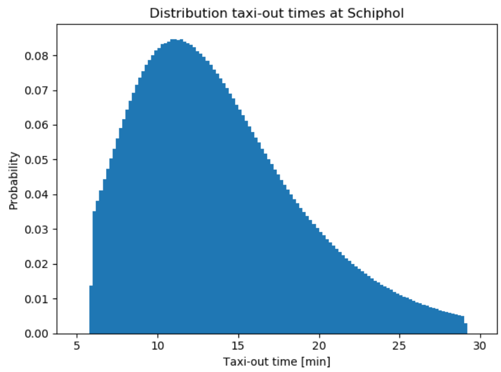

Figure 2. Distribution of taxi-out times at Schiphol.

least efficient airports in terms of mean taxi-out times. Especially at the high taxi time airports, electric aircraft taxiing has serious potential to reduce costs and emissions because every minute of taxiing the main engines burn kerosene.

Airport (IATA Code)	*Taxi-out time [min]*
New York (JFK)	34.6
Philadelphia (PHL)	29.2
Washington (IAD)	28.7
Mosjoen/Kjaerstad (MJF)	2.2
Svolvaer/Helle (SVJ)	2.2
Stokmarknes/Skagen (SKN)	2.0

Table 1. Top three and bottom three airports in terms of taxi-out time.

Global Impact

By using the airport taxi time distributions together with the flight schedule, a global estimate of the impact is computed. Combining the large number of individual distributions forms a normal distribution with a mean of 846 million kg of fuel that could be saved on a yearly basis if electric aircraft taxiing would be adopted on a global scale. This translates to 2.67 million tonnes of carbon dioxide emissions that could be reduced. This appears to be in line with the estimate of Vaishnav (2014) [10], stating the United States domestic aviation industry could save 1.5 million tonnes of carbon dioxide, representing 1% of the total aviation emissions. In terms of costs, the currently low oil price (0.22 euro/kg jet fuel) causes the total cost reduction to be 186 million euros. The question is whether this cost reduction is worthwhile for airlines. This might differ per airline, which will be discussed later in this section.

Impact on KLM

A detailed analysis of the situation at the Dutch airline KLM yields the outcome that a 100% adoption of electric taxiing systems brings a reduction of 17.3 million kg of fuel annually, representing a cost of 3.8 million euros. The average profit of KLM in the years 2011-2018 has been 128 million euros. That means the theoretical impact of electric aircraft taxiing on KLM could be an improvement of 3% on its annual profits. Even though that is purely the fuel cost side of this operational change, without taking into account potential costs for acquisition, installment and maintenance, it still is a substantial change for the better. Combined with a carbon emission saving of 55 million kg, it should absolutely be considered for the future.

Before making large investments to bring about the full fleet transformation from old-fashioned jet engine taxiing to electric taxiing, airlines are likely experimenting on a smaller scale with such innovation projects. For that reason, it is interesting to look at the impact per aircraft or per flight. At first, the probability distribution of impact per flight is shown in Figure 3. Then, later on in this section, results will be presented showing optimal adoption strategies in terms of flight network and how many aircraft to transform. In the flight schedule used in this study, KLM features a yearly 161 thousand flights. This means that the mean fuel reduction per flight lies at 107 kg, as can be seen in the figure. Again, the probability distribution appears to be normal and this is caused by the convolution of many different distributions. This is dictated by the Central Limit Theorem (CLT). The uncertainty related to the mentioned mean fuel saving is indicated by the curve. The 95% confidence interval is fixed at [97, 118] kg jet fuel. Looking at the costs and emissions related to this outcome, the average KLM flight with a range no higher than 4000 km would have the impact of a cost reduction of 24 euros and a carbon dioxide emissions reduction of 338 kg.

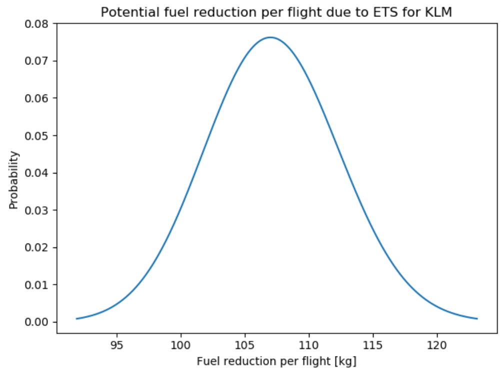

Figure 3. Potential fuel reduction per flight due to ETS for KLM.

The optimal adoption strategy of electric taxiing systems for KLM can be examined by means of the fleet assignment optimization performed in this study. A full week of operations are simulated, in which the algorithm chooses on which routes in the flight schedule the aircraft with installed electric taxiing systems should fly ideally. The computation of these schedule changes is done for an adoption of electric taxiing systems to up to 100 aircraft. Note that the current operational fleet size of KLM is 116 aircraft.

Figure 4 shows the marginal annual cost reduction accomplished by adding electric taxiing systems to the fleet. To make this more clear, it tells us that if KLM installs ETS on one of its aircraft, it will cause a yearly cost reduction of 82 thousand euros. However, if after this first system a second system is installed, the additional yearly cost reduction caused by this second system will be 72 thousand euros. As can be seen from the chart, this cost reduction number reduces all the way to 10 thousand euros after installing 100 electric taxiing systems. This phenomenon is also known as the law of diminishing returns. To find the potential cost reduction for KLM, an estimation must be made of the lifetime left on the aircraft on which the electric taxiing systems are to be installed. The current average lifetime of the Boeing 737 fleet of KLM is 12.6 years [25], while previous 737 models have been in service in the KLM fleet for 22 and 25 years (737-300 and 737-400, respectively) [26]. Assuming a negligible discount rate in the current economy, this leads to an average remaining lifetime of approximately 11 years.

This result shows that, from a cost perspective, KLM should invest in a first electric taxiing system if the estimated costs of this installment are lower than 900,000 euros. For example, if an ETS company offers to install their systems with an initial cost per product of 550 thousand euros, KLM is advised to invest in no more than 18 systems.

However, as airlines such as KLM are driven towards more sustainable operations from governments and the European Commission, the emission component of each electric taxiing system should be taken into account as well. Naturally, the emissions follow a similar trend as shown in the cost component, ranging from a 1.2 million kg reduction in carbon dioxide emissions after installing the first system to 150 thousand kg after 100 systems have been installed.

Now that the impact has been estimated, the strategic component of electric taxiing systems should be discussed. For KLM, it is crucial to know on which routes to assign their aircraft with electric taxiing systems such that they can maximize the impact of their investment in terms of costs and emissions. Logically, the algorithm

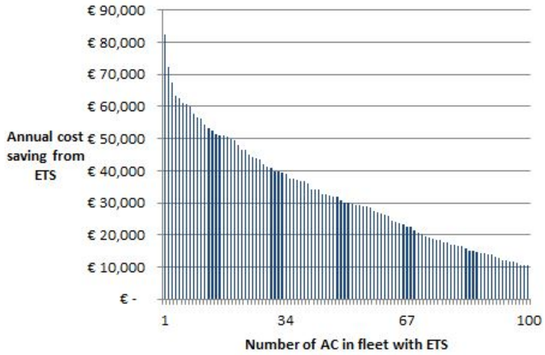

Figure 4. Marginal annual cost savings per additional aircraft with ETS in the fleet of KLM.

chooses flights concerning airports with long taxi times and flights with low range such that the system needs to be carried as short as possible. Figure 5 shows the evolution of the network of KLM after the introduction of the first 10 electric taxiing systems. The airports of Paris (CDG) and London (LHR) clearly have a large impact with their high taxi times (26 and 31 minutes of combined taxi-in and taxi-out time) and relatively short flight ranges to Amsterdam (430 km and 357 km). However, an interesting development is that after the first few electric taxiing systems have been installed, flights to Manchester Airport (MAN) are selected most often. Other popular destinations are Edinburgh (EDI) and Frankfurt (FRA).

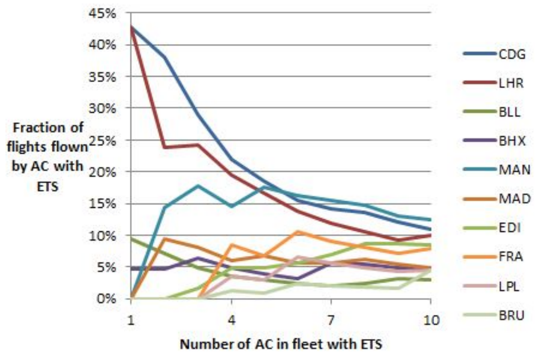

Figure 5. Development of KLM network after introduction of ETS aircraft.

The network development according to the fleet optimization algorithm has to choose destinations different from the most ideal ones because these flights might already be assigned and it can be more efficient to operate them with the same aircraft. To validate the functionality of the model, it is worthwhile to view the average range of each of the flights assigned to aircraft with electric taxiing systems. Theoretically, this should increase, as the algorithm prefers assigning ETS aircraft to low-range flights. This hypothesis is confirmed by Figure 6. Starting at a mean range of only 400 km, it quickly rises to more than 600 km after introducing more aircraft with ETS.

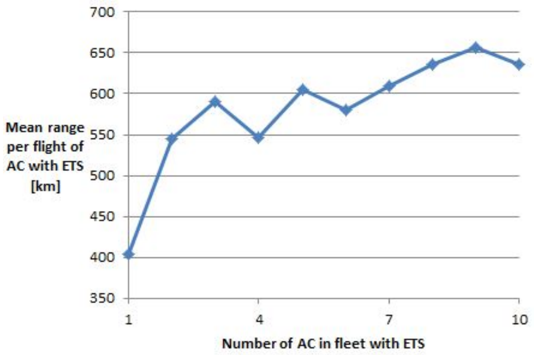

Figure 6. Mean range of flights performed by aircraft with ETS in fleet of KLM.

As the airport-specific taxi times are the second major factor in this analysis, another validation method is looking at the mean taxi time that the ETS aircraft have to deal with, on the basis of which airports they visit. Again, the theoretical hypothesis is that while more aircraft with electric taxiing systems are added to the fleet, they start flying at airports with lower taxi times. This is confirmed by the results in Figure 7. While the first aircraft with ETS spends an average of more than 24 minutes taxiing per flight, the tenth will only spend 22 minutes of taxiing per flight.

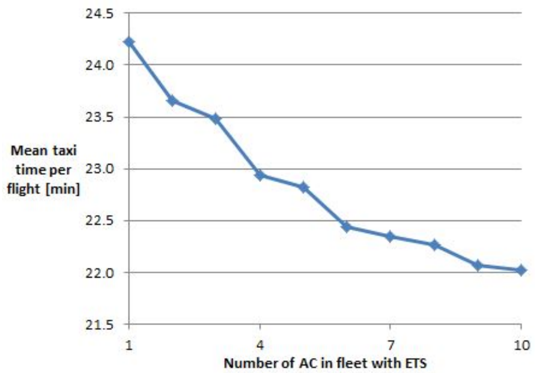

Figure 7. Mean taxi time of flights performed by aircraft with ETS in fleet of KLM.

Airline Comparison

The detailed analysis for KLM has certainly shown the potential of electric aircraft taxiing, but how is KLM positioned compared to other airlines in terms of the potential impact of this innovation? For a total of ten airlines, the results have been computed to find what their potential reduction in fuel from ETS could be. An overview of the results is shown in Table 2. There are several insights to be gathered from this outcome. Firstly, the major difference between European and American airlines (American, Delta and United) is interesting. All three American airlines show more than twice the impact per flight compared to KLM. The main reason for this is the high taxi time at many airports in the United States.

Furthermore, the low-cost carriers Transavia, RyanAir and EasyJet have relatively low expected fuel savings per flight, which might seem counterintuitive. The most probably origin of this outcome is that these airlines largely fly to secondary airports, which are often smaller and cope with fewer flights, leading to lower taxi times than the busier primary airports of large cities.

Comparing the traditional European hub-and-spoke airlines KLM, British Airways, Air France and Lufthansa, leads to a ranking in which the French have the lowest benefit from ETS, while the British can reap the largest benefits, while KLM and Lufthansa show fairly similar results. The high impact on British Airways is explained by its most important hub, London Heathrow (LHR), which has a combined taxi-in and taxi-out time of 31 minutes, which is high compared to the other hubs of Amsterdam, Paris and Frankfurt, which show taxi times of 22, 26 and 23 minutes, respectively.

	Mean fuel savings	
Airline	*Per flight [kg]*	*Annual [mln kg]*
KLM	107.2	17.32
Transavia	60.8	1.48
BA	141.9	27.66
Air France	95.8	39.29
Lufthansa	100.0	56.72
RyanAir	75.7	27.03
EasyJet	100.0	28.03
American	232.8	54.73
Delta	245.8	34.18
United	251.9	49.64

Table 2. Comparison of potential impact of ETS on key airlines.

Together, these ten airlines are expected to save 74 million euros in fuel costs and 1.1 million tonnes of carbon dioxide emissions in a situation where they have fully adopted electric aircraft taxiing.

Sensitivity Analysis

The performed analyses take into account the variability in taxi times in each of the airports, but this is only one factor that brings uncertainty with it. Four other causes of uncertainty have been examined to find the degree of their effects. Firstly, the weight of the electric taxiing system is researched, after which the oil price and the engine warm-up and cool-down times are analyzed. Lastly, the range limit used by airlines is looked at to see the impact at several different range intervals.

Weight of ETS The weight of the electric taxiing system is the disadvantage of this internal-motor alternative to aircraft taxiing. Carrying it in the air costs additional fuel, which is exactly the opposite of its desired effect. Looking at the existing electric taxiing system concepts that are powered through the auxilliary power unit of the aircraft, a weight of 200-450 kg appears to be a reasonable margin. However, as battery development continues due to increased efficiency, these might be integrated in future ETS designs too. These batteries will add weight and the effect of this additional weight is visualized in Figure 8. This curve is computed for the KLM fleet, seeing the 107 kg fuel savings at 400 kg ETS weight as assumed throughout the earlier analysis.

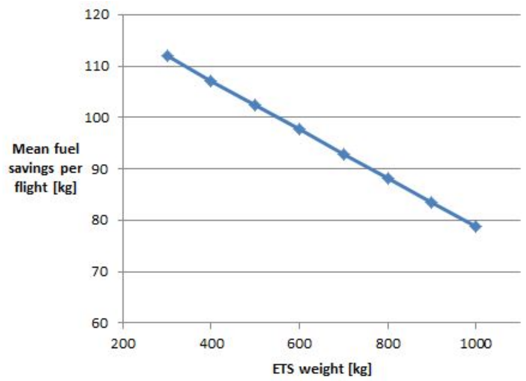

Figure 8. Sensitivity of impact to weight of ETS.

Jet Fuel Price Figure 9 shows the sensitivity of the cost savings to the jet fuel price. Given the global turmoil in the oil market in recent times combined with the pandemic crisis of 2020, this price is very volatile. That volatility is very important to the investment decision of airlines in the case of electric taxiing. This innovation has the most cost reduction potential if the oil price rises again.

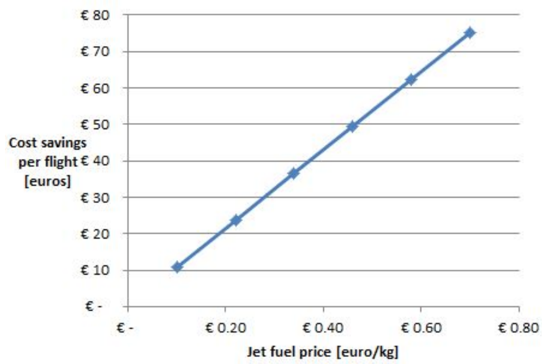

Figure 9. Sensitivity of impact to the price of jet fuel.

Warm-up and Cool-down Time The main analysis of this study is done using the current estimations of mean warm-up and cool-down times for the main engines of the aircraft before take-off and after landing, namely 5 and 3 minutes respectively. However, these phases can in the future be improved by innovations such as external heating and cooling of the engine. The impact on electric aircraft taxiing of these innovations is shown in Figure 10.

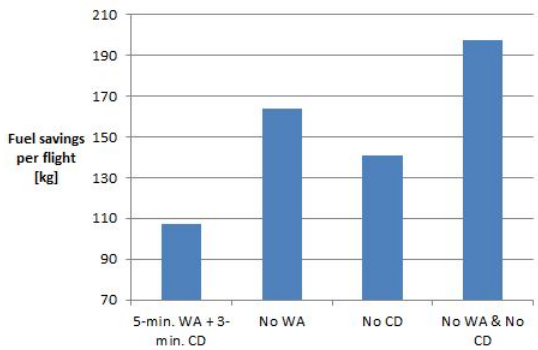

Figure 10. Sensitivity of impact to warm-up (WA) and cool-down (CD) time.

Range The last sensitivity parameter is the range limit. If airlines are free to assign their electrically taxiing aircraft on routes, which flight ranges have the most impact? To answer this question, the marginal annual fuel savings are computed in Figure 11. It shows that especially the flights between 500 and 1000 km are important to include in the network of the ETS aircraft.

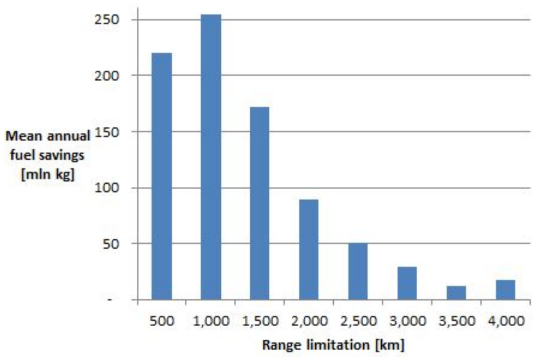

Figure 11. Sensitivity of impact to flight range limitation.

Discussion

The innovation of electric aircraft taxiing is expected to show promising results in the future, but this is still dependent on design adequacy, policy-making and external circumstances. The performance of the available concepts will not only have to be extremely reliable, but also meet the safety regulations. Political decision-making is expected to present obstacles as airports have less direct benefits from electric aircraft taxiing than airlines. This is because airlines accomplish cost reductions, while airports benefit only in terms of reduced emissions while they do have to facilitate the required infrastructure and processes to accommodate sustainable taxiing. The target of the European Commission is a first step, but getting all stakeholders on board will take serious regulation. At the moment, the low jet fuel prices represent an external circumstance that reduces the need for airlines to adopt this innovation. Furthermore, this analysis has not included potential costs of electric taxiing such as acquisition, installation and maintenance, but focused purely on reduction in fuel.

This study is an attempt to more clearly show the impact of electric aircraft taxiing such that stakeholders are able to make decision with more accurate information at hand. However, several points of discussion concerning the analysis have to be noted. Firstly, the 2020 pandemic has serious effects on the number of flights, causing the results of this study to be less accurate. This consequences stems not only from the reduced flight frequencies of aircraft in the fleets of airlines, but also because the taxi times are expected to be reduced due to less busy airports. Ending on a more detailed point, this analysis assumed the fuel flow during the taxiing phase to be constant throughout the taxi time because of the limited data concerning this specific aspect, but this does not include the uncertainty concerning transitions between idle and taxiing modes.

Conclusions

Looking at the current state of electric taxiing, external systems are to a higher degree industry-ready than on-board systems. External systems are definitively part of the solution, but due to logistical issues likely to be limited in number. These could therefore be used for long-haul aircraft models, while future short-haul aircraft models can be propelled by an on-board system. Clear advantages of the on-board systems are the fuel reduction they cause, autonomous push-back from the gate and lack of logistical complexity, while its main disadvantage is the in-flight fuel penalty caused by its weight. The reduction in fuel usage therefore depends on the flight range and taxi time, but during the taxiing phase ETS achieve a fuel reduction of 9.8 kg per minute, equivalent to 82%.

The analysis in this study shows the global impact of electric taxiing is expected to be a reduction in jet fuel usage of 846 million kg per year, in the scenario that all aircraft are equipped with an electric taxiing system. In terms of costs and climate effects, this is equivalent to a cost reduction of 186 million euros with the current low oil prices and a reduction of 2.67 million tonnes of carbon dioxide emissions. Given the total annual aviation emissions of 915 million tonnes carbon dioxide, this means that ETS could reduce 0.3% in emissions. Locally however, airports and their surroundings will benefit seriously from the reduced emissions, because 56% of airport emissions are due to the taxiing phase.

Factors with major effect on the potential impact of electric aircraft taxiing are weight of the system and the price of jet fuel. If designs cannot be made lightweight, the sustainable effect diminishes quickly and the current low jet fuel prices lower the pressure on aviation organizations to adopt electric aircraft taxiing.

Analysis of the effect of electric aircraft taxiing to key stakeholders such as airlines shows that American airlines would reap substantially larger benefits than European competitors because of consistently higher taxi times in the United States. Low-cost carriers are expected to see smaller impact than traditional hub-and-spoke airlines, due to short taxi times in the secondary airports they predominantly fly on.

A special focus on KLM shows that the Dutch airline could save 17.3 million kg of jet fuel annually, representing a cost of 3.8 million euros, increasing profits by 3%, and a carbon dioxide emission of 55 million kg. Since the road to full adoption is still long, a strategic analysis of the fleet shows the marginal cost reduction per installed electric taxiing system starts at 82 thousand euros for the first product, which reduces to 10 thousand after 100 systems have been installed. Especially the flights between Amsterdam and London Heathrow, Paris Charles de Gaulle and Manchester Airport should be assigned to aircraft with electric taxiing systems, because these flights would have the most impact given their relatively low flight distance and high taxi times.

A sensitivity analysis leads to additional insights to the effect of warm-up and cool-down times and the flight range of aircraft with electric taxiing systems. Especially the reduction in warm-up time is expected to be beneficial for the impact, while flights with ranges between 500 and 1000 km are likely to be the most important in absolute terms.

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Appendices

Three appendices are provided to make sure it is possible to reproduce the experiments done in this thesis study. Firstly, the model is described in detail such that all external modules and steps in the code are clear. Next, excerpts from the input data are presented such that these formats and parameters can be used in the described model. Finally, several additional results are presented that could not be fitted in the main text of this thesis paper and are of smaller importance.

A: Model Details

The model is formulated in Python programming language using the integrated development environment of (IDE) PyCharm.

API modules

- Data analysis and visualization: Pandas, NumPy and Matplotlib
- Probability distribution sampling and convolution: SciPy (.stats and .signal)
- Distance computation using Vincenty's formulae: GeoPy
- Fleet Assignment Optimization: PuLP

Code Description

1. Import modules
2. Set input parameters
3. Import input data
4. Filter input data such that flights only include the airports in the taxi time data and below the maximum flight range
5. Convert frequency, start and end dates to unique flights
6. Filter for airline and aircraft capacity to only include narrow-body aircraft

7. Fit probability distributions of airport taxi-in and taxi-out times by using the given distribution parameters mean and variance
8. Generate samples from initial distributions and remove samples to obey percentile distribution parameters and lower bounds while keeping mean and variance level
9. Create histograms out of the final sample sets and use those in further analysis
10. Compute flight distances per origin-destination pair using Vincenty's formulae
11. Include fuel factor based on aircraft type on each of the flights
12. For each combination of origin, destination and aircraft type, match the origin taxi-out time and the destination taxi-in time and convolve the two distributions to find the total probability distribution of the two combined
13. Compute probability distribution of fuel savings based on taxi time distribution, aircraft type (fuel factor), flight range and consequential fuel penalty while taking into account the warm-up and cool-down times
14. To find aggregate (total probability distribution) of fuel savings across all flights in selection, convolve the fuel savings probability distributions of all these flights
15. Fleet Assignment Optimization: start by using the mean fuel savings for each combination of origin, destination and aircraft type
16. Reformat departure and arrival times and dates such that one number can be used for continuous date-time
17. Create sets for optimization problem (especially the flights departing from the given airport previously are crucial in this implementation)
18. Set starting airport (AMS used in this study because KLM is looked at in detail)
19. Set cost function and objective function (to maximize total fuel savings)
20. Initiate decision variables
21. Use loops to create all constraints
22. Call optimization software solver and validate results by filtering out the scheduled flights per aircraft
23. Translation to costs and emissions

B: Input Data

Input Parameters

- Maximum flight range taken into account: 4000 km
- Weight of ETS system: 400 kg
- 5 minute warm-up time and 3 minute cool-down time of the main engines
- Oil price: 0.22 euro/kg
- Turn-around time: 60 minutes
- Carbon emission per kg fuel: 3.15 kg
- Fuel flow of aircraft taxiing with main engines: 11.97 kg/min (engines) and 1.58 kg/min (APU)
- Fuel flow of aircraft taxiing with ETS: 2.17 kg/min

Taxi Times Data Rows: 433 (for both taxi-in and taxi-out times)

	Taxi time [min]				
IATA	*Mean*	*Stdev.*	*10 pctl*	*Med.*	*90 pctl*
AAL	4.7	1.4	3	5	6
...	...	...	...	...	...
ZTH	4.2	1.8	2	4	6

Flight Schedule Data Rows: 680,447

Left Side of Flight Schedule

Origin	*Dest*	*Airline*	*Start*	*End*
AAA	MKP	VT	4/1/10	4/1/10
...	...	...	...	...
ZYP	ZVE	2V	1/1/10	31/12/10

Right Side of Flight Schedule

Days of Week	*Deptime*	*Arrtime*	*ACType*
1	725	805	AT5
...	...	...	...
12345	1600	1726	THS

	Potential Fuel Reduction KLM [kg]	
	Total	***Per flight***
Mean	17.3 mln	107.2
95% CI	[15.7, 19.0] mln	[97, 118]

	Potential Cost Reduction KLM [EUR]	
	Total	***Per flight***
Mean	3.8 mln	23.6
95% CI	[3.5, 4.2] mln	[21.4, 25.9]

	Potential CO2 Emission Reduction KLM [kg]	
	Total	***Per flight***
Mean	54.6 mln	338
95% CI	[49.5, 59.9] mln	[306, 370]

C: Additional Results

Potential Impact (KLM)

Potential Impact (Global)

	Global Potential Impact		
	Fuel mln kg	***Costs mln EUR***	***CO2 mln kg***
Mean	846	186	2.67
95% CI	[834, 856]	[183, 188]	[2.63, 2.70]

Fleet Assignment Optimization In the main text of this thesis paper, only the most important airports selected in the fleet assignment optimization are presented. Here, a full overview of all airports is given, after introducing 10 aircraft with ETS in the fleet of KLM. To analyze the role of flight distance (between Amsterdam and the given airports) and taxi times, these two variables are normalized and combined into one coefficient by adding the positive normalized taxi time (as a high taxi time causes high potential fuel savings) to the negative normalized flight distance (as high flight distances cause higher fuel penalties and thus lower potential fuel savings), while reducing outliers using factors for the two variables. Note that the combined taxi-in and taxi-out times are used. Balancing the factors lead to the conclusion that combined taxi time is 13% more important than flight distance in this experiment. The plot associated with these coefficients confirms the hypothesis that the optimization algorithm converges to flights to and from airports with low flight distance to Amsterdam and high taxi times. An important side-note to these results is the fact that flight availability is not taken into account at this stage. Given the fact that KLM faces unequal demand on each of their network routes, they schedule more flights to popular destinations and fewer to less popular destinations. This can bias the results.

	%	*Dist. [km]*	*Norm. dist.*	*TT [min]*	*Norm. TT*	*Coeff.*
MAN	12.4	493	0.16	22.1	0.48	0.38
CDG	10.9	430	0.13	25.8	0.70	0.66
LHR	10	357	0.09	30.9	1.00	1.04
EDI	8.5	646	0.23	19.7	0.33	0.15
FRA	8	364	0.09	23.5	0.56	0.54
BCN	5.5	1211	0.51	23.5	0.56	0.12
MAD	5	1482	0.64	27.1	0.77	0.23
BHX	4.5	460	0.14	19.3	0.31	0.21
LPL	4.5	547	0.18	16.7	0.15	-0.01
BRU	4.5	174	0.00	17.4	0.20	0.22
BLL	3	466	0.14	14.1	0.00	-0.14
ZRH	3	615	0.22	18.2	0.24	0.06
MUC	3	666	0.24	18.9	0.29	0.08
FCO	2.5	1299	0.55	26.4	0.73	0.28
SVO	2	2129	0.96	23.7	0.57	-0.31
GLA	2	696	0.26	17.7	0.21	-0.01
DUS	1.5	177	0.00	17.3	0.19	0.21
TXL	1.5	569	0.19	15.7	0.10	-0.09
CPH	1.5	622	0.22	19.2	0.30	0.12
VIE	1.5	954	0.38	19.1	0.30	-0.05
ABZ	1	725	0.27	15.5	0.08	-0.18
HAJ	0.5	329	0.08	16.5	0.14	0.09
GOT	0.5	744	0.28	13.8	-0.02	-0.30
BRS	0.5	525	0.17	14.9	0.05	-0.12
LBA	0.5	467	0.14	17.4	0.20	0.08
IST	0.5	2212	1.00	29.5	0.92	0.04
MXP	0.5	784	0.30	19.5	0.32	0.06
GVA	0.5	692	0.25	14.7	0.04	-0.21
VCE	0.5	943	0.38	18.4	0.26	-0.09

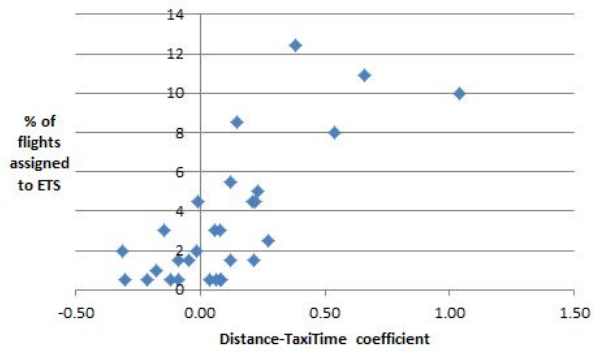

Figure 12. Visualization of the importance of flight distance and combined taxi time.