MSc Aerospace Engineering Thesis

Evaluating passenger leakage of Dutch travellers to foreign airports under the influence of the aviation tax

AE5322: Control & Operations Thesis

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by

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to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on June 25th, 2026

Student number:	5483158	
Project duration:	November 2025 - June 2026	
Thesis Committee:	Ir. P.C. Roling	TU Delft, Chair
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TU Delft

Preface

I guess this is it, the end of a very challenging road. Throughout the past five years, I have had the privilege of being an Aerospace Engineering student at the Delft University of Technology. While those years certainly had both positive and negative moments, I could not have imagined how much I would enjoy studying at this university. I have been blessed to have pursued such a degree, while also encountering so many valuable people along the way. Looking back at myself from 2021, I can see how much I have changed as a human being, and regardless of what the future brings, I will always cherish my university experience.

The Thesis presented in this document is undoubtedly a cherry on top of this journey. Over the last 32 weeks, I have been steadily expanding my understanding of the factors affecting the passenger leakage phenomenon. This also included the opportunity to create a mathematical model that resembles the real-life situation. I first stumbled upon the idea of evaluating passenger leakage after contributing to this occurrence myself. In 2023, when booking flights to see my family back in Poland, I realised that I could save a considerable amount if I were to fly from Brussels rather than Amsterdam. After doing some more research, I discovered the vast differences in the aviation taxes charged by the Netherlands and its neighbours. As such, in the following years, I would often end up flying from Brussels in pursuit of lower airfares, eventually even convincing several of my friends to do the same.

While analysing the changes to the airport selection probabilities under differing aviation tax levels was extremely satisfying, I could not have done this alone. Throughout every step of the way, I could always count on my supervisor, Alessandro, to guide me in the right direction and answer the many questions I had. I would also like to thank you, Alessandro, personally for your continuous support throughout the entire duration of this project.

Finally, I want to thank my parents, Iwona and Jarek, for providing me with the support, care and more than a little motivation throughout the entirety of my studies. After all, every bump on the road should be treated as a challenge rather than a problem. Although those five years have certainly required a lot from the three of us, it is now, at the end of this journey, that I really would like to say to you “Dziękuję!”. I also want to thank my girlfriend, Ola, who has been there for me every step of the way, no matter what, and on whom I could count every time. I definitely would not have been where I am right now if it weren’t for you. Lastly, I want to thank all my friends for sticking with me throughout all those years, even though my aerodynamic hairstyle from the beginning of my studies is long gone.

To new adventures!

Adam Wójciński
Delft, June 2026

Contents

Introduction

When planning their next flight, Dutch passengers are often presented with a number of options regarding the departure airport. Depending on where they live, both the domestic airports, such as Amsterdam Schiphol and their foreign competitors, akin to Brussels Zaventem, could present viable alternatives. The decision of where to fly from, however, is a complex one, and properly modelling it requires extensive research. Usually, however, the ground accessibility to each of the considered airports, their respective connectivities and the charged airfares are considered to be the most crucial factors affecting airport selection.

The last of those factors, however, is inherently dependent on, among others, the charges that the airline is obliged to pay for operating the flight from a given airport. This includes the aviation taxes, which were first introduced in the Netherlands in 2008. Although the initial tax was short-lived, having been abolished after only a year since its introduction, there was evidence to suggest that its introduction prompted some Dutch residents to fly from abroad in search of lower airfares. This, in turn, contributed to the phenomenon of passenger leakage, where the residents of a given country choose to travel across the border and fly from there instead. This occurrence could be very strong among Dutch residents, as the Netherlands, Belgium and Western Germany jointly form a very interconnected region. As such, the occurrence of leakage can be greatly impacted by an increase in departure costs from one of the countries. For that reason, quantifying the potential leakage that the Dutch airports may experience is imperative to assess how many passengers they are set to welcome and how the potential outflow of Dutch residents to foreign countries could impact their operations.

In recent years, the Netherlands decided to reintroduce the air passenger tax, while also increasing it each year to account for inflation. In 2027, its structure is to be further modified, resulting in an additional increase in the aviation tax. As a result, for each departing passenger on a long-haul flight, the tax levy would reach in excess of €70. Although this has raised concerns about the increased leakage of Dutch residents to foreign airports, the quantification of this phenomenon is yet to be modelled. As such, a research gap was identified, which is to be addressed by this Thesis. The project will aim to evaluate the impact of the proposed 2027 air passenger taxes on the occurrence of passenger leakage among Dutch residents, while also evaluating their sensitivity to changes to the tax structure.

This Thesis report contains a total of three parts. In Part I, the Scientific Article containing the main contributions of the Thesis will be presented. The document will introduce the obtained results, in turn, addressing the conceived research objective. The potential extensions of the performed research will also be identified. Afterwards, the detailed literature review is to be presented in Part II. This will include a comprehensive analysis of the topic of airport selection and passenger leakage. Furthermore, the official Research Proposal of the project will also be presented. Lastly, Part III will introduce the Supporting Work, containing the supplementary documents. Those will aim to provide additional background regarding the creation of the mathematical model presented in the Scientific Article.

Part I

Scientific Article

Evaluating passenger leakage of Dutch travellers to foreign airports under the influence of the aviation tax

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Abstract

The reintroduction and subsequent increases of the aviation tax in the Netherlands have raised questions regarding the leakage of Dutch passengers to nearby foreign airports. In 2027, the Netherlands is set to modify its existing aviation tax, creating a distance-based structure, while also heavily increasing the charged amounts. This study evaluates the expected impact of the tax increases on airport substitution, which exacerbates the leakage phenomenon. To simulate the behaviour of Dutch passengers, a two-level Nested Logit model is developed. At the upper level, the airport choice is modelled, while the lower level simulates the selection of a given flight and airport ground access mode. The corresponding utilities are then calculated, incorporating the airfare, ground access time and cost, airline types, flight departure times and the inherent preference for domestic airports. The coefficients corresponding to each parameter are calibrated against real-life observed data, while accounting for the different behaviours of business and leisure travellers. The calculation of the leakage for each postcode location in the Netherlands reveals an increase in foreign-airport departures among Dutch residents. The leakage is exacerbated, particularly among those living in the border regions and those embarking on medium and long-haul journeys, where the tax effects are the most prevalent. The findings highlight the increased probability of Dutch citizens selecting foreign departure airports in order to save additional funds.

I Introduction

The topic of airport selection among multi-airport systems (MAS) has been subject to extensive research in recent years [1–3]. The authors of those papers would often conclude that accessibility of each airport, its connectivity, as well as the average airfare, would often be the main factors affecting travellers' airport choice [1]. As such, when the Netherlands first introduced the aviation tax in 2008, discussions emerged as to what the implications of this may be. One of the main concerns was that Dutch residents would now travel to foreign airports, such as Brussels or Düsseldorf, to fly from there instead. Although the tax was short-lived and was abolished after only one year, there was evidence to suggest that a fraction of passengers indeed opted for such an approach [4].

In recent years, the tax was reintroduced with the aim of promoting more sustainable travel alternatives[1]. To further enhance this measure, the Dutch government announced that, in 2027, it would be further increasing the aviation tax, reaching in excess of €70 for each departing passenger on a long-haul flight. This has, just like in 2008, raised concerns about the 'leakage' of passengers who are going to fly from foreign airports rather than domestic ones [4]. The exact effects of this proposal, however, are yet to be modelled. As such, it remains unclear how many passengers would modify their choices and which airports they would select instead. This, in turn, creates a research gap, which is to be explored as part of this research.

This paper aims to document the evaluation of the impact of the aviation tax on the propensity of selecting foreign departure airports by Dutch citizens. For this, an extensive literature review is to be conducted, which will be presented in section II. Afterwards, the methodology behind the creation of the mathematical model will be introduced in section III. The section will also present the model itself, as well as the undertaken data acquisition and processing. The results of the model will then be presented in section IV. The section will also discuss the sensitivity of passengers to the changes in the taxation structure. Finally, the implications of the obtained results will be discussed in section V, along with the description of the limitations of the model and the recommendations for future work.

II Literature Review

With the rapid expansion of the aviation market in the 1970s [5], the number of commercial airports in use would also increase. On a more local scale, this meant that numerous regions started being served by more than one airport, in turn, providing the passengers with a choice regarding the airport of origin. This led to an additional occurrence, however. Even if an airport were to be much further away than its competitors but were to be deemed attractive by departing passengers, its market share would

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[1] `https://aviationsourcenews.com/netherlands-air-ticket-tax-hike-sparks-airline-and-airport-concerns/`

still be significant [6]. For that reason, making an airport as appealing as possible turned into an ever-more crucial aspect for aviation executives across the world, while simultaneously making the analysis of multi-airport regions (MARs) an ever-relevant study area.

A Airport selection

The concept of airport selection in multi-airport regions was first researched by Harvey [7] in 1987. As one of the outcomes of the study, it was concluded that there are multiple factors affecting airport selection. The main ones were deemed to be related to the airport ground access time as well as the flight frequency to the desired destination. Furthermore, the paper concluded that the impact of those factors greatly depends on the passenger type, business or leisure. Several additional studies followed, confirming the results presented by Harvey [8–10].

The airport selection was also found to be closely related to the connectivity of considered airports [11, 12]. For a defined destination, passengers might first filter out all the airports that do not offer flights there. Only afterwards will they select the airport of origin from the refined list [13]. Furthermore, during the final airport selection, the flight schedules from different airports are also simultaneously considered [3, 8]. If the flight to the desired destination were to depart in the early morning from a distant airport, it may experience lower demand, with early morning and late evening flights being considerably less desired [14].

Another crucial concept, which was found to greatly affect passengers' decisions of where to fly from, is the ground accessibility of airports [10, 11]. The easier it is to reach a given airport, the more likely it is to be chosen. As a result, when considering airports across the world, it can be observed that in numerous instances, there will be a highway and/or a railway link right next to the airport. Moreover, with growing passenger numbers, many airports may consider increasing the number of ground access alternatives, especially if they are located further away from the centre of the respective metropolitan area [15].

B Passenger leakage

Another heavily researched aspect covers the topic of passenger leakage. Within the aviation industry, it can be defined as passengers who live in the catchment area of Airport A, but choose to fly from Airport B instead. This means that passengers may choose to bypass their closest airport in order to fly from one which is further away. There are usually several factors behind this phenomenon. One of those is the average airfare associated with flights out of a given airport, as well as the airport connectivity itself. Passengers will be more likely to fly from an airport which is further away if it serves more destinations. This is especially the case if the local airport is a small regional airfield, which does not offer many direct destinations [16, 17]. This occurrence has also been present among Dutch residents, with some of them travelling to neighbouring airports in Belgium and Germany in pursuit of lower airfares [18].

C Impact of taxation

In light of increasing greenhouse gas emissions and the associated global warming, governments have started taking various steps in order to disincentivise air travel. To date, aviation has been responsible for up to 4% of global warming, extensively contributing to climate change [19]. In order to curb the demand for air travel and hence the associated emissions, some governments have decided to introduce an aviation tax. Although several countries have since backed out of the idea[2], the Netherlands has decided to continue and expand the process[3].

After debating upon the concept of the aviation tax within the Netherlands for multiple years, on 1 July 2008, the Netherlands introduced its first-ever air passenger tax. In order to preserve the competitiveness status of Amsterdam Schiphol Airport (AMS), however, the tax only applied to directly departing passengers (OD), with transferring individuals being fully exempt from it. The air passenger tax was also dependent on the flight distance. For intra-EU flights or other short-haul flights no longer than 2500 kilometres in length, a lower level of €11.25 was imposed, while all remaining flights were subject to a higher bracket of €45.00 [18]. This can be observed in Table 1:

Table 1: Dutch Air Passenger Tax (2008)

Passenger Type	Distance	2008
OD passengers	EU flights	€11.25
OD passengers	$\leq$ 2500 km	€11.25
OD passengers	$\geq$ 2500 km	€45.00
Transfer	All distances	€0.00

In the first few months after the introduction of the tax, all Dutch airports experienced lower-than-anticipated OD passenger numbers, with a total of 7% of Dutch residents stating that they chose to fly from a different airport due to the tax instead [18]. Simultaneously, a very interesting phenomenon occurred just across the border in Germany. Weeze Niederrhein Airport (NRN) is an airport located less than three kilometres away from the Dutch border. In the second half of 2008, NRN saw its operations increase in volume by more than 40% [18]. Although the air passenger tax certainly was an important factor influencing this phenomenon, it coincided with the peak of the Global Financial Crisis, which lasted between 2007 and 2009. The Netherlands, especially, experienced its effects in the second half of 2008, potentially affecting the numbers [20]. As such, it is difficult to estimate how large

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[2] `https://www.dw.com/en/german-aviation-tax-cut-to-offer-little-lift-amid-jet-shortage/a-75022175`

[3] `https://aviation.direct/en/Netherlands-introduces-tiered-airline-ticket-tax`

the impact of the tax itself was and how big a role the crisis played. This is because, in order to boost the economy, the Dutch government quickly abolished the tax in 2009. This, in turn, led to a quick growth in air traffic numbers before the full effects of the tax could be truly understood.

After the abolishment of the air passenger tax in 2009, passenger numbers quickly started growing. With time, however, so did the calls to reintroduce the tax. After more years of heated debates, the tax was ultimately reintroduced. Starting at €7.45 per departing passenger in 2021, it has been subject to steady increases with each passing year. This, in turn, made the Netherlands the most expensive destination within the European Union[4], with the tax rate for 2026 reaching €30.25, prompting many potential travellers to search for alternative departure airports located outside of the Netherlands. A visual comparison of the tax rate over the years can be found in Figure 1.

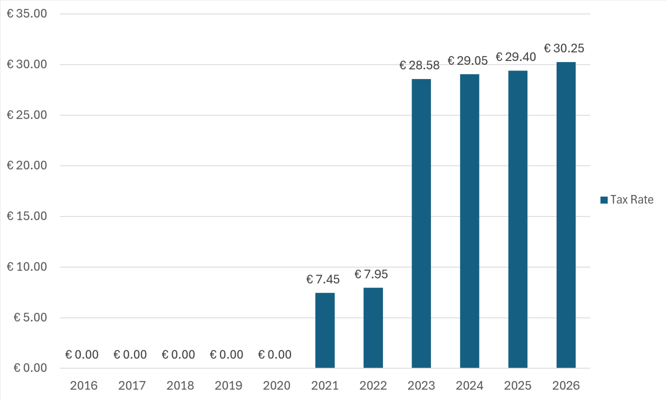

Figure 1: History of the Air Passenger Tax in the Netherlands

Although flying from the Netherlands is already very expensive, its costs are set to rise even further in 2027. Going back to its roots, the Netherlands is set to introduce a multi-tier air passenger tax, depending on the covered distance, with transferring passengers being, once again, exempted [21]. The duty charged on short-haul flights within the European Union or not exceeding 2000 km will slightly decrease to €29.40. Some further destinations will also be subject to that lower fee. Those include Aruba, Bonaire, Curaçao, the Canary Islands, or Madeira[5]. The major increases will occur on longer flights, however. For destinations outside of the EU, located between 2000 and 5500 kilometres away from the departure airport, the air passenger tax will be €47.24 [21]. This includes flights to Morocco or Turkey. For longer flights, though, the difference will be even more drastic. Flights longer than 5500 kilometres will be subject to a tax of €70.86 per departing passenger [21]. An overview of the tax levels, per passenger type (Pax type), can be found in Table 2, which is located below.

Table 2: Dutch Air Passenger Tax (2025 - 2027)

Pax type	**Distance**	**2025**	**2026**	**2027**
OD	EU flights	€29.40	€30.25	€29.40
OD	$\leq$ 2000 km	€29.40	€30.25	€29.40
OD	2000 - 5500 km	€29.40	€30.25	€47.24
OD	$\geq$ 5500 km	€29.40	€30.25	€70.86
Transfer	All distances	€0.00	€0.00	€0.00

As can be observed, the increases are considerable. Although the Dutch government has repeatedly stated that these will not lead to drastic price increases, airlines have already announced that those costs will inevitably be passed on to consumers, hence making flying from the Netherlands even more expensive than it is today.

Germany first introduced a national aviation tax in 2011 as part of its Aviation Tax Act [22]. The tax structure was implemented in a very similar manner to the upcoming 2027 Dutch air passenger duty. There, a tiered system was created, depending on the flight distance. Rather than sticking to the actual distance itself, however, destination countries were listed. Each country would then be allocated to one of the three tax tiers, depending on its relative distance to Germany. Furthermore, akin to the Netherlands, only departing passengers would be subject to the fee, with transferring passengers exempted from the excise duty. When introduced in 2011, the short-haul flights were taxed at €8.00 per departing passenger, medium-haul flights at €25.00, and long-haul flights at €45.00 [22]. Over the years, the tax charges fluctuated with the newest tax rates, which will be fully in force in 2027, being similar to the original amounts. The rates will amount to €12.73 for short-haul flights, €32.25 for medium-haul flights and €58.06 for long-haul flights. Although the charged amounts are very costly to the German travellers, they will be somewhat lower than for their Dutch counterparts.

A stark comparison to the air passenger taxes in Germany or the Netherlands can be observed in Belgium. Although the country has, just like the rest of the region, also introduced an air passenger tax (Embarkation tax), its rate is much lower than that of its neighbours. The tax itself is also much newer, having been implemented in 2022. Unlike its neighbours, however, Belgium wanted to disincentivise travel on shorter routes, where other modes of transport can be a realistic alternative to flying. As such, as of 2025, the air passenger tax amounts to €10.00 for short-haul flights, which are less than 500 kilometres in length. For longer flights, however, a lower €5.00 tax rate applies. Furthermore, just like in other countries, only departing OD passengers are subject to the fee, with transfer passengers being exempted[6].

Similar to its neighbours, though, the Embarkation tax is to undergo a significant increase in Belgium[7]. First,

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[4] https://dutchreview.com/news/netherlands-now-priciest-flying-destination-in-the-eu/

[5] https://www.nationalerecreatiegids.nl/ondernemen/vliegvakanties-worden-vanaf-2027-fors-duurder-door-nieuwe-vliegbelasting/

[6] https://www.fccaviation.com/regulation/belgium/embarkation-tax

[7] https://newmobility.news/en/2025/11/25/belgian-air-passenger-tax-to-double-from-2027-for-flights-over-500-km/

in 2027, the tax is to equate to €10.00 regardless of the flight distance. Subsequently, in the following years, the short-haul flights, which are less than 500 kilometres in length, will be subject to 50-cent increases both in 2028 and 2029. As such, the tax rate will then reach €11.00 per departing passenger on short-distance routes. While these changes represent a significant increase, which already sparked sharp criticism from the representatives of the aviation industry[8], this remains vastly below the tax rates observed in the neighbouring countries.

If the airfares remain lower in Belgium compared to the German and Dutch counterparts, the country's airports of Brussels Zaventem (BRU) and Brussels Charleroi (CRL) may observe a significant influx of other residents, especially from the well-connected Netherlands. This becomes even more apparent when directly comparing the tax levels between the three countries, depending on the respective flight distances, as depicted by Table 3.

Table 3: Air Passenger Taxes for OD Passengers

Haul Type	**Origin Country**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**
Short-haul	Netherlands (EU flights)	€29.05	€29.40	€30.25	€29.40		
	Germany (EU/EEA flights)	€15.53	€15.53	€12.73	€12.73		
	Belgium ($<$ 500 km)	€10.00	€10.00	€10.00	€10.00	€10.50	€11.00
Medium-haul	Netherlands ($<$ 5500 km)	€29.05	€29.40	€30.25	€47.00		
	Germany (Middle East, Central Asia)	€39.34	€39.34	€32.25	€32.25		
	Belgium ($\geq$ 500 km)	€5.00	€5.00	€5.00	€10.00	€10.00	€10.00
Long-haul	Netherlands ($\geq$ 5500 km)	€29.05	€29.40	€30.25	€70.86		
	Germany ($>$ 6000 km)	€70.83	€70.83	€58.06	€58.06		
	Belgium ($\geq$ 500 km)	€5.00	€5.00	€5.00	€10.00	€10.00	€10.00

As can be observed from the three tables, the Netherlands is set to become the most expensive country to fly from, regardless of the distance. For passengers with competitive access to German and especially Belgian airports, this will present an opportunity to fly from abroad in order to save additional funds, exacerbating the passenger leakage phenomenon.

Lastly, it is to be noted that aviation taxes do not fully determine the differences in airfares for flights from different airports. Several other factors are also included. Each airport charges departing aircraft different types of fees. Those may be related to the ground handling of an aircraft, generated noise, or the number of passengers onboard. In light of the strive for sustainability, they can also correspond to the NO_x or CO_2 emissions associated with the given aircraft/engine type[9]. For the purpose of this study, those have been neglected, with a greater focus placed on the air passenger taxes themselves. This, however, should be further explored in the future so as to enhance the findings in the area of passenger leakage.

D Preferences of different travel groups

Different travel groups may have differing preferences regarding air travel. Although it is difficult to group every traveller by their habits and likings, the distinction between business and leisure travellers can always be made. Although the differences between the two groups are substantial, they are mainly related to the relative value of time and money.

Making up only 12% of total air passengers, but a much larger portion of total airline revenue[10], business travellers are extremely crucial for the airlines. One of the main reasons for that is related to business travellers not paying for the flights themselves. As such, the costs of getting to the airport as well as the flight itself are not a factor for the individuals. Business trips also tend to be quite busy in terms of schedules. As a result, the main aspect that business travellers will focus on is time. For that reason, they will be much more likely to fly from an airport that offers the fastest overall itinerary to their desired destination, at the most preferable time, regardless of the incurred costs [23–25].

Leisure passengers, on the other hand, focus much more on the incurred costs. As such, their relative value of time will be considerably diminished, up to three times lower than that of business travellers [25]. For that reason, they will be more likely to fly from a further airport in order to save additional funds. The time-money trade-off for that group will vastly differ between individuals, however, largely depending on their income [2, 9].

E Modelling the passenger choices

The strive to model airport selection has already been subject to extensive research in the past [2, 26, 27]. Although different models were utilised, in almost all in-

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[8] `https://www.aviation24.be/miscellaneous/environment/belgiums-eco-tax-on-flights-hike-sparks-backlash-led-by-ryanair/`

[9] `https://media.brusselsairport.be/bruweb/default/0001/39/d96fce90431fe6e443ad1b3a4b35a3b139d9ee63.pdf`

[10] `https://financesonline.com/business-travel-statistics/`

stances, they could be categorised as a logistic regression (logit) model. Logit models themselves have several different types, such as nested, multinomial, or mixed, all of which aim to estimate the probability of an event occurring based on several factors that may or may not be independent from one another[11]. This, in turn, facilitates the modelling of the airport selection in numerous scenarios, which can even incorporate the influence of an aviation tax on some of the considered airports.

Logit models themselves are statistical models. They are mainly created in order to predict the probabilities of discrete, binary outcomes. At its core, the model combines several parameters that may influence the final decision. It then links them to the probabilities of different outcomes, Y, occurring. Computing the probabilities themselves, however, vastly depends on the type of model used. Irrespective of the utilised model type, though, all probability functions use utility functions, which capture the relative attractiveness of each alternative. The expression for a given utility function, defining the attractiveness of alternative j for individual i, U_{ij}, can be described by means of Equation 1:

$$U_{ij} = V_{ij} + \varepsilon_{ij} = X_{ij}\beta + \varepsilon_{ij} \tag{1}$$

where V_{ij} is the deterministic part of the utility j based on individual i and X_{ij} is a deterministic parameter related to an individual i, affecting utility j. Furthermore, β is a coefficient defining the marginal effect of the parameter on a given utility, whereas ε_{ij} is the (unobserved) random utility term. This random error term allows for capturing the unobserved preferences of individuals. The utility functions themselves capture all factors that may affect the to-be-made choices, such as airport selection. Moreover, the models assume that an alternative j rather than alternative k will be chosen by individual $i \iff$ the value of utility U_{ij} will exceed the value of utility U_{ik} ($U_{ij} \geq U_{ik} \quad \forall k \neq j$). The calculation of probabilities based on the obtained utility functions, however, varies with different types of logit models.

Among the most common model types is the Multinomial Logit model (MNL). One of the main reasons behind its popularity is its relative straightforwardness and efficiency. It does not allow, however, for capturing dependencies between alternatives and assumes an unrealistic random error distribution. This is addressed by another model type, namely the Nested Logit, in which similar alternatives can belong to the same nest. Furthermore, each alternative belongs to exactly one nest. This allows for much more realistic results, on the condition that the nesting structure is correctly designed. A variation of the Nested Logit model is the Cross-Nested Logit model (CNL). It is used when several decisions are made simultaneously. This can include a situation where the airport selection as well as the airport access mode choices are made jointly. To obtain an even greater accuracy of the model, a Mixed Logit model may be used. Its main differentiator, when compared to previous types, is that it allows parameters, $\beta = \beta_i$, to vary between individuals, i. As such, β_i becomes a parameter unique to each individual, in turn, making the utility also vary per individual, i. Such a modification results in $\beta = \beta_i \sim f(\beta \mid \theta)$, where θ represents the distribution of parameters of a considered density function affecting β. This, in turn, forces the calculation of P_{ij} to become an integration over the distribution of parameters.

Each of the four distinct types of logit models can be characterised by distinct features and applications. Furthermore, each type also has its own set of relative advantages and drawbacks. In order to better visualise those, Table 4 has been made comparing the four model types with one another, as depicted below.

Table 4: Comparison of discrete-choice logit models

Model Type	Key Feature	Strengths	Weakness	Probability Function
MNL	Errors are uniformly distributed, simple	Easy, fast	Unrealistic random error distribution	$P_i = \dfrac{e^{V_i}}{\sum_j e^{V_j}}$
Nested Logit	Correlation within nests	Handles grouping	Requires correct nesting structure	$P_{ij} = P_{ij\|m} \cdot P_m$
CNL	Alternatives belong to multiple nests	Very flexible	Complex estimation	$P_{ij} = \displaystyle\sum_m P_{ij\|m} \cdot P_m$
Mixed Logit	Captures differences between individuals	Very robust	Heavy computation	$P_{ij} = \int \frac{e^{(X_{ij}\beta)}}{\sum_{k=1}^{J} e^{(X_{ik}\beta)}} f(\beta\|\theta)\, d\beta$

As can be observed from the above table, each model has its distinct advantages, but also its own set of drawbacks. For the purpose of this project, it has been determined that the Nested Logit will be the best choice. This is due to it having the required balance between accuracy and the required computational complexity, hence making it the most desirable alternative for this project [13]. Such a selection still allows for correlation, for example, within airports, allowing for the grouping of similar alternatives.

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[11] `https://www.sciencedirect.com/topics/economics-econometrics-and-finance/logit-model`

F Research gap

The phenomenon of Dutch passenger leakage has already been rather extensively analysed in 2010 [18]. As part of the study, it has been observed that 7% of Dutch residents chose to fly from a foreign airport [18]. The findings from that time period cannot be translated into current or future simulations, however. This is due to two very important factors. First, the effects of the tax in 2008 were heavily distorted due to the Global Financial Crisis. Furthermore, the neighbouring countries of Germany and Belgium did not have any aviation taxes in place at the time, which could have skewed the results. What can be extracted from the analysis, however, is the estimation of the impact that a unit tax increase will have on the choices among Dutch residents. This, however, requires a further analysis of the topic. In order to quantify the potential passenger leakage depending on the aviation tax rates in different countries, a mathematical logit model is to be created. The findings of the model will then be used to evaluate the passenger leakage for the proposed 2027 tax levels and analyse the passenger sensitivity to hypothetical changes to the taxation structure.

III Methodology

To evaluate the passenger leakage of Dutch residents to foreign airports, a discrete-choice model was to be designed. The model would capture different factors affecting passengers' choices, such as airfare, airport access time, or service frequency through utility functions [10]. These would then be used to quantify the probability of selecting a given airport among Dutch travellers, based on which the passenger leakage would be quantified. Furthermore, by examining the changes in probabilities depending on the aviation tax level, the effects of the surcharge on the passenger leakage would be examined.

A Assumptions for the model

Before designing the model, a decision must be made regarding which factors should be incorporated and which can be neglected. For that, a list of assumptions was created, with the aim of aiding in the creation of the mathematical model.

- **ASS-01:** To maintain competitiveness, transit passengers are not affected by the imposed taxes. As such, they are excluded from the study.
- **ASS-02:** The analysis focuses exclusively on departing Dutch passengers, with Belgian and German residents being disregarded.
- **ASS-03:** The airport charges are assumed to be fully absorbed by the airlines.
- **ASS-04:** The aviation taxes are fully passed onto the passengers.
- **ASS-05:** Business and leisure passengers exhibit differing preferences, with the former placing a much greater value on travel time.
- **ASS-06:** The selection of airport, airline and access mode is assumed to be interrelated, all of which make up distinct alternatives.
- **ASS-07:** Train schedules are neglected and assumed to always allow for airport access in time for the desired flight.
- **ASS-08:** The passengers' loyalties to a given airport or airline are neglected, with only a preference expressed for a given airline type (such as low-cost carriers).
- **ASS-09:** Only non-connecting itineraries are considered.
- **ASS-10:** Every Dutch citizen exhibits equal flying propensity characteristics, regardless of the location of residence.
- **ASS-11:** The travel demand is assumed not to be changing due to the changes to the aviation tax structure.
- **ASS-12:** Only commercial flights are considered for the analysis.
- **ASS-13:** All factors affecting airport selection are assumed to be limited to the list of parameters incorporated into the model.

B Model design

In order to properly analyse the airport selection among Dutch residents, a mathematical model was to be created. By encompassing a discrete-choice modelling approach, the model would be able to estimate the probabilities of a given airport being chosen by an individual residing in a given region of the Netherlands. Furthermore, this would also allow for quantifying the occurrence of passenger leakage and analysis of its dependence on the imposed aviation taxes.

B.1 Model scope

For the analysis, several airports have been considered. Although there are a considerable number of airports within the Netherlands alone, due to the influence of the aviation tax, some of the country's residents may choose to fly from abroad, contributing to the passenger leakage phenomenon. As such, airports outside of the Netherlands also had to be included in the analysis. For that, a total of four Dutch (NL) airports, four German (DE) airports and two Belgian (BE) airports have been identified, the complete list of which can be found in Table 5, together with the corresponding airport codes (IATA) and the 2024 passenger numbers.

Table 5: Analysed airports

Country	Airport	IATA	pax_{2024}
NL	Amsterdam Schiphol Airport	AMS	66.8 million
	Eindhoven Airport	EIN	6.9 million
	Rotterdam/The Hague Airport	RTM	2.2 million
	Maastricht Aachen Airport	MST	0.2 million
DE	Cologne Bonn Airport	CGN	10.0 million
	Düsseldorf Airport	DUS	20.0 million
	Dortmund Airport	DTM	3.1 million
	Weeze Niederrhein Airport	NRN	2.0 million
BE	Brussels Zaventem Airport	BRU	23.6 million
	Brussels Charleroi Airport	CRL	10.5 million

Although there exists one more airport in the Netherlands, Groningen Airport (GRQ), it does not have any commercial flights serving it as of 2026. As such, it has been excluded from the analysis.

The scope of the model was also defined. As part of the model, there shall be a decision maker, i, representing a Dutch resident, living in a specified four-digit postcode area (PC4), pc_r, who is travelling either for business or leisure purposes. This, in turn, leaves an individual, i, with a set of possible alternatives to choose from, J_i. The obtained set provides feasible flight options that would serve the desired destination on the selected day of travel, representing all possible choices that are available to individual i. The alternatives themselves, $j = (x, y, TYPE, p)$, can be inherently defined by five separate factors:

- x, departure airport
- y, destination
- $TYPE$, airline type (ultra-low-cost (ULC), low-cost (LC), full-service (FC), premium) operating a given flight
- p, ground access mode, where $p \in \{\text{car, public transport}\}$

Furthermore, for each individual, i, the alternatives form part of the choice set, $\mathcal{J}_i$, which can be defined by Equation 2:

$$\begin{aligned} \mathcal{J}_i = \{ & j = (x, y, TYPE, p); \\ & x \in \mathcal{X}_i,\ y \in \mathcal{Y}_i,\ p \in \mathcal{P}\}, \end{aligned} \tag{2}$$

where $\mathcal{X}_i$ denotes the set of feasible departure airports for individual i, $\mathcal{Y}_i$ the set of feasible arrival airports, and $\mathcal{P} = \{\text{car}, \text{public transit}\}$ describes the set of selectable ground access modes. This, in turn, results in the airport choice being an integral factor throughout the flight selection process, as defined by ASS-06 in subsection A.

B.2 Utility framework

To model the passenger behaviour, a utility framework had to be specified. This would define the perceived attractiveness of an alternative j for an individual i, in accordance with Equation 1, presented in subsection E. In order to create such a utility function, the utilised parameters had to be identified. This was done in accordance with the literature review research, which was described in section II. Based on that, a list of parameters has been created, which can be observed below.

- $Fare_j$, the base airfare of an alternative j, excluding any aviation taxes that would apply.
- $Tax_{x,y}$, the aviation tax charged at departure airport x for a flight to a destination y.
- $T^{GA}_{r,x,p}$, the ground access travel time of individual i from postcode area r to the departure airport x by means of access mode p, where $p \in \{\text{car, public transport}\}$.
- $C^{GA}_{r,x,p}$, the financial cost of accessing airport x from postcode area r by individual from postcode r using access mode p.
- ST_j, a schedule time binary parameter, which captures the relative undesirability of early-morning or late-evening departures. If the flight departs before 7 am or after 8 pm, it is equal to one and equal to zero in other scenarios.
- $FREQ_{x,y}$, the daily frequency of flights from departure airport x to destination y.
- $TYPE_j$, the airline service category (such as a low-cost or a full-service carrier), as part of an alternative j. A different value was assumed for each airline service category: ULC $= -0.6$, LC $= -0.3$, FC $= 0.0$, Premium $= 0.3$, with the aim of differentiating between the various perceived attractiveness of airline types.
- CAR_j, a binary parameter equal to one in case a given alternative j entails accessing the departure airport by car. Its aim is to capture the inherent preference by individuals for the greater comfort of the trip associated with the journey by car.
- $BUS_r = 0.12 \quad \forall r$, a parameter defining the fraction of business trips taken, in accordance with subsection D.
- NL_x, a domestic airport binary parameter equal to one if the departure airport x is located in the Netherlands, equal to zero otherwise. This allows for capturing the inherent preferences for flying out of the domestic airports among passengers [28].
- $\ln(pax_{2024_x})$, an airport-specific constant related to the number of passengers served by a given departure airport x. It is used to correlate airport size with perceived attractiveness, where the additional gain diminishes with increasing passenger numbers, which could be approximated by a logarithmic scale [29]. As such, the values for pax_{2024_x} were to be used based on what was presented in Table 5.

Based on the presented parameters, the deterministic utility function of the model, V_{ij}, was defined, as expressed by Equation 3.

$$
\begin{aligned}
V_{ij} = {} & \beta_{Fare}\, Fare_j + \beta_{Tax}\, Tax_{x,y} \\
& + \beta_{T^{GA}}\, T^{GA}_{r,x,p} + \beta_{C^{GA}}\, C^{GA}_{r,x,p} \\
& + \beta_{ST}\, ST_j + \beta_{FREQ}\, FREQ_{x,y} \\
& + \beta_{TYPE}\, TYPE_j \,+\, \beta_{CAR}\, CAR_j \\
& + \gamma_{BUS}\left(BUS_r \times T^{GA}_{r,x,p}\right) \\
& + \beta_{\mathrm{NL}}\mathrm{NL}_x + \beta_{pax}\ln(pax_{2024_x})
\end{aligned}
\tag{3}
$$

where β and γ are the to-be-estimated coefficients affecting the marginal utilities of the corresponding parameters. It is also to be noted that all utility coefficients related to the incurred costs and time, such as $C^{GA}_{r,x,p}$ or $T^{GA}_{r,x,p}$, are to be negative. This is due to the alternatives, which are more costly or result in a longer overall travel time, being deemed less desirable. Simultaneously, coefficients corresponding to service-related parameters, such as $FREQ_{x,y}$ or CAR_j, are to be positive, representing increased desirability of that alternative. Moreover, in the case of business travellers, their relative value of time is up to three times larger than in the case of leisure travellers [25]. As such, the corresponding utility coefficient, γ_{BUS}, was assumed to be equal to $\gamma_{BUS} = 3 \cdot \beta_{T^{GA}}$. Lastly, due to the model only considering non-connecting itineraries, as defined by ASS-09, the directness aspect was neglected.

B.3 Model description

To accurately model the passenger choices, a Nested Logit model was employed. This was done in order to allow for correlation among utilities and the grouping of alternatives. As part of the model, a two-level nesting structure was adopted. This includes:

- **Upper level:** designed to resemble airport choice
- **Lower level:** reflects flight options and ground access mode alternatives given the selection of a given airport.

Such a nesting structure was envisioned due to the standardised grouping of different flight choices. When selecting a given flight, first, a grouping of all flights departing from a given departure airport, x, is performed. Only afterwards does an analysis of the flights departing from that airport occur. Furthermore, ground access mode choice has been placed in the lower level. This is due to the flight selection decisions being performed jointly with the selection of a ground access mode to reach the given departure airport, making the two aspects correlated.

As described in section II, within the Nested Logit model, the probability of an individual i selecting an alternative j is dependent on both the conditional probability $P_{ij|x}$ and the marginal probability P_{ix}. While the first one describes the likelihood of a given alternative being selected given the selection of a given nest (departure airport), the latter determines the probability of selecting that nest. As such, $P_{ij|x}$ was defined, as depicted by Equation 4.

$$
P_{ij|x} = \frac{\exp\left(\frac{V_{ij}}{\mu_x}\right)}{\sum_{k\in\mathcal{J}_x}\exp\left(\frac{V_{ik}}{\mu_x}\right)},
\tag{4}
$$

where $\mathcal{J}_x \subset \mathcal{J}_i$ is the subset of alternatives departing from airport x and $\mu_x \in (0,1]$ is the dissimilarity parameter of a nest corresponding to departure airport x. Its values represent correlation among parameters in a given nest, with values closer to one indicating a lower correlation. While the conditional probability determines the likelihood of a given alternative being selected, given the selection of a particular nest, the marginal probability determines the likelihood of the selection of the nest itself. To calculate that, however, the inclusive value must be defined. It represents the expected maximum utility that can be obtained from all alternatives in a given nest, therefore describing the overall attractiveness of a departure airport. This can be summarised by:

$$
IV_{ix} = \ln\left(\sum_{k\in\mathcal{J}_x}\exp\left(\frac{V_{ik}}{\mu_x}\right)\right).
\tag{5}
$$

The inclusive value, in turn, allows for obtaining the marginal probability, as visualised by Equation 6, located below.

$$
P_{ix} = \sum_{j\in\mathcal{J}_x} P_{ij} = \frac{\exp\left(\mu_x\, IV_{ix}\right)}{\sum_{z\in\mathcal{X}_i}\exp\left(\mu_z\, IV_{iz}\right)},
\tag{6}
$$

Calculating both the conditional and marginal probabilities is crucial in order to obtain the probability of a given alternative, j, being selected by individual, i. This can be expressed by Equation 7.

$$
P_{ij} = P_{ij|x}\cdot P_{ix}.
\tag{7}
$$

Obtaining the probability of selecting a given alternative is also crucial for another reason. It allows for the quantification of the passenger leakage phenomenon, where Dutch residents choose to fly from foreign rather than domestic airports. For an individual, i, the leakage probability, L_i, can be defined as:

$$
L_i = \sum_{x\in\mathcal{X}^F} P_{ix}
\tag{8}
$$

where $\mathcal{X}^F \subset \mathcal{X}_i$ is a set of foreign departure airports. The obtained leakage probabilities would then be used to calculate the aggregate passenger leakage rate. This, however, greatly differs depending on the postcode location of a given resident. To account for that, Equation 9 was created.

$$
L = \frac{\sum_r n_{\mathrm{residents},r}\cdot L_r}{\sum_r n_{\mathrm{residents},r}}
\tag{9}
$$

where $n_{\mathrm{residents},r}$ denotes the number of individuals residing in a given postcode in the Netherlands. The obtained leakage rate quantifies the number of residents who would choose to depart from a foreign airport. However, this occurrence can already be observed, irrespective of the proposed changes to the aviation tax structures. As such, the relative change in passenger leakage due to the modifications to the imposed aviation taxes, ΔL, needs to be quantified. As the tax levels change, $Tax^0_{x,y} \rightarrow Tax^1_{x,y}$, so will the leakage rate, $L^0 \rightarrow L^1$. This has been conceptualised by means of Equation 10, as presented below.

$$\Delta L = L^1 - L^0 \tag{10}$$

where L^0 is the original leakage rate and L^1 is the newly obtained rate. The difference between them then allows for the quantification of the influence of air passenger taxes on the propensity of Dutch travellers to fly from foreign airports. Lastly, it is to be noted that the described mathematical model requires extensive data collection. For that, a data acquisition and analysis process had to occur. This resulted in several different data types, the overview of which can be found in Appendix A.

IV Results

After creating the mathematical model, the analysed data were evaluated to obtain the results. This required calibration of the utility coefficients of the model by means of an optimiser that would adjust them so that the results of the model resembled real-life data. The optimiser would evaluate the deterministic utility functions (Equation 3) and compute the corresponding leakage (Equation 9) using initial assumed coefficient values. Those values would then be iteratively modified until the model outcomes matched reality, as documented in subsection A. The calibrated model was then used to analyse the 2024 benchmark results (subsection B). Following that, the results for the upcoming 2027 tax levels were obtained (subsection C). Lastly, the sensitivity analysis was performed (described in subsection D), with the process being used to evaluate the susceptibility of passengers to changes in the aviation tax, thereby completing the analysis.

A Calibration of the model

To obtain the results, all coefficients corresponding to the parameters used in the utility function (Equation 3) had to be calibrated against real-life data. This would then allow for the direct analysis of the impact of the aviation tax on the passenger leakage. To perform the calibration, a multi-step approach was used. First, the data directly used in the model itself were standardised on a $[-1, 1]$ scale within their respective categories. This was necessary so as to evaluate the relative importance of the different parameters against each other. Afterwards, the calibration of the coefficients themselves was performed, with two joint loss functions being defined. First, the difference in leakage between 2007 and 2008 was compared, as described in section II. When comparing the two years with each other, it was found that 7% of Dutch residents, or $7\% \cdot \frac{1}{2/3}$ of Dutch travellers, saw their plans modified because of the aviation tax introduced in 2008 [18]. For that part, the following loss function was defined:

$$\text{loss}_{\text{leak}} = [(L_{2008} - L_{2007}) - \text{target}_{\text{leak}}]^2 \tag{11}$$

where L_{2008} and L_{2007} correspond to the leakage in the respective years, and $\text{target}_{\text{leak}} = (7\% \cdot \frac{1}{2/3})$ represents the target leakage change [18]. To calibrate all coefficients, however, more data had to be evaluated. For that, the 2024 airport selection probabilities data were used [30], as presented in Table 6.

Table 6: Airport selection probabilities (2024)

IATA	Airport	Share
AMS	Amsterdam Schiphol Airport	67%
EIN	Eindhoven Airport	11%
RTM	Rotterdam The Hague Airport	7%
DUS	Düsseldorf Airport	5%
BRU	Brussels Airport	3%
NRN	Weeze Airport	1%
-	Other	6%

Based on the above values, the second loss function could be defined:

$$\text{loss}_{\text{airports}} = \sum_{x \in \mathcal{X}} \left(\text{share}^{\text{model}}_x - \text{share}^{\text{target}}_x \right)^2 \tag{12}$$

where $\text{share}^{\text{model}}_x$ is the probability of selecting airport x as calculated by the model and $\text{share}^{\text{target}}_x$ is desired airport selection probability. Lastly, to obtain the total loss function, loss_{tot}, the two losses were summed:

$$\text{loss}_{\text{tot}} = \text{loss}_{\text{leak}} + \text{loss}_{\text{airports}} \tag{13}$$

The presented loss function was then used to calibrate the coefficients, using a `scipy.optimize.minimize` optimiser in Python. Its method was set to "`L-BFGS-B`", a limited-memory quasi-Newton code for bound-constrained optimisation. It was selected due to its efficiency and low computational cost for large problems. Furthermore, an upper limit of 100 iterations was selected. The performed procedure concluded the calibration process, with the resulting coefficient values presented in Table 7.

Table 7: Calibrated utility coefficients of the model

Coefficient	Value
β_{Tax}	-0.8028
β_{Fare}	-0.3111
β_{TGA}	-1.9559
β_{CGA}	-1.4269
β_{ST}	-0.5200
β_{FREQ}	0.0000
β_{CAR}	0.4871
γ_{BUS}	-5.8678
β_{TYPE}	0.0100
β_{NL}	1.2274
β_{pax}	0.0000
Final loss	0.001388

The obtained coefficients were subsequently used to compare the model against real-life 2024 benchmark data

[30]. What is worth noting is that the coefficients corresponding to the flight frequency as well as the airport size are equal to zero. This, in turn, suggests that those parameters do not influence passenger behaviour in the model environment. This could also be observed in reality, where many might be indifferent to the number of flights offered out of the departure airport to the given destination as long as the direct connection itself exists. To confirm this and to evaluate the calibration process, the differences in distinct airport market shares were calculated by rerunning the model. This also included recomputing the difference in total experienced leakage. The results of the calculations were then compared with the benchmark data, as can be observed in Table 8.

Table 8: Calibrated airport selection probabilities (2024)

IATA	Actual	Calibrated	Difference
AMS	67%	66.78%	-0.22%
EIN	11%	13.43%	+2.43%
RTM	7%	6.76%	-0.24%
DUS	5%	2.73%	-2.27%
BRU	3%	5.34%	+2.34%
NRN	1%	2.48%	+1.48%
Other	6%	2.49%	-3.51%
CRL	-	1.44%	-
DTM	-	0.66%	-
CGN	-	0.39%	-
Leakage	**13.00%**	**13.04%**	**+0.04%**

As can be observed from the above table, the data regarding Maastricht Aachen Airport is missing. This is due to the airport not having any commercial flights scheduled in 2026. As such, it has been excluded from the remainder of the analysis. Furthermore, it can be observed that the calibrated model outputs resemble real-life airport selection probabilities, with the overall aggregate leakage remaining very comparable to the benchmark data. The actual choices of distinct foreign airports experience differences of ≈ 2 p.p.. This could, however, be attributed to the limited size of the dataset, as the obtained flight schedules only accounted for one day of departures. In order to obtain the most accurate dataset, a full week of flight schedules would have to be incorporated. Implementing this approach, however, would demand computational resources beyond those available for this project and would considerably expand the thesis scope. As such, this was not implemented, with the existing dataset providing sufficient aggregate accuracy.

B Results of the calibration process

Based on the performed calibration, the airport selection probability distributions were calculated. Those, however, depend heavily on the geographical location, PC4 postcode, of the Dutch residents. As such, the obtained probabilities were plotted on the map of the Netherlands, with each postcode having a unique airport selection probability distribution. The obtained plots have been visualised and can be observed in Figure 2, located below.

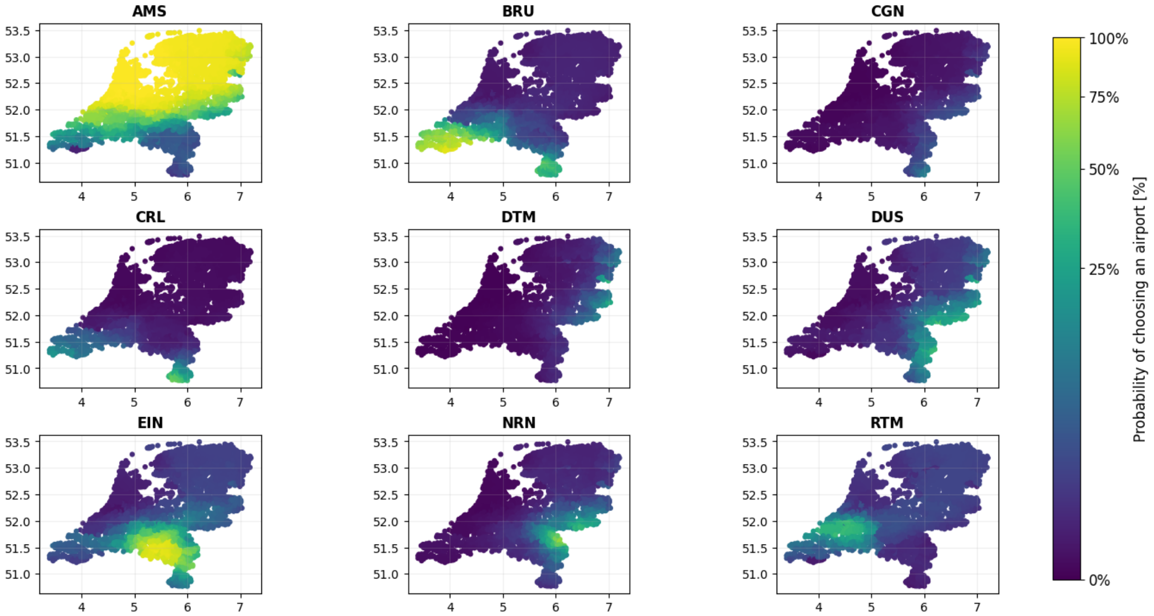

Figure 2: Airport selection probabilities by PC4 postcode (2024)

As can be observed, the Northern part of the Netherlands is mostly limited to flying from AMS. The South of the country, as well as the border regions, are the only areas in which other airports become more likely choices. These are, however, to a large extent, the remaining two domestic Dutch airports of EIN and RTM. When analysing the Southeastern region of Noord-Brabant, a strong affinity for the local Eindhoven airport can be observed. Simultaneously, the RTM airport seems to be mostly catered to the local residents of the Rotterdam/The Hague metropolitan area. The airport, however, is not the dominant choice for the residents of the region, which can be mostly attributed to its considerably smaller number of offered destinations than the relatively nearby Schiphol. Furthermore, the two largest foreign airports, BRU and DUS, only seem to be capturing the border regions, with BRU becoming the default alternative for the residents of Zeeland. Lastly, the remaining airports fail to attract Dutch residents, with NRN and CRL being the only airports exceeding 1% market share, as documented by Table 6. This, in turn, results in the aggregate leakage of 13.04%, the distribution of which can be observed below.

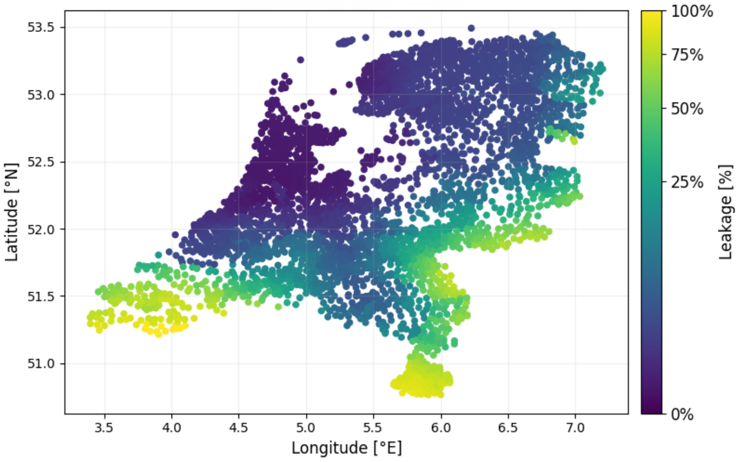

Figure 3: Aggregate leakage (2024)

It is to be noted that the above results only represent the aggregate probabilities, which may largely differ depending on the distinct destinations and flight lengths, which are subject to different tax levels. To evaluate this, the distribution of airport selection probabilities was evaluated against a sample of distinct destinations. One of those was Alicante Airport (ALC). The airport is characterised by rather extensive leisure demand, which, in turn, prompts a lot of low-cost carriers to offer flights to the destination. As a result, numerous alternatives on this route are available from many airports, as characterised by Figure 4.

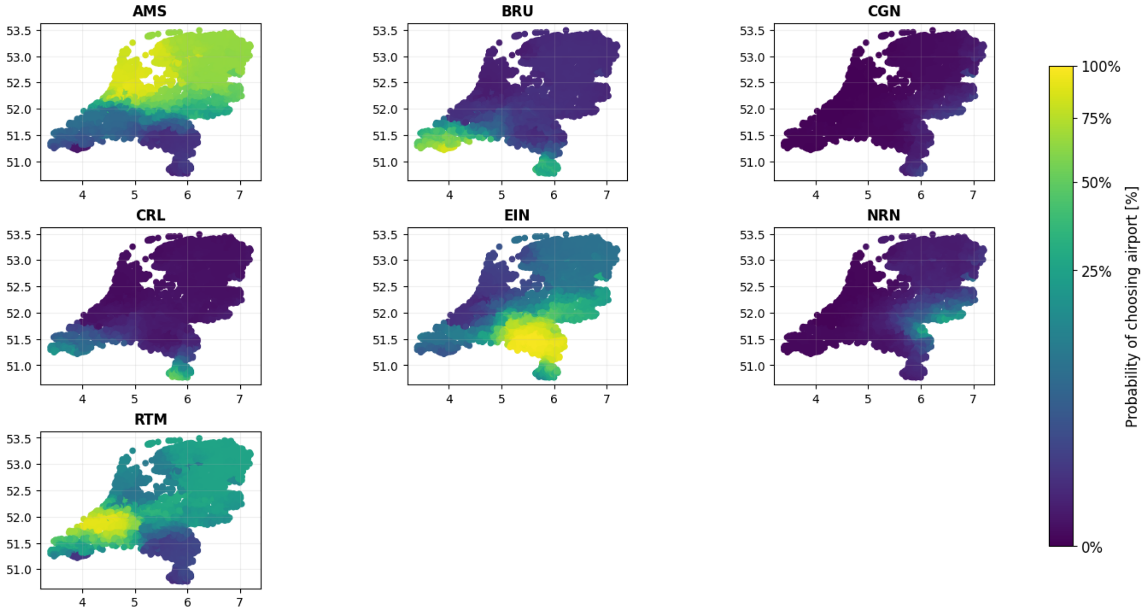

Figure 4: Airport selection probabilities for ALC-bound flights by PC4 postcode (2024)

The above figure showcases a rather different picture compared to the aggregate probability distribution. When only considering the ALC-bound flights, it can be observed that AMS is no longer the clear choice, with its selection probability dropping to 40.12%. As such, most of the country is extensively considering other Dutch airports. This includes EIN (22.86%) and especially RTM (31.15%). The airports prove to be a feasible alternative for most of the country, driving passengers away from the hub of AMS. The foreign airports fail to attract large numbers of Dutch residents on the route, with only BRU being a viable alternative, albeit for a small fraction of the population (3.59%). The route is characterised by rather small values of passenger leakage, with total values reaching 5.87%. This is considerably lower than the aggregate leakage of 13.04% and also lower than the leakage experienced on similar short-haul (< 2500 km) routes (12.71%).

Apart from the short-haul ALC route, longer routes were also analysed. This included Doha Hamad International Airport (DOH). The airport serving the capital of the Middle Eastern country was particularly interesting as it is one of the few airports that is served by only one airline, Qatar Airways. As of 2026, DOH sees approximately two flights per day from all three bigger airports in the region: AMS, BRU, DUS. This, in turn, results in no differences in the airfare or airline type being present on the route. As such, the only factors affecting airport selection should be the aviation tax as well as the airport access time and cost. This is indeed confirmed by the model, as can be observed in Figure 5 below.

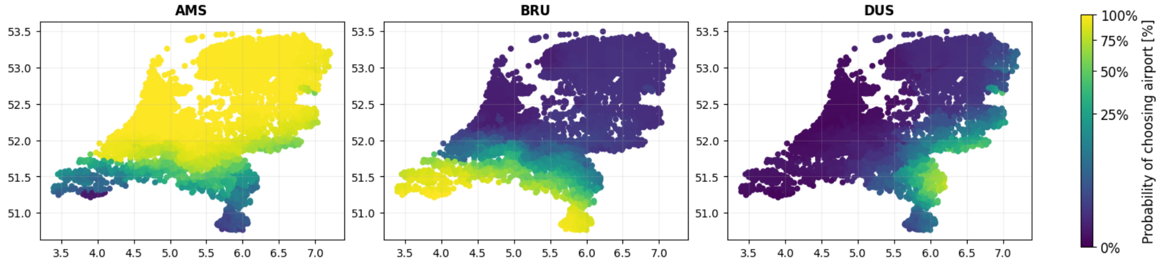

Figure 5: Airport selection probabilities for DOH-bound flights by PC4 postcode (2024)

As can be observed, AMS is the dominant airport for most of the country on this route, attracting a total of 80.52% of the Dutch population. Its share, however, significantly decreases in the South of the country, where BRU becomes the default choice, being selected by 15.53% of the population. DUS, however, does not attract many Dutch residents (3.95%), only being considered in the regions bordering Germany. As such, the leakage on this route amounts to 19.48%, marginally higher than the 18.67% leakage on medium-haul flights (2500 - 5500 km). It should also be noted that medium-haul flights experience the most extensive leakage of the three types of flight lengths. Apart from the aforementioned categories, long-haul flights (> 5500 km) experience a leakage of 11.59%. Its relatively lower value of aggregate leakage could be mostly attributed to the lack of long-haul flights out of the considered German airports, with the only foreign airport offering long-haul destinations being BRU. The overview of the relative differences in passenger leakage depending on the flight length can be observed in Table 9.

Table 9: Passenger leakage by flight length (2024)

Leakage type	Flight length	L_{2024}
Short-haul	< 2500 km	12.71%
Medium-haul	2500 - 5500 km	18.67%
Long-haul	> 5500 km	11.59%
Aggregate	All distances	13.04%

The above results have also been evaluated on a PC4 postcode level. For that, the leakage has been plotted on the map of the Netherlands, as depicted by Figure 6.

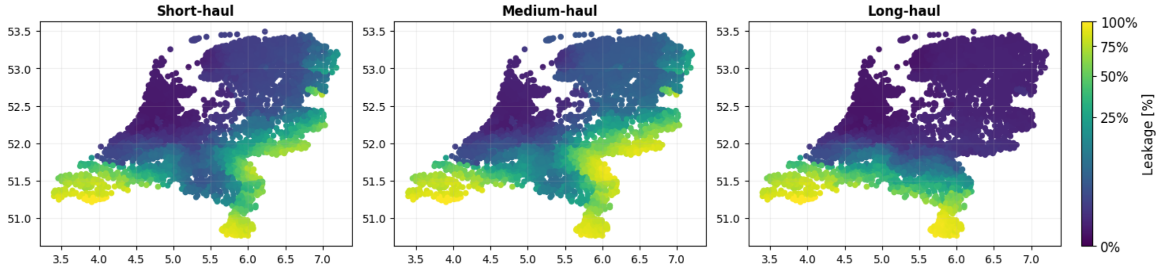

Figure 6: Leakage by haul type (2024)

When comparing the above figure to Figure 3, it can be observed that short-haul flights closely match the aggregate leakage values. This is to be expected as the short-haul flights make up the majority of all flights offered. The leakage distribution, however, changes a lot when analysing longer flights, where a significant difference can be observed. There, the medium-haul flights exhibit substantially greater leakage, especially in the Eastern part of the Netherlands, while long-haul leakage can be observed only in the South of the country. This, however, can be explained by the lack of long-haul flights out of the considered German airports, leaving BRU as the only foreign alternative. The above figure highlights yet another aspect, though. It shows that different types of flights are subject to different passenger behaviour, which can be significantly affected under different tax levels.

C Passenger behaviour under 2027 tax levels

The calibrated model was subsequently used to evaluate and predict the passenger behaviour for the upcoming 2027 tax levels, with the emphasis placed on the changes in leakage with respect to the 2024 benchmark levels. The results of this can be observed in Table 10.

Table 10: Predicted airport selection probabilities (2027)

IATA	2024	2027	Difference
AMS	66.78%	66.41%	-0.37%
EIN	13.43%	13.12%	-0.31%
RTM	6.76%	6.60%	-0.16%
DUS	2.73%	3.61%	+0.88%
BRU	5.34%	4.56%	-0.78%
NRN	2.48%	3.13%	+0.65%
CRL	1.44%	1.20%	-0.24%
DTM	0.66%	0.83%	+0.17%
CGN	0.39%	0.54%	+0.15%
Leakage	**13.04%**	**13.87%**	**+0.83%**

As can be observed, under the new tax levels, all Dutch airports experience a decrease in popularity among Dutch passengers. The higher tax levels of the Netherlands, combined with a reduction in aviation taxes across the border in Germany, result in Dutch passengers becoming more likely to fly from there instead. This is evidenced by all German airports experiencing a noticeable increase in selection probabilities. As such, DUS is set to become the largest beneficiary of the new tax structure, with an increase in popularity of close to one percentage point. The increase in leakage to foreign airports is not uniform, however. Both Belgian airports, BRU and CRL, experience a decrease in airport selection probabilities among Dutch residents. This can be attributed to the upcoming increase in air passenger tax on all flights over 500 kilometres in length, as described in section II. Despite that, the aggregate leakage is set to increase by a total of 0.83 p.p. from 13.04% to 13.87%, showcasing the impact of air passenger tax on airport selection among Dutch residents.

To better visualise the new airport selection probabilities, the results were plotted on the map of the Netherlands. This can be observed in Figure 7, which is located below.

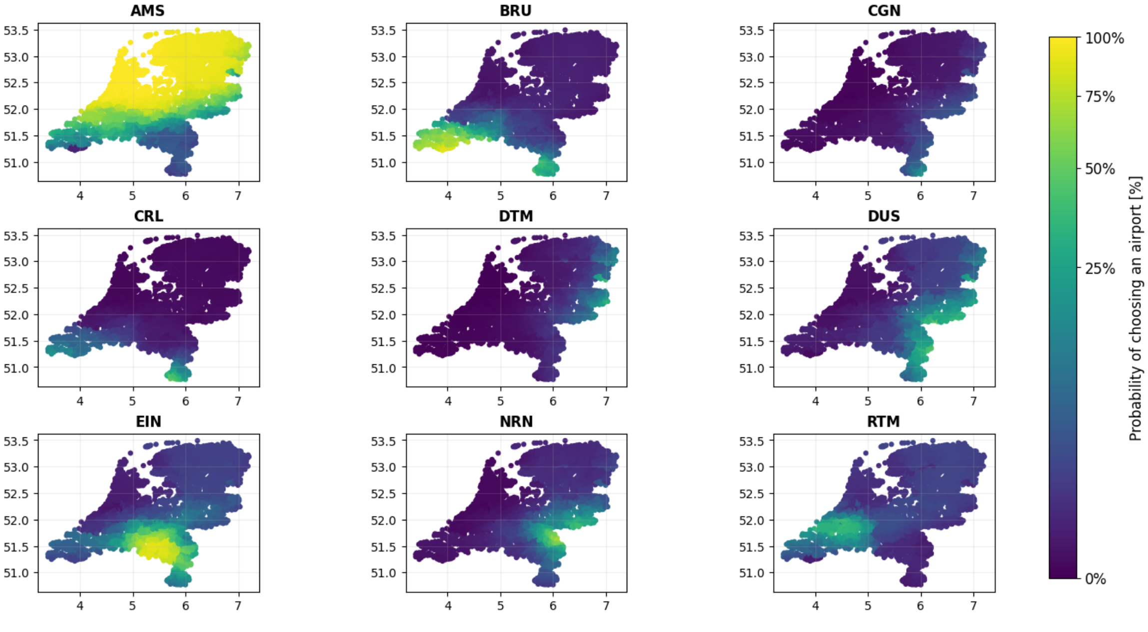

Figure 7: Airport selection probabilities by PC4 postcode (2027)

When comparing Figure 7 with Figure 2, it can be observed that the two figures are very similar to one another. Some subtle differences remain, however. Those are mostly the border regions, in which the largest changes in the aggregate leakage can be observed. Just like described in Table 10, the largest increases in popularity among foreign airports can be observed in close proximity to the German border, whereas the decreases are observed close to the Southern neighbour of the Netherlands.

Apart from the airport selection probabilities, the passenger leakage was also analysed. Given that, just like airport selection probabilities, the leakage varies heavily with geographic locations, its distribution had to be plotted against the map of the Netherlands. This can be observed in Figure 8 below.

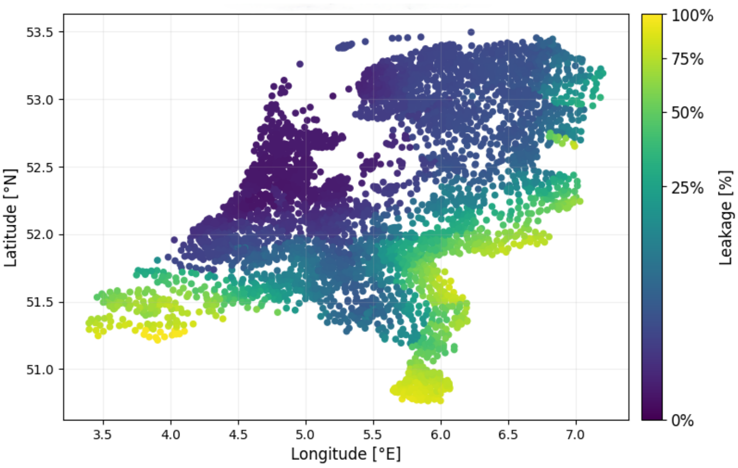

Figure 8: Aggregate leakage (2027)

Just like the airport probability selection graphs, the 2027 aggregate data closely resembles its 2024 counterpart. This can be attributed to the less than one percentage point (< 1 p.p.) increase in the passenger leakage value. Just like before, the largest leakage can be observed in the Southern provinces of Zeeland and Limburg, as well as in the Eastern regions bordering Germany, where the foreign airports are the default choice. To better visualise the comparison between the two leakage plots, Figure 9 has been created, which can be observed below.

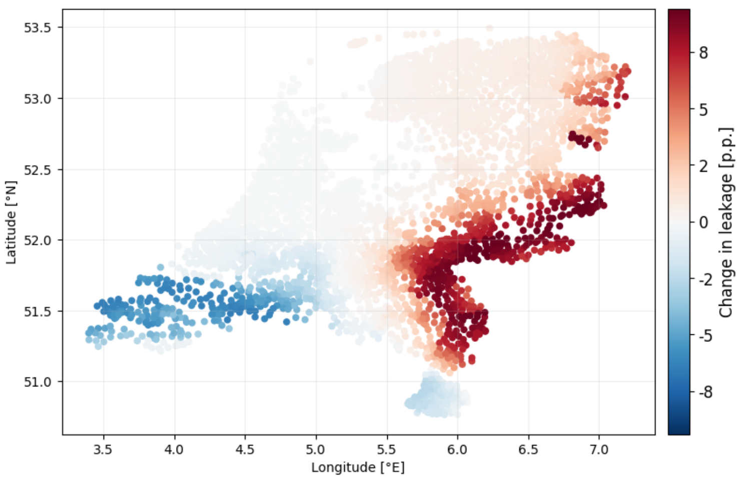

Figure 9: Change in aggregate leakage (2027 vs. 2024)

The above figure shows the change in the aggregate leakage values between 2024 and 2027 on a PC4 postcode level. As can be observed, the aggregate leakage does not increase uniformly in the country, but rather fluctuates across regions. The largest increase in passenger leakage can be observed in regions which are in close proximity to Germany. This phenomenon is mostly exacerbated in the areas surrounding the NRN airport or with good land access to the nearby DUS airport. As such, some PC4 postcodes experience an increase in passenger leakage reaching $\Delta L = 0.094 = 9.4$ p.p., showcasing the considerable increase in desirability of the nearby German airports. The regions neighbouring the Belgian border, however, experience a completely different phenomenon. In those areas, a decrease in passenger leakage is actually observed. Several PC4 postcodes in the Zeeland province are experiencing a decline of up to $\Delta L = 0.065 = 6.5$ p.p., in turn increasing the desirability of domestic airports. The presented plot closely reflects the data presented in Table 10, where the German airports are set to welcome 1.85 p.p. more Dutch passengers than previously. Simultaneously, Belgian airports are set to experience a net decrease in Dutch passengers of 1.02 p.p.. Once again, though, when analysing different types of flights separately, a completely different picture can be observed.

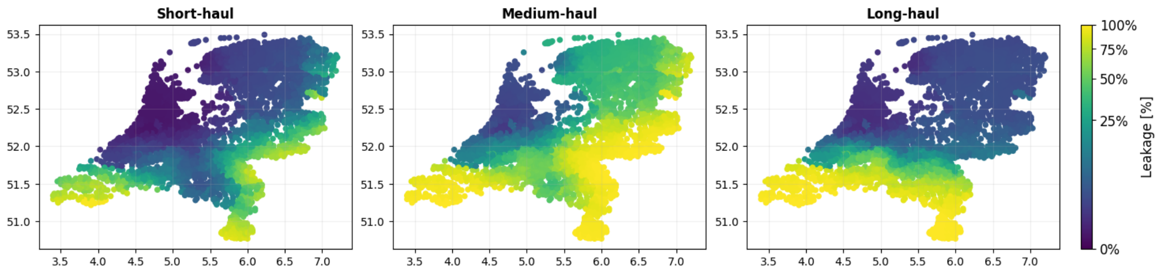

Figure 10: Leakage by haul type (2027)

Figure 10 showcases the passenger leakage per PC4 postcode depending on the flight distance. Although the leakage associated with short-haul flights is very comparable to the aggregate values, this is not the case for longer flights. When analysing medium-haul and long-haul flights, it can be observed that in some regions the Dutch airports are very rarely selected, with the leakage values reaching close to 100%. This can be attributed to the effects of the aviation tax on longer flights, where the difference in total fare is much larger than on short-distance routes. As such, unless there is no other option, the residents of those regions will not select Dutch airports when flying. This is especially true for medium-haul routes, where the foreign airports of BRU and DUS still offer ample destinations, making them viable alternatives. As a result, a vast majority of Dutch residents will consider flying from them in search of lower prices. This is also present on long-haul routes, albeit to a much smaller degree, caused by the lack of long-haul flights offered from the considered German airports. As such, only regions with good access to BRU will consider flying from abroad. To better visualise the changes in passenger leakage by flight length, Table 11 was created, which contains an overview of the passenger leakage values for 2024 (L_{2024}) and 2027 (L_{2027}), as well as the respective changes in leakage (ΔL).

Table 11: Passenger leakage by flight length (2027)

Leakage type	Flight length	L_{2024}	L_{2027}	ΔL
Short-haul	< 2500 km	12.71%	13.16%	+0.45%
Medium-haul	2500-5500 km	18.67%	41.85%	+23.18%
Long-haul	> 5500 km	11.59%	25.60%	+14.01%
Aggregate	All distances	13.04%	13.87%	+0.83%

As can be observed, the passenger behaviour greatly differs depending on the flight length. Medium-haul flights, which were already subject to the most extensive leakage, experience the largest increase. This equals a total of 23.18 p.p., which results in almost half of all Dutch residents (41.85%) opting to fly from foreign airports instead of domestic ones. As such, this passenger segment is to undergo the largest changes. Passenger leakage is also expected to increase substantially on long-haul journeys, as indicated by the 14.01 p.p. increase. The smallest changes are to occur on the short-haul market, where the increase in leakage does not exceed 0.5 p.p.. Those values are comparable to the aggregate changes, as the short-haul routes make up the vast majority of all flights. Furthermore, just like before, the changes in passenger behaviour are also location-dependent. For that reason, the changes in leakage were evaluated on a PC4 postcode level, as depicted by Figure 11.

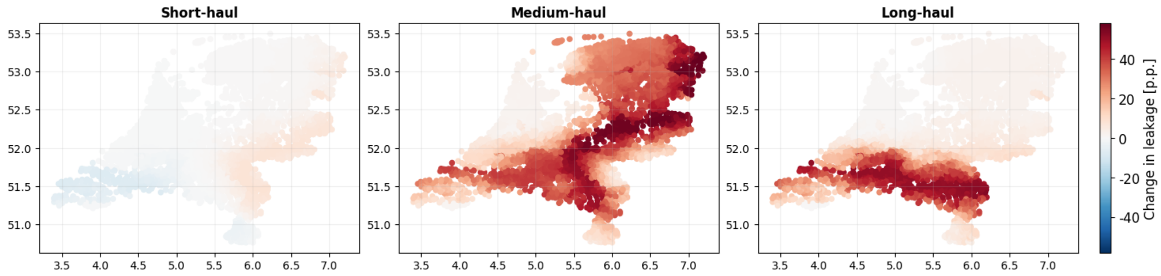

Figure 11: Change in passenger leakage by haul type

The above figure depicts the changes to the leakage experienced among Dutch residents on varying flight lengths. As can be observed, when considering the short-haul flights, only minor changes occur. In case of medium-haul and long-haul journeys, however, the changes in leakage are substantial. This is especially true in the Southern and Eastern regions of the country. Those are the areas which are better connected to the foreign airports, in turn becoming more likely for the local residents to reevaluate their preferences under the new tax regime.

Just like in subsection B, two specific case scenarios have been evaluated, namely ALC and DOH. For both of them, the airport selection probabilities have been analysed on a PC4 postcode level, with the aim of evaluating the impact of the aviation tax on the selected routes.

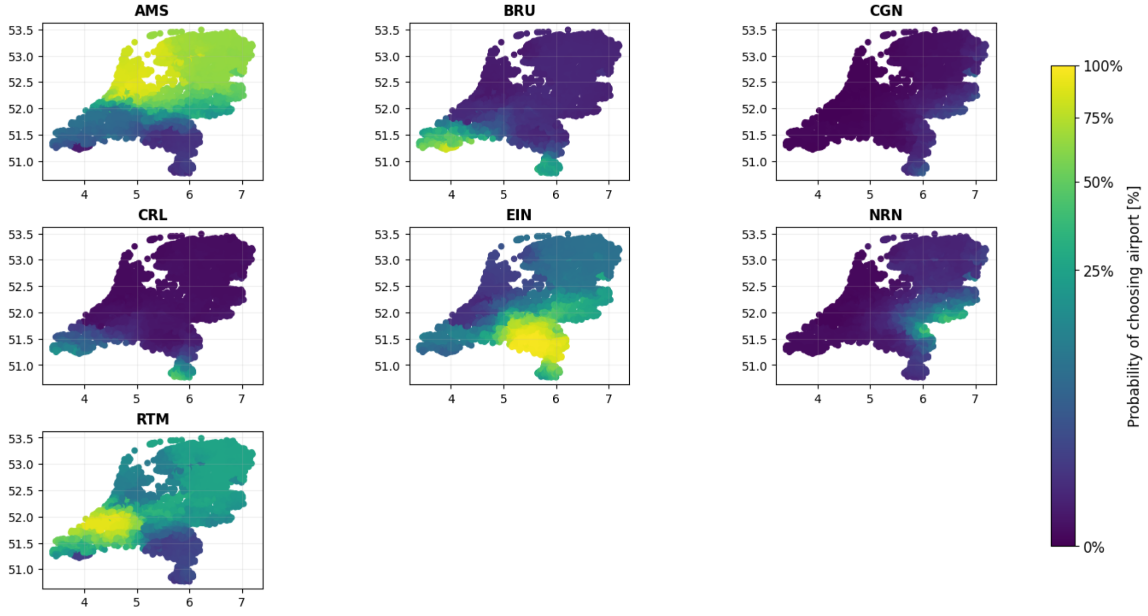

Figure 12: Airport selection probabilities for ALC-bound flights by PC4 postcode (2027)

Figure 12 showcases the airport selection probabilities among Dutch residents who are to fly to ALC in 2027. When compared with Figure 4, it can be observed that the two look rather similar, with only minor changes occurring. This can also be confirmed by considering the changes in airport selection probabilities, as depicted by Table 12.

Table 12: Airport selection probabilities for ALC-bound flights

IATA	2024	2027	Difference
AMS	40.12%	40.01%	-0.11%
EIN	22.86%	22.90%	+0.04%
RTM	31.15%	31.52%	+0.37%
BRU	3.59%	2.77%	-0.82%
NRN	0.88%	1.56%	+0.68%
CRL	1.32%	1.09%	-0.23%
CGN	0.08%	0.15%	+0.07%
Leakage	**5.87%**	**5.57%**	**-0.30%**

As can be observed, the passenger leakage on this route is actually set to decrease. This is mostly due to the Belgian airports of BRU and CRL experiencing a rather substantial decrease in airport selection probabilities. This entails a 0.82 p.p. decrease for BRU and a 0.23 p.p. decrease for CRL and can be attributed to the upcoming increase in air passenger tax for travellers departing from Belgian airports. As such, the passengers who would have otherwise chosen those airports will now opt for other alternatives. In the case of Dutch residents located in the Southwestern parts of the country, the new airport of choice would mostly become RTM, given its relative proximity. The passengers residing in the Southeastern parts, however, will be more likely to depart from EIN airport, as well as the foreign NRN. The latter of the two is set to experience the biggest increase among Dutch residents (0.68 p.p.). Although the short-haul flights do not experience major changes in passenger traffic, the picture becomes rather different when analysing distinct medium-haul routes, such as DOH.

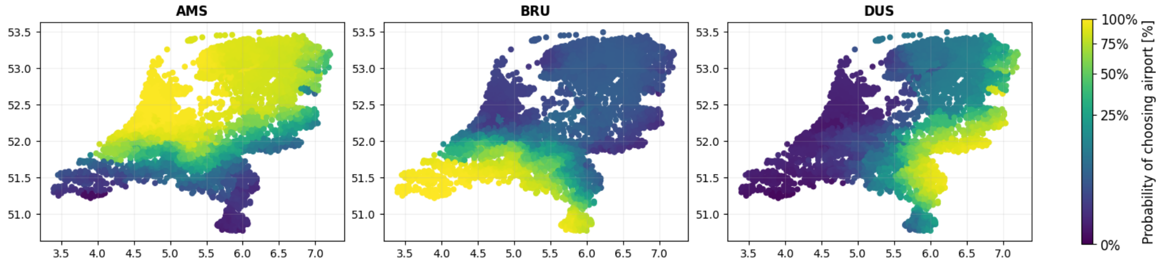

Figure 13: Airport selection probabilities for DOH-bound flights by PC4 postcode (2027)

When comparing Figure 13 with Figure 5, significant differences can be observed. First, the dominance of AMS has considerably decreased, with its selection probability dropping from 80.52% to 59.39%, signalling a 21.13 p.p. decrease. This, in turn, showcases the effect of the new tax levels in the region, resulting in the 21.13 p.p. increase in passenger leakage on this route. Under the new tax levels, DUS is set to experience the largest increase, attracting 11.47 p.p. more Dutch residents than before. Those are mainly the residents of Groningen, Friesland and the Eastern Dutch provinces. BRU, on the other hand, would attract 9.66 p.p. more Dutch residents, mostly the residents of the Noord-Brabant and Zuid-Holland provinces, with the overview of the changes in the experienced passenger leakage presented in Table 13.

Table 13: Airport selection probabilities for DOH-bound flights

IATA	2024	2027	Difference
AMS	80.52%	59.39%	-21.13%
DUS	3.95%	15.42%	+11.47%
BRU	15.53%	25.19%	+9.66%
Leakage	**19.48%**	**40.61%**	**+21.13%**

As part of the analysis, additional case scenarios were also considered. Among them were New York John F. Kennedy International Airport (JFK) and Sabiha Gökçen International Airport (SAW) in Istanbul. Those have also been extensively analysed, with their airport selection probabilities and passenger leakage being evaluated for both the 2024 and 2027 tax levels, as documented in Appendix B.

D Sensitivity analysis

As part of the research objective of the project, the evaluation of the passenger sensitivity to changes in the tax structure had to be examined. This entailed the creation of several scenarios, during which distinct air passenger taxes in the Netherlands would be modified by +/− 5% with respect to the 2027 tax structure (Scenario O). The corresponding changes in aggregate passenger leakage would then be evaluated as the passenger sensitivity. For that, the following scenarios were defined:

Table 14: Sensitivity analysis scenarios

	Short-haul	Medium-haul	Long-haul
Scenario A	+5%	+5%	+5%
Scenario B	+5%	-	-
Scenario C	-	+5%	-
Scenario D	-	-	+5%
Scenario E	-5%	-5%	-5%
Scenario F	-5%	-	-
Scenario G	-	-5%	-
Scenario H	-	-	-5%
Scenario O	-	-	-

Each of the eight scenarios entailed either a 5% increase or a 5% decrease in at least one of the aviation tax levels in the Netherlands. While Scenarios B-D and F-H specifically focus on modifying just the short, medium or long-haul flights, Scenarios A and E modify all the taxes by 5%. As such, by evaluating each scenario, it would be possible to determine how sensitive the Dutch residents are to the changes to the tax structure. To evaluate the outcomes, the aggregate leakage values were calculated once again for each scenario. Those have subsequently been summarised and can be observed in Table 15, which is located below.

Table 15: Sensitivity analysis aggregate results

	Leakage	Difference
Scenario A	14.72%	+0.85%
Scenario B	14.70%	+0.83%
Scenario C	13.89%	+0.02%
Scenario D	13.87%	+0.00%
Scenario E	13.06%	-0.81%
Scenario F	13.08%	-0.79%
Scenario G	13.85%	-0.02%
Scenario H	13.87%	-0.00%
Scenario O	13.87%	-

When analysing the results presented in Table 15, it can be observed that changes to the tax structure impact the aggregate passenger leakage, with Dutch residents choosing to fly from abroad given the lower prices offered across the border. Moreover, it can be noted that the changes to the short-haul flights are the most impactful. While a 5% increase across all tax levels increases passenger leakage by 0.85 p.p., increasing just the short-haul flights results in a 0.83 p.p. increase. The same situation can be observed when evaluating decreases in passenger taxes (Scenario E-H). In this case, a reduction across all tax levels results in the passenger leakage reduction of 0.81 p.p., while reducing the tax on just the short-haul flights will reduce the aggregate leakage by 0.79 p.p.. When analysing the changes to the taxes applicable to longer routes, however, the overall impact is much lower. Changes to the medium-haul routes (Scenario C and G) result in leakage changes of $\approx$ 0.02 p.p.. Simultaneously, changes to long-haul flights affect the aggregate leakage to an even smaller degree, with the resultant change not exceeding 0.01 p.p..

The changes in passenger leakage are not expected to be uniform on a geographic level, however. To verify this, the changes in the aggregate leakage were evaluated on a PC4 postcode level. The obtained outcomes were subsequently plotted on the map of the Netherlands, with the obtained results presented in Figure 14.

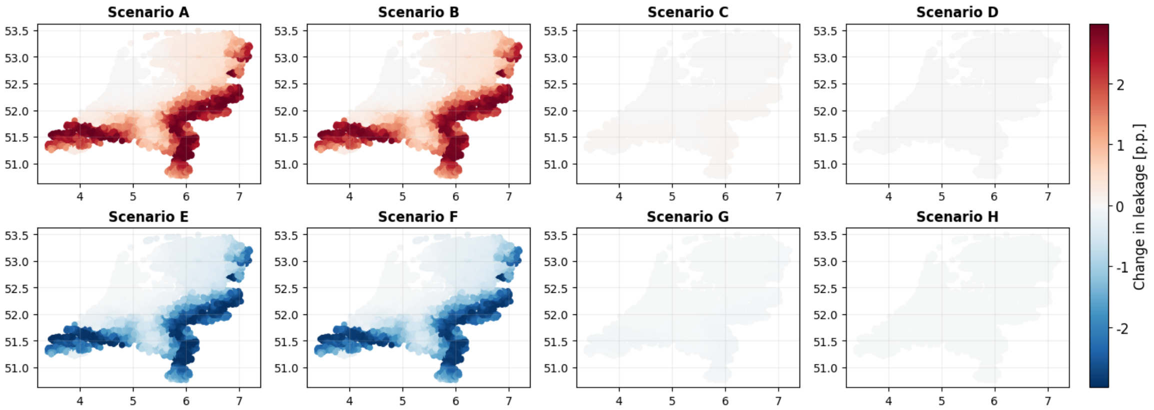

Figure 14: Aggregate sensitivity changes in leakage by PC4

The above figure showcases the absolute changes to the aggregate passenger leakage in each of the eight evaluated scenarios. When modifying the passenger tax, the majority of the leakage changes occur in the border regions of the country. This mainly includes the border between the Netherlands and Germany, as well as the Zeeland province, which is located in close proximity to neighbouring Belgium. As part of the modifications to the aviation taxes, some postcodes are to undergo significant changes in leakage. While the Randstad regions remain largely unaffected, the residents of the border regions could experience an increase in passenger leakage reaching $\Delta L = 0.0298 = 2.98$ p.p. for a 5% increase in passenger taxes. While those changes are substantial when the aviation tax on short-haul flights is modified, they become considerably lower when just the taxes for medium or long-haul routes are adjusted. For those scenarios, the aggregate leakage changes are too small to be captured by Figure 14, with the maximum observed change in leakage for Scenario C being $\Delta L = 0.0007 = 0.07$ p.p.. In the case of Scenario D, the maximum observed change was even lower, equalling $\Delta L = 0.0001 = 0.01$ p.p..

Thanks to the obtained results, the last aspect of the sensitivity analysis could be evaluated, namely, passenger leakage elasticities. This entailed quantifying how much a unitary change in aggregate aviation tax affects passenger leakage. At first, the elasticities were considered by means of relating the different leakage levels to different tax levels. Given the non-linear nature of the model, however, this approach would yield differing results depending on the direction of the hypothetical modifications to the 2027 tax structure (increase vs. decrease). To account for that, a different approach had to be considered. This, in turn, led to the adoption of the arc elasticity approach. This allowed for symmetry in responses while also reducing the bias from the non-linear outcomes of the model. For that, Equation 14 was defined:

$$E = \frac{(L_2 - L_1)/\bar{L}}{(T_2 - T_1)/\bar{T}} \tag{14}$$

The above equation quantifies elasticity, E, which, for the purpose of this project, was defined as the ratio between relative changes in passenger leakage and the relative changes in aviation tax levels. As such, L_1 and L_2 describe the passenger leakage given the positive (decreasing) and negative (increasing) changes to the tax levels, respectively. Simultaneously, T_1 and T_2 represent the corresponding tax levels ($T_1 = 0.95 \cdot T_{2027}$ and $T_2 = 1.05 \cdot T_{2027}$). Furthermore, the arithmetic means for both the passenger leakage levels and tax levels were calculated by means of $\bar{L} = \frac{(L_1+L_2)}{2}$ and $\bar{T} = \frac{(T_1+T_2)}{2}$. As a result, based on Equation 14, the passenger elasticity could be calculated. This was achieved by taking into account changes across all tax levels so as to allow for the aggregate passenger leakage elasticities (Scenario A and E). This resulted in $E = 1.195$, which, in turn, means that for each 1% change in the overall tax structure, the aggregate passenger leakage will change by 1.195%. This can be confirmed by considering Scenario A. In that case, the overall tax structure was increased by 5%. At the same time, the passenger leakage increased by 0.85 p.p. or $\frac{14.72\% - 13.87\%}{13.87\%} = 1.0613 = 6.13\%$. When using the elasticity formula, the predicted change in leakage would be $5\% \cdot 1.195 = 5.975\%$, with the slight discrepancy between the two values being attributed to the non-linearity of the model. As such, the obtained value of elasticity, $E = 1.195$, could be used for predicting passenger behaviour in case of future tax modifications.

It is to be noted that the above values only represent aggregate leakage changes. They do not evaluate the changes in leakage for particular routes or even different flight length types. The aim of the sensitivity analysis was to evaluate how the distinct tax changes affect the entire Dutch population as a whole. Based on the obtained results, it can be concluded that Dutch residents are indeed sensitive to the changes to the passenger taxes, with an elasticity of $E = 1.195$. Simultaneously, the greatest impact is observed as a result of changes affecting the largest fraction of all flights, namely short-haul routes.

V Discussion

The results of the created model present several relevant takeaways for both the airlines and policymakers. As such, crucial insights can be extracted from the performance of the model, which would shape the aviation industry in the region for many years to come. This section aims to discuss the insights obtained based on the performed work, as well as what the implications of those might be, while also addressing the limitations of the model.

A Implications of the model

Under the proposed 2027 aviation tax structure, the aggregate passenger leakage is set to increase from 13.04% to 13.87%, resulting in a total increase of 0.83 p.p.. The leakage change, however, is not uniform, as it depends heavily on the geographic location as well as the length of the undertaken flight. On a geographic level, the regions located in proximity to Belgian and German borders are set to undergo the largest leakage changes, with the municipalities located in the East of the Netherlands experiencing an increase in leakage of up to 9.4 p.p.. Simultaneously, the residents of the Zeeland province could experience a reduction in leakage reaching 6.5 p.p.. Those changes can be attributed to the modifications to the existing air passenger tax structures, where the taxes in Germany are set to undergo a considerable decrease of $\approx$ 20%. At the same time, most flights departing from Belgium and the Netherlands will be subject to increases in air passenger taxes, as presented by Table 3. The changes are also heavily dependent on flight length, where the medium and long-haul flights out of the Netherlands are set to become much less competitive. This, in turn, presents several crucial insights for the airlines operating in the region. In order to attract more customers, they could focus on advertising longer flights in the border regions of the country. This would allow them to increase the number of passengers flying from foreign airports, largely thanks to the increases in taxes on the longer routes departing from the Netherlands. This, however, is also an important metric for the Dutch policymakers.

When the proposal for the 2027 air passenger taxes was originally introduced, it aimed to ultimately disincentivise air travel, especially on long-haul routes, which produce disproportionately more greenhouse gases than their short-haul counterparts. While the new tax levels may indeed prompt some Dutch residents to reconsider their flight choices, many will simply commute across the border to Belgium to fly from there, assuming there is an alternative flight departing from that country. This risk can be visualised by Table 11, where the medium and long-haul flights are set to experience an increase in leakage of 15-20 p.p.. This, in turn, would actually contribute to an increase in greenhouse gas emissions due to the additional distances covered by the Dutch residents to reach the desired airports. The new tax levels present another issue, however. The refined tax structure poses a great risk for the AMS-based KLM, which could experience a considerable drop in passenger numbers on its longer routes. For that reason, KLM could become an airline that focuses solely on transferring passengers, thereby reducing its benefits to Dutch society. Furthermore, the tax changes could severely undermine the airline's competitiveness, effectively forcing AMS to focus solely on the transfer passengers while neglecting the local travellers, who pay the tax. Lastly, this could also create indirect problems for the Dutch government, which relies heavily on the revenue from the aviation taxes for its budget. To fully achieve the goal of disincentivising the Dutch residents from flying, however, Dutch policymakers would have to resort to international cooperation with their Belgian and German counterparts. Without doing so, the demand will be redistributed to foreign airports rather than diminished, thereby undermining the policy's objective.

When evaluating the passenger behaviour, the analysis concluded that for every 1% change in the aggregate aviation taxes, the aggregate passenger leakage would change by 1.195%. As such, this presents a unique opportunity for the policymakers who would aim to strike a balance between the environmental impact of aviation, tax revenues and the interests of Dutch residents. The obtained elasticity provides a linear approximation of the predicted passenger behaviour, which could be used for further modifications to the tax structure. By using the elasticity value, it would be possible to estimate the impact of hypothetical changes to the aviation taxes. This would then allow for fine-tuning of the tax levels so as to obtain the optimal leakage level that the policymakers would be satisfied with.

While the tax rates may affect passenger behaviour when it comes to airport selection probabilities, there are other factors in play which could also be used to offset the negative effects of the tax. This includes, among others, the airport access time and costs. As such, should policymakers want to offset the negative effects of the passenger tax, they could explore possibilities of allowing quicker and cheaper access to the airport. While the access time to AMS is already extensively optimised, with the airport having an intercity railway station located right underneath the terminal building, the access costs could be improved. This would have to be subject to separate research, but, if implemented correctly, could offset the negative effects of the higher tax rates for medium and long-haul flights. Furthermore, in the case of the remaining domestic airports, EIN and RTM, the airport access times could be reduced should a railway connection be built at the airport. Such measures could reduce the occurrence of passenger leakage on short-haul routes, in turn, greatly reducing the aggregate leakage values.

B Limitations of the model

As part of the project, several simplifications and assumptions were made. This was necessary to ensure the completion of the project during its anticipated timeline, while also delivering the expected results. As such, the model does possess some limitations, presenting a compromise between accuracy and practicality. This subsection aims to discuss the limitations of the model as well as their effects on the obtained results.

For the model to perform properly, extensive data acquisition and processing were required. This was necessary to obtain the relevant data and incorporate it into the model itself. One such data file was the flight departures from each of the considered airports. The obtained file was, however, simplified by only considering one day of departures. For the purpose of this study, the date of 19 January 2026 was selected. To obtain a more robust overview, however, a full week should be included. Doing so would allow for the incorporation of all routes into the analysis, as some flights only depart 2-3 times in a given week. As such, they could have been excluded from the used flight schedules dataset. Incorporating a full week of flights would inevitably increase the computational time required, though. It would also require the creation of another parameter, which would address the preferred day of departure. This could also lead to scenarios where, in case of strong preferences for a given departure day, a different airport is selected. This, however, was not analysed by the created model.

Another area that included simplifications was the airport ground access part of the model. When evaluating the airport access time by means of public transit, several aspects were excluded from the analysis. First, when calculating the travel times, only rail services were considered. Although train travel is the dominant public transport mode in the Netherlands, it is not the only alternative. In the case of cross-border travel, long-distance bus services often appear as a viable alternative. This includes Flixbus[12], which directly serves Brussels Zaventem Airport from several Dutch cities, but also Flibco[13], which offers a direct connection between the city of Maastricht and Brussels Charleroi. Furthermore, only the travel times were calculated, while neglecting the actual schedules. In practice, especially for early-morning flights, it may be impossible to reach the airport in time for the desired flight. By neglecting this aspect, some early-morning departures could have been artificially classified as much more desirable than they actually are.

The model itself also contains another limitation. In accordance with ASS-09, the airport selection probabilities are only evaluated on the basis of non-connecting itineraries. As such, the probabilities are calculated based on a limited number of alternatives. In reality, passengers often have an option of flying directly for a larger amount or paying a lower fee for a connecting itinerary. This is especially true for medium and long-haul routes, where the differences in airfare can be quite substantial. Furthermore, the air passenger taxes charged by the authorities would only cater to the first flight from the origin airport, which often is a short-haul flight to a nearby hub. As such, the tax levy would also be lower in the case of a connecting scenario. This, however, was excluded from the analysis as incorporating all viable connecting itineraries would greatly extend beyond the time frame and scope of this project.

When calculating the ticket prices, the model assumes that the base airfare does not differ between airports. This is in accordance with ASS-03, which states that the airport charges are assumed to be fully absorbed by the airlines. In reality, some airports charge much more per departing flight than others. As a result, some of those costs could be carried onto the consumer by means of a higher base airfare. Although the implementation of the differing airport charges into the model was considered, it was ultimately excluded from the analysis due to the lack of publicly available data on the matter.

The last major limitation of the model is related to the demand and supply changes as a consequence of the new tax levels. ASS-11 of the model states that the travel demand does not change in response to modifications to the aviation taxes. In reality, this could very well not be the case. Some Dutch residents could become disincentivised by the higher prices and choose not to fly altogether, thereby fulfilling the goal of Dutch policymakers. This, in turn, also becomes a relevant factor for the calculation of elasticities. The existing model only considers demand redistribution when calculating E. To obtain more accurate values, however, the changes to the total demand would be required. The same occurrence could be observed on the supply side, where the airlines would reduce the capacity from Dutch airports given the higher operating costs and potentially reduced passenger demand. This would also tie into the goals of the Dutch government, with fewer flights resulting in fewer emissions being produced. Incorporating this was deemed to be beyond the scope of the project, however. This is due to extensive additional research needed to accurately model the demand changes as well as the total greenhouse gas emissions.

VI Conclusion

The goal of this research was to quantify the passenger leakage phenomenon among Dutch residents under the influence of the aviation tax. Furthermore, the sensitivity of travellers to the changes in the tax levels was also to be evaluated. To accomplish that, a Nested Logit model was developed for the purpose of the study. Its goal was to incorporate different parameters affecting airport selection probabilities and return the passenger leakage experienced under the given tax level. The parameters used in the model were selected based on an extensive literature study and included the flight schedules, as well as the associated ground access time and costs, with each parameter having an associated utility coefficient defining its importance in the airport selection process. To calibrate the coefficients of the model, the model outcomes were compared to the existing airport selection probability distribution for the 2024 tax levels. This included a total of ten airports across the Netherlands, Belgium and Germany. Based on the performed calibration, the model was subsequently used to predict the passenger leakage for the upcoming higher tax levels of 2027.

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[12] `https://www.flixbus.com/`

[13] `https://www.flibco.com/en`

The results of the study show a small-to-moderate increase in the aggregate leakage of 0.83 p.p., from 13.04% in 2024 to 13.87% in 2027. The results, however, strongly differ depending on the region of the country. This is characterised by a rather small decline in the aggregate passenger leakage in the areas bordering Belgium and a somewhat larger increase close to the border with Germany. Furthermore, the total change in leakage was also found to be considerably higher in the case of medium and long-haul flights. While the short-haul journeys experience an increase in passenger leakage of 0.45 p.p. between 2024 and 2027, this number is ≈ 50 times higher in the case of medium-haul flights, for which the increase amounts to 23.18 p.p.. This segment also experiences the largest increase in passenger leakage, as for the long-haul flights an increase of 14.01 p.p. can be observed. As such, the obtained results show that the changes in passenger behaviour considerably differ depending on their location of residence as well as the type of flight.

The study also evaluated passenger leakage on a selection of distinct routes. Based on the obtained findings, it was concluded that the results also vastly differ for each route, with numerous factors affecting the passenger distribution. Apart from the varying aviation tax levels, these included the departure airports serving the given destination and the airlines operating the route. To further evaluate the effects of the aviation taxes, the analysis of the passenger sensitivity to the changes in the tax levels was also performed. For that, different scenarios were considered, each modifying a portion of the tax catered towards short/medium/long-haul flights by $+/-$ 5%. Based on that, the passenger demand substitution elasticity was calculated, resulting in $E = 1.195$. As such, for each 1% change in the aggregate tax level, it was found that the aggregate passenger leakage would also change by 1.195%.

Although the study provided a comprehensive analysis of the problem, it did not produce an exhaustive overview. As such, several future extensions of the model have been identified. Incorporating those would allow for an increase in the real-life accuracy of the model, while also facilitating a more holistic approach to the passenger leakage phenomenon. When the air passenger taxes were being introduced in the region, one of their goals was to disincentivise air travel altogether. It was hoped that, by increasing air passenger taxes, Dutch residents would choose not to fly, thereby reducing demand for air travel. The analysis of how many individuals could ultimately be discouraged from air travel due to the higher aviation taxes was not performed as part of this study, however, with all the demand being redistributed instead. The existing model could be extended by implementing modifications to the existing Nested Logit structure and incorporating an option not to fly. Another potential extension could involve expanding the analysed dataset. This would entail incorporating a full week of departures instead of a single day, hence allowing for comprehensive flight coverage while also addressing the departure date preferences. It would require, however, additional parameters and data points to accommodate this, therefore increasing the complexity of the model. Furthermore, the completeness of the dataset could also be expanded by implementing additional airport access mode alternatives, including the actual schedules. This would entail calculating the minimum travel times to the given airport across different alternatives, such as long-distance coach or intercity rail, based on the departure time of a particular flight.

The accuracy of the model could also be increased by incorporating income differences across postcode locations, allowing for a more detailed representation of leakage distribution across the country [31]. This approach could also be incorporated on a more granular level, where the preferences of travellers would vary between individuals. This would, in turn, affect the parameters of the model as the calibrated coefficients would then become dependent on the given individual, i. As a result, each individual would exhibit a different set of sensitivities to each of the parameters. To accommodate this, however, the existing logit model would have to be transformed from the Nested Logit structure into a Mixed Logit one. While this does pose several implications, especially regarding the extra computational power required, it would greatly increase the accuracy and robustness of the model.

Finally, the model could be expanded to examine the passenger leakage in a more holistic manner. This could include the calculation of the total emissions depending on the aviation tax levels and the corresponding passenger leakage. Based on that, an optimal tax level could be obtained, which would result in the lowest possible total emissions given a set of predetermined constraints. The outcomes of such analysis could later be used by policymakers. This would allow them to shape the desired tax structure as well as coordinate with the neighbouring countries on a cross-border aviation strategy, jointly addressing the leakage phenomenon.

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A Model data files

As part of the data acquisition process, several different types of data were obtained. Those involved the aviation taxes in the Netherlands, Belgium and Germany, flight departures from the considered airports, or the airport ground access costs. The obtained data files were subsequently preprocessed so as to be later used in the model, with their overview presented in Table 16.

Table 16: Overview of model data files

Type of data	File format	Purpose of processing
Aviation taxes	.csv files	To quantify the differences in aviation taxes between the Netherlands, Belgium and Germany
Geographic locations	.csv files	To obtain the geographical location of every airport and every PC4 postcode in the Netherlands
Airport driving accessibility	.csv files	To model the airport temporal driving distances
Train operations	.csv files	To extract temporal distances between each PC4 postcode and the considered airports
Airport ground access costs	.csv files	To model the costs of accessing airports by car or public transit
Flight schedules	.csv files	To quantify the attractiveness of different routes and airport competition
Data analysis & processing	.py files	To process the obtained .csv files into model-ready format
Model outputs	.py files	To quantify and evaluate passenger leakage to foreign airports

B Additional airport selection case scenarios

As part of the analysis, additional case scenarios were evaluated. Those included JFK and SAW. While the American airport was selected due to falling into the long-haul category, SAW was chosen for a different reason. Within the considered flight schedules dataset, it was the destination with the most origin airports, eight, serving it. As such, extensive changes in passenger behaviour were anticipated. For both cases, the airport selection probabilities were plotted on the map of the Netherlands to determine the impact of the geographical location on the selection of the departure airport. As such, Figure 15 and Figure 16 depict airport selection probabilities for JFK-bound flights by PC4 postcode for 2024 and 2027, respectively. Simultaneously, Figure 17 and Figure 18 present the same plots, albeit for SAW-bound flights.

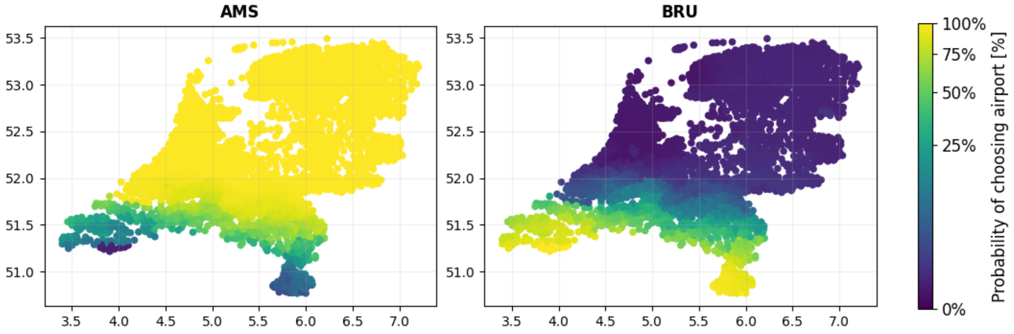

Figure 15: Airport selection probabilities for JFK-bound flights by PC4 postcode (2024)

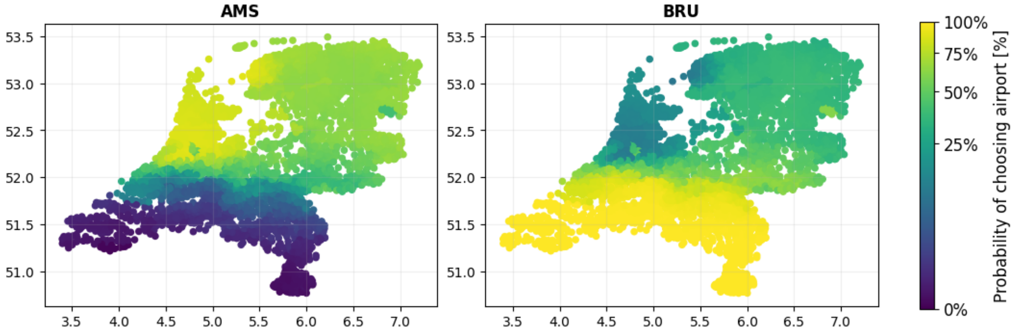

Figure 16: Airport selection probabilities for JFK-bound flights by PC4 postcode (2027)

As can be observed, the passenger distribution undergoes significant changes between 2024 and 2027. While in 2024, seven out of eight Dutch residents would fly to JFK on aircraft departing from AMS, in 2027, Schiphol would become a secondary choice for many. This results in its selection probability dropping to 40.86%, signalling a 46.47 p.p. drop. Those residents turn to BRU as an alternative departure airport instead, prompted by the substantial increase in air passenger taxes for long-haul flights departing from the Netherlands. As a result, the only region which remains loyal to AMS is its home province of Noord-Holland. The Southern regions, on the other hand, almost unilaterally choose to fly from Belgium in search of lower prices. The total airport selection probability distribution has also been analysed and can be observed in Table 17 below.

Table 17: Airport selection probabilities for JFK-bound flights

IATA	2024	2027	Difference
AMS	87.33%	40.86%	-46.47%
BRU	12.67%	59.14%	+46.47%
Leakage	**12.67%**	**59.14%**	**+46.47%**

Apart from JFK-bound flights, other case scenarios were also evaluated. One of those was the secondary airport of Istanbul, SAW. The airport was selected for the analysis due to being served by the most airports (a total of eight) from the considered region. As such, the corresponding airport selection probabilities have been plotted and can be observed below.

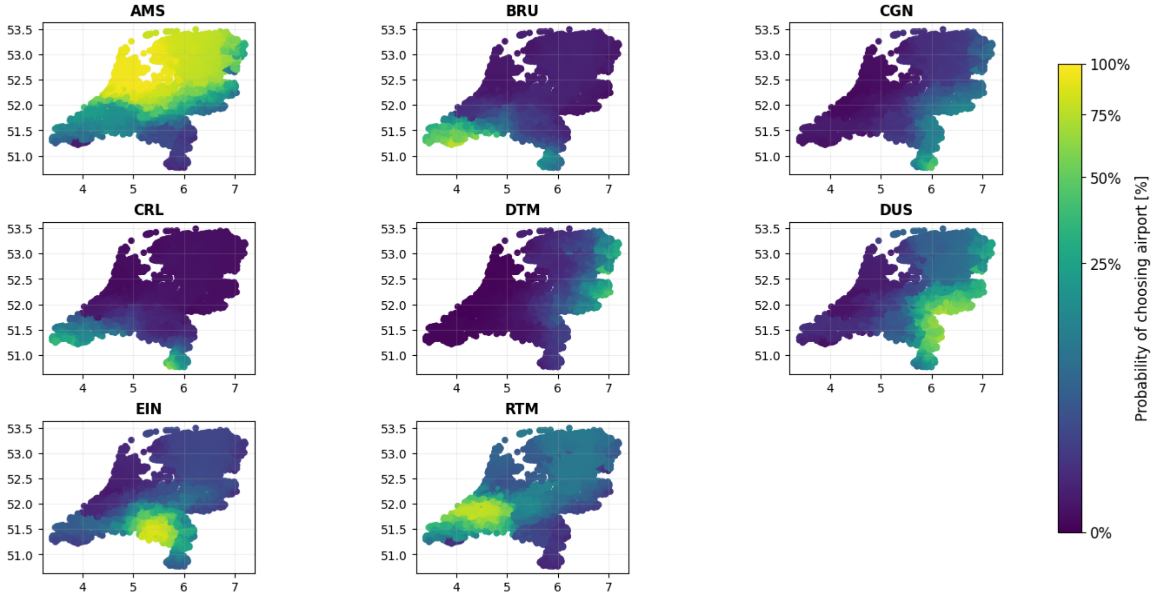

Figure 17: Airport selection probabilities for SAW-bound flights by PC4 postcode (2024)

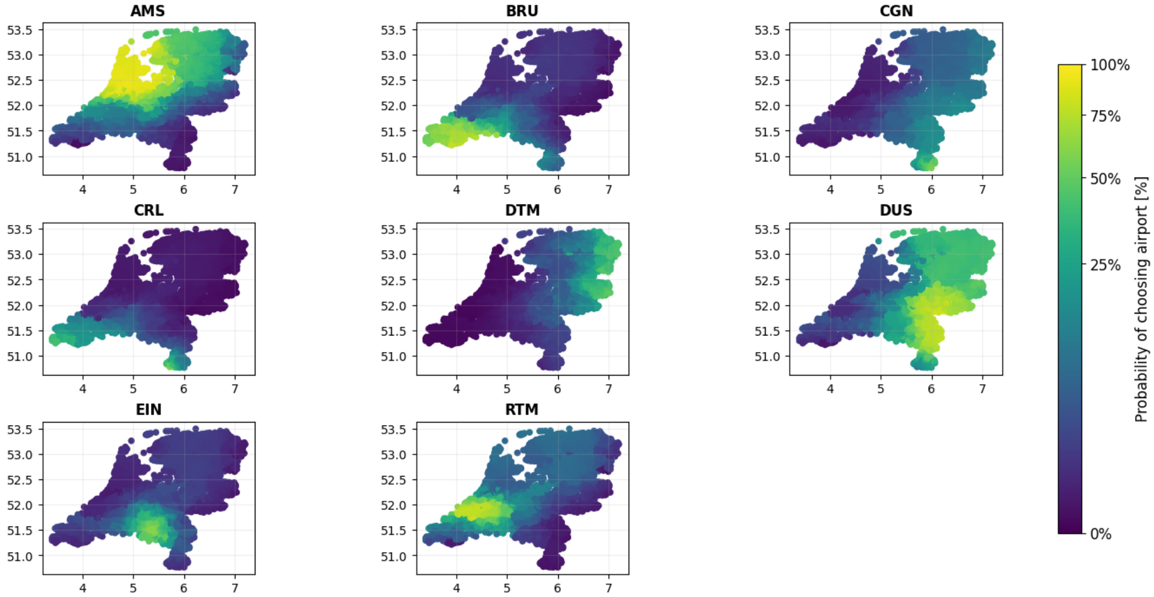

Figure 18: Airport selection probabilities for SAW-bound flights by PC4 postcode (2027)

The above figures depict the airport selection probabilities for SAW-bound flights. When comparing them against each other, the observed changes are rather significant. This can be confirmed by a 14.30 p.p. decline in the popularity of AMS, which proved to be much larger than in the case of any other Dutch airport. While EIN experiences a decline of 5.47 p.p., RTM is even less affected with a 1.94 p.p. reduction in the selection probability. This, in turn, results in a leakage increase of 21.69 p.p., more than half of which is absorbed by DUS (13.40 p.p.). The airport attracts a vast majority of passengers in the Eastern regions of the country, given its geographical proximity and lower passenger taxes. The distinct airport selection probabilities on the route can be observed in Table 18.

Table 18: Airport selection probabilities for SAW-bound flights

IATA	2024	2027	Difference
AMS	49.81%	35.51%	-14.30%
EIN	11.64%	6.17%	-5.47%
RTM	20.66%	18.72%	-1.94%
DUS	8.95%	22.35%	+13.40%
BRU	2.83%	5.82%	+2.99%
CRL	1.72%	2.31%	+0.59%
DTM	1.95%	4.06%	+2.11%
CGN	2.44%	5.06%	+2.62%
Leakage	**17.91%**	**39.60%**	**+21.69%**

Part II

Research Proposal

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1

Introduction

The topic of airport selection among multi-airport systems (MAS) has been subject to numerous research papers in recent years [1, 2, 3]. The authors of those papers would often conclude that accessibility of each airport, its connectivity, as well as the average airfare, would often be the main factors affecting travellers' airport choice [1]. As such, when the Netherlands first introduced the aviation tax in 2008, lengthy discussions emerged as to what the implications of this may be. One of the main discussion points was that Dutch residents would now travel to nearby foreign airports, located in places such as Brussels or Düsseldorf, to fly from there instead. Although the tax was short-lived and was abolished after only one year, there was evidence to suggest that a fraction of passengers indeed opted for such an approach [4]. As such, quantifying the total number of passengers who choose to fly from abroad is imperative to assess the potential 'leakage' that Dutch airports may experience and how this may hinder their operations.

In recent years, the tax was reintroduced with the aim of promoting more sustainable travel alternatives [1]. To further enhance this measure, the Dutch government announced that, in 2027, it would be further increasing the aviation tax, reaching in excess of €70 for each departing passenger on a long-haul flight. Naturally, this has, just like in 2008, raised concerns about the 'leakage' of passengers who are going to fly from foreign airports [4]. This, however, is yet to be modelled for the proposed tax levels, hence creating a research gap, which is to be explored as part of this Thesis. Apart from quantifying the passenger elasticity of airport choice, the Thesis will also aim to quantify the sensitivity of passengers to the changes in the aviation tax structure. The result of this analysis would help address the research objective of the Thesis:

Research objective: "*To develop a model that can quantify the influence of Dutch aviation tax on the propensity of Dutch residents to fly from foreign airports and evaluate passenger sensitivity to changes in the taxation structure.*"

As part of this proposal, first, the conducted literature study will be discussed in Chapter 2. The chapter will introduce the research covering the topic of multi-airport systems, along with the models that were used for the analysis. Furthermore, the main factors affecting the airport choice among departing passengers will also be discussed. As part of Chapter 2, the research analysing the topic of passenger leakage will also be presented. Based on the performed literature review, a research gap will be identified, with the research question also being formalised. Following that, the planning of the project is to be described in detail. In Chapter 3, the description of different phases of the thesis will be presented, together with the deliverables of each phase. Finally, the official timeline of the project will also be discussed, ensuring that the Thesis remains on schedule and any potential hurdles are accounted for.

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[1] `https://aviationsourcenews.com/netherlands-air-ticket-tax-hike-sparks-airline-and-airport-concerns/`

2

Literature Review

With the rapid expansion of the aviation market in the 1970s [5], the number of commercial airports in use would also increase. On a more local scale, this meant that numerous regions started being served by more than one airport, in turn, providing the passengers with a choice when it came to the airport of origin. This led to an additional occurrence, however. Even if an airport were to be much further away than its competitors but were to be deemed attractive by departing passengers, its market share would still be significant [6]. For that reason, making an airport as appealing as possible turned into an ever-more crucial aspect for aviation executives across the world. Simultaneously, however, the analysis of multi-airport regions (MARs) themselves came under the scrutiny of research and extensive modelling, making the topic an ever-relevant study area.

This chapter will aim to address all aspects related to the concept, as well as identify the research gaps that are yet to be explored. First, an overview of different topics related to MARs will be presented in Section 2.1 - Section 2.4, with Section 2.1 describing the concept of airport selection in a multi-airport system (MAS). Afterwards, Section 2.2 will focus on the ground accessibility of airports and the impact on the perceived attractiveness of an airport. Those will subsequently be elaborated upon in Section 2.3, which will introduce the concept of airport catchment area and passenger leakage. Section 2.4 will then address the effect of taxation and the demand elasticity, comparing the taxes in the Netherlands, Germany and Belgium. Afterwards, in Section 2.5, an analysis of different travel groups will be performed. Finally, a discussion on different model types, which could be used in order to model the airport selection choices and quantify the potential passenger leakage due to the tax, will be presented in Section 2.6. This will then be followed by the formal identification of a research gap in Section 2.7. Finally, in this section, the research question will also be formulated along with the supportive subquestions.

2.1. Airport selection

The concept of airport selection in multi-airport regions was first researched by Harvey [7] in 1987. As one of the outcomes of the study, it was concluded that there are multiple factors affecting airport selection. The main ones were deemed to be related to the airport ground access time as well as the flight frequency to the desired destination. Furthermore, the paper concluded that the impact of those factors greatly depends on the passenger type, business or leisure. Those findings have later been confirmed and expanded upon, stating that the airport selection is also dependent on whether one is a resident of a given region or a visitor [8, 9, 10]. Furthermore, the income of a given individual is also of importance [2, 11, 12]. This, in turn, exposed the differences in demand elasticity with respect to the airfare. Individuals with lower incomes would be much more likely to choose an airport that offers cheaper flights to their destination and/or has lower ground access costs. As such, those individuals would be more likely to travel to airports, which are considerably further away, if it were to correspond to a lower total incurred cost [2, 6, 13].

The airport selection was also found to be closely related to the connectivity of considered airports [14, 15]. For a defined destination, passengers might first filter out all the airports that do not offer flights there. Only afterwards will they select the airport of origin from the refined list [16]. Furthermore, during the final airport selection, the flight schedules from different airports are also simultaneously considered [3, 8]. If the flight to the desired destination were to depart in the early morning from a distant airport, it may experience lower demand, with early morning and late evening flights being considerably less desired [17].

When considering the geographic locations of different airports in a given MAS, it can be observed that, in the case of departing passengers, the perceived attractiveness of an airport's location differs greatly. This is primarily due to where that particular passenger resides. This can be observed by means of Table 2.1

Table 2.1: Spatial distances of example airports to passenger locations [km].

	Passenger 1	Passenger 2	Passenger 3
Airport A	13	32	51
Airport B	46	24	26
Airport C	62	35	23

As can be observed in the above table, the locations where passengers reside can have a tremendous impact on the preferred airport. Furthermore, if there are multiple airports at very comparable distances, as evidenced by Passenger 3, they will be much more likely to switch from Airport C to Airport B, should the latter start offering more preferable flights to the desired destination.

As can be seen, the process of selecting an airport to fly from is subject to numerous factors. Not only does it depend on whether or not an airport offers flights (direct or connecting) to the desired destination, but also on the airfares offered. The time of departure of the aircraft will also affect the decision process, with early morning and late evening flights being considerably less desirable. Finally, the airport location and ground accessibility with respect to the location of an individual also need to be considered [18]. All those aspects jointly affect the airport-airline selection process, making any model striving to analyse it much more complex.

2.2. Airport ground accessibility

A crucial concept, which greatly affects passengers' decisions of where to fly from, is the ground accessibility of airports [10, 14]. The easier it is to reach a given airport, the more likely it is to be chosen. As such, local governments would often dedicate extensive resources in order to improve access to local airports, which would, in turn, boost their perceived attractiveness. As a result, when considering airports across the world, it can be observed that in numerous instances, there will be a highway and/or a railway link right next to the airport. Moreover, with growing passenger numbers, many airports may consider increasing the number of ground access alternatives, especially if they are located further away from the centre of the respective metropolitan area [19].

Ground accessibility of an airport often relates to numerous different modes of transport, as passengers may have differing preferences as to how to reach their departure airport. Those may naturally differ across the world due to cultural differences. Within the European Union, though, the vast majority of travellers, 67%, access their departure airport by road, either by driving themselves or by being driven by a friend/family or a taxi driver [20]. As a result, fast and convenient road access is crucial for airport attractiveness. In the case of the Netherlands, as well as its neighbours, each commercial airport is located either adjacent to or at the very least in close proximity to a highway.

Although most passengers reach their departure airports by road, the portion arriving by public transit remains significant, 33% [20]. This number is also bound to increase if public transit access were to be significantly improved. A very successful idea on how this can be achieved has been implemented at Amsterdam Schiphol Airport (AMS) and Flughafen Frankfurt Main (FRA), where a cross-country intercity rail station has been built at the same location as the airport itself. This, in turn, allowed passengers from more distant regions to conveniently reach the airport.

A very important aspect related to the attractiveness of public transit as an airport ground access mode is its reliability and frequency. This is crucial as passengers may have their flights depart at vastly different times of day. As such, should there be no viable public transit option that would get them to the airport around the desired time, they will opt for a different airport access mode [8]. Furthermore, the perceived reliability of public transit also plays a role. In case of departing flights, passengers tend to place a much greater value on avoiding potential delays in airport access [21]. This, in turn, means that they will only consider public transit as an airport ground access mode if they deem it to be sufficiently reliable. As such, usage of public transit is very dependent on the services offered. If it is extremely reliable and rather frequent, allowing travellers to arrive at the airport at the desired time, then it will be much more likely to be chosen. On the other hand, if it were to have a limited frequency or often suffer from unscheduled service disruptions, then it would be rarely chosen due to not being considered a viable alternative. Interestingly, though, for some travellers, the overall journey time was deemed not to be a major factor [11].

The final element related to airport ground accessibility is the directness aspect. When analysing airport attractiveness, an important consideration for departing passengers is how convenient it is to access an airport. In the case of road access, this would relate to how many times one has to change the highway/road they are to travel on. In the case of public transit, this would mean the required number of connections. The time spent on connections, the out-of-vehicle travel time (OVTT), not only extends the total duration of the airport trip but is also perceived to be much more impactful than the in-vehicle travel time (IVTT) [11, 19]. As such, each required change will inherently extend the airport access time, also known as temporal distance, reducing the perceived attractiveness of an airport [11].

2.3. Passenger leakage

Another heavily researched aspect covers the topic of airport catchment areas and passenger leakage. The catchment area of an airport can be defined as the geographic region in which the market served by a given airport is located[1]. As such, quantifying such a catchment area is a crucial metric from an airport's perspective. It allows it to analyse where its passengers are coming from and how far its sphere of influence extends. Naturally, the airport's catchment area and corresponding market share will be much larger in areas where competition between airports is very sparse [22]. This is usually present in more remote areas, with a very limited number of airports. A prominent example of that would be the Canary Islands, where, except for Tenerife, there is only one commercial airport per island. As such, the airports on the respective islands experience little to no competition, allowing their catchment areas to cover entire islands. On the other hand, in MARs, such as London, airport catchment areas will differ greatly between airports, depending on their locations. This has been summarised in Figure 2.1, which can be observed below.

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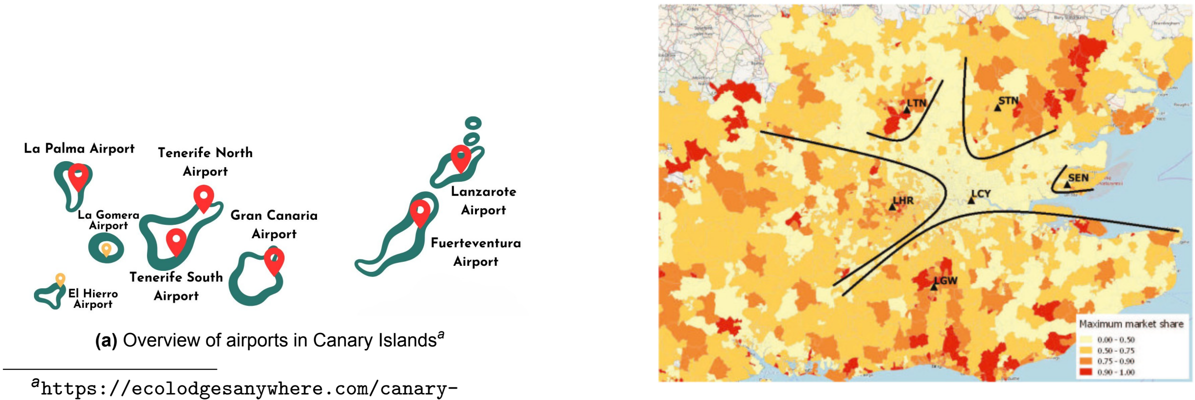
[1] `https://crp.trb.org/acrpwebresource12/measuring-air-service-and-regional-economic-activity/airport-catchment-areas-and-statistical-areas-differ/`



(a) Overview of airports in Canary Islands[a]

(b) Market shares among London airports [23]

Figure 2.1: Comparison of different catchment areas across the world

In case of larger competition between airports, the differences in their catchment areas and especially market shares will differ greatly depending on the quality of service offered at a given airport, the average airfare, as well as its ground accessibility and airport connectivity [24]. Some of those factors may matter more to particular groups of people, such as business travellers, while other factors may be more important to, for example, leisure passengers [24, 25]. Although the differences will be heavily described in Section 2.5, understanding their relative impact on different travel groups is crucial to identify the reasons why more passengers choose to fly from Airport A rather than Airport B.

An aspect closely related to the concept of airport catchment areas is passenger leakage. Within the aviation industry, it can be defined as passengers who live in the catchment area of Airport A, but choose to fly from Airport B instead. This essentially means that passengers choose to bypass their closest airport in order to fly from one which is further away. There are usually numerous factors behind this phenomenon. One of those is the average airfare associated with flights out of a given airport, as well as the airport connectivity itself. Passengers will be more likely to fly from an airport which is further away if it serves more destinations. This is especially the case if the local airport is a small regional airfield, which does not offer many direct destinations [26, 27]. This occurrence has also been present among Dutch residents, prompting some of them to travel to nearby airports in Belgium and Germany in pursuit of lower airfares [28].

Interestingly, though, the concept of leakage drastically changes in the event of cross-border travel. Country borders seem to matter to a larger extent than airport temporal distances when it comes to defining airport catchment areas [29]. As a result, passenger leakage across borders seems to be fairly limited. This is understandable, given that in one's mind, crossing borders adds to the complexity of the journey. According to Zijlstra [30], a border crossing is equivalent to an additional 100 km of spatial distance to be covered domestically, hence greatly skewing airports' catchment areas. This, however, differs per nation as some residents, such as Dutch travellers, are much more mobile than their German counterparts [30]. Unfortunately, not a lot of research has been conducted on this matter, especially in cases where average airfares were to significantly differ across country borders. In such a case, passenger leakage could potentially play a major role in passenger air travel from a given region.

2.4. Impact of taxation

In light of increasing greenhouse gas emissions and the associated global warming, governments have started taking various steps in order to disincentivise decisions which would contribute to more emissions being produced. To date, aviation has been responsible for up to 4% of global warming, extensively contributing to climate change [31]. In order to curb the demand for air travel and hence the associated emissions, some governments have decided to introduce an aviation tax. Although several countries have since backed out of the idea[2], the Netherlands has decided to continue and expand the

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[a] `https://ecolodgesanywhere.com/canary-islands-airports/`

[2] `https://www.dw.com/en/german-aviation-tax-cut-to-offer-little-lift-amid-jet-shortage/a-75022175`

process[3].

2.4.1. Aviation taxes in the Netherlands

The concept of the aviation tax within the Netherlands has been debated upon for multiple years already. The notion of introducing a tax on commercial flights was first introduced in 1995 by the Dutch Environment Minister Margreeth de Boer, who had claimed that an excise duty on kerosene is “an absolute must”[4]. She also stated that flying in Europe ought to become considerably more expensive. Although the measure was not implemented then, the widespread political support remained. As such, in 2005, an excise duty on domestic commercial flights was introduced[5]. The true tax would come just a few years later, though.

On 1 July 2008, the Netherlands introduced its first-ever air passenger tax. In order to preserve the competitiveness status of Amsterdam Schiphol Airport (AMS), however, the tax only applied to directly departing passengers (OD), with transferring individuals being fully exempt from it. Furthermore, the air passenger tax also entailed two separate levels, depending on the covered flight distance. For intra-EU flights or other short-haul flights no longer than 2500 kilometres in length, a lower level of €11.25 was imposed. For all remaining flights, a higher bracket of €45.00 was in effect [28]. The overview of the 2008 air passenger tax can be found in Table 2.2 below.

Table 2.2: Dutch Air Passenger Tax (2008)

Passenger Type	Distance	2008
OD passengers	EU flights	€11.25
OD passengers	≤ 2500 km	€11.25
OD passengers	≥ 2500 km	€45.00
Transfer	All distances	€0.00

The introduction of the tax had numerous effects. Firstly, due to the air tax, KLM Royal Dutch Airlines (KLM), the main operator at AMS, immediately stopped operating its domestic route to Maastricht Aachen Airport (MST). Prior to the tax, the route was being served with up to three daily flights. After the introduction, however, the operations shifted to other German airports, such as Düsseldorf (DUS), in order to promote connecting traffic and avoid the tax [28]. Furthermore, when evaluating passenger numbers in terms of both traffic originating at AMS (OD) and passengers transferring at AMS, from the very introduction of the tax, the OD traffic experienced a sharp decrease [18].

AMS was not the only airport that experienced changes due to the introduction of the tax, however. Although Schiphol is the main hub of the Netherlands, there are other airports in the country which also see international flights, with Eindhoven Airport (EIN) being the prime example. In the months following the introduction of the air tax, the number of weekly flights offered out of the airport decreased by approximately 10% [28]. Simultaneously, though, a very interesting phenomenon occurred just across the border in Germany. Weeze-Niederrhein Airport (NRN) is an airport located less than three kilometres away from the Dutch border. In the second half of 2008, NRN saw its operations increase in volume by more than 40% [28]. Although the main reason may have been the judiciary ruling allowing Ryanair, the airport’s main airline, to offer more flights out of NRN, the onset of the air passenger tax certainly accelerated the phenomenon [28].

In the first few months after the introduction of the tax, all Dutch airports experienced lower-than-anticipated OD passenger numbers. Although the air passenger tax certainly was an important factor influencing this phenomenon, it coincided with the peak of the Global Financial Crisis, which lasted

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[3] `https://aviation.direct/en/Netherlands-introduces-tiered-airline-ticket-tax`

[4] `https://www.volkskrant.nl/voorpagina/ministers-maken-plannen-voor-accijns-op-kerosine~bba1481f/`

[5] `https://www.volkskrant.nl/nieuws-achtergrond/coalitie-stelt-21-wijzigingen-voor~bef85b80/`

between 2007 and 2009, which the Netherlands, especially, experienced in the second half of 2008 [32]. As such, it is difficult to estimate how large the impact of the tax itself was and how big a role the crisis played. This is because, in order to boost the economy, the Dutch government quickly abolished the tax in 2009. This, in turn, led to a quick growth in air traffic numbers before the full effects of the tax could be truly understood.

After the abolishment of the air passenger tax in 2009, passenger numbers quickly started growing. With time, however, so did the calls to reintroduce the tax. After more years of heated debates, the tax was ultimately reintroduced on 1 January 2021. The new tax rate, however, was much lower than before, sitting at €7.45 per departing passenger, with transferring passengers being once again exempted from the tariff[6]. While this did accomplish the goal of increasing the government budget, it did not truly discourage Dutch residents from flying. As such, more tax increases followed, with the biggest one coming into effect at the start of 2023. In order to promote more sustainable modes of travel and to accomplish more environmental goals, the Dutch government has opted for an increase in the air passenger duty to €28.58 per departing passenger[7]. Furthermore, the tax would then increase each year, accounting for inflation. This, in turn, made the Netherlands the most expensive country within the European Union in terms of the cost of flying[8], with the tax rate for 2026 reaching €30.25, prompting many potential travellers to search for alternative departure airports located outside of the Netherlands. A visual comparison of the tax rate over the years can be found in Figure 2.2.

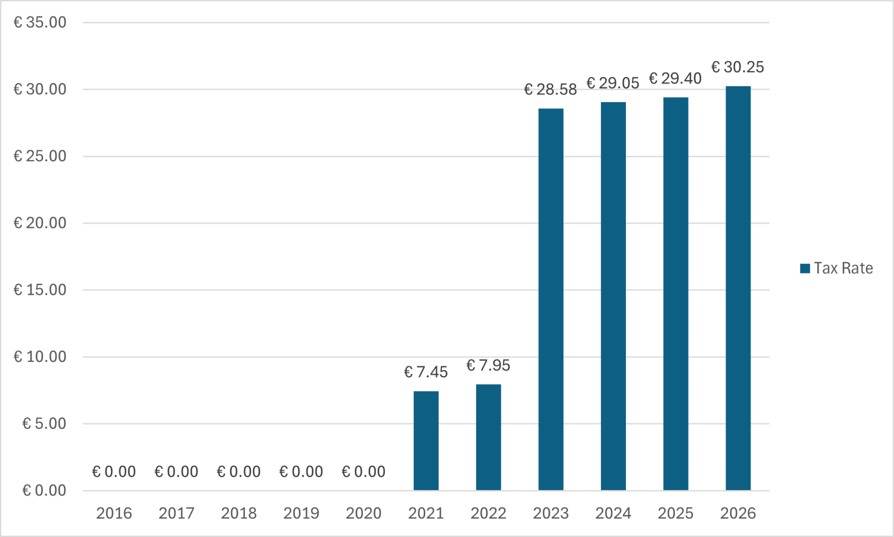

Figure 2.2: History of the Air Passenger Tax in the Netherlands

Although flying from the Netherlands is already very expensive, its costs are set to rise even further in 2027. Going back to its roots, the Netherlands is set to introduce a multi-tier air passenger tax, depending on the covered distance, with transferring passengers being, once again, exempted [33]. The duty charged on short-haul flights within the European Union or not exceeding 2000 km will slightly decrease to €29.40. Some further destinations will also be subject to that lower fee. Those include Aruba, Bonaire, Curaçao, the Canary Islands, or Madeira[9]. The major increases will occur on longer flights, however. For destinations outside of the EU, located between 2000 and 5500 kilometres away from the departure airport, the air passenger tax will be €47.24 [33]. This includes flights to Morocco or Turkey. For longer flights, though, the difference will be even more drastic. Flights longer than 5500 kilometres will be subject to a tax of €70.86 per departing passenger [33]. As such, the price of the

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[6] `https://www.eerstekamer.nl/behandeling/20201223/publicatie_inwerkingtreding/document3/f=/vletg0l3ujza.pdf`

[7] `https://www.telegraaf.nl/binnenland/prijs-vliegticket-knalt-omhoog/64504256.html`

[8] `https://dutchreview.com/news/netherlands-now-priciest-flying-destination-in-the-eu/`

[9] `https://www.nationalerecreatiegids.nl/ondernemen/vliegvakanties-worden-vanaf-2027-fors-duurder-door-nieuwe-vliegbelasting/`

ticket could easily rise by an additional €40-50 for long-haul flights to, for example, New York City. An overview of the upcoming tax levels can be found in Table 2.3, which is located below.

Table 2.3: Dutch Air Passenger Tax (2024 - 2027)

Passenger Type	Distance	2024	2025	2026	2027
OD passengers	EU flights	€29.05	€29.40	€30.25	€29.40
OD passengers	≤ 2000 km	€29.05	€29.40	€30.25	€29.40
OD passengers	2000 - 5500 km	€29.05	€29.40	€30.25	€47.24
OD passengers	≥ 5500 km	€29.05	€29.40	€30.25	€70.86
Transfer	All distances	€0.00	€0.00	€0.00	€0.00

As can be observed, the increases are considerable. Although the Dutch government has repeatedly stated that these will not lead to drastic price increases, airlines have already announced that those costs will inevitably be passed on to consumers, hence making flying from the Netherlands even more expensive than it is today.

2.4.2. Aviation taxes in Germany and Belgium

The Netherlands is not the only country in the region to have implemented air passenger taxes, however. When looking at its neighbours, Germany and Belgium, it can be observed that both countries have also implemented an air passenger duty, albeit with a somewhat different approach.

Germany first introduced a national aviation tax in 2011 as part of its Aviation Tax Act [34]. The tax structure was implemented in a very similar manner to the upcoming 2027 Dutch air passenger duty. There, a tiered system was created, depending on the flight distance. Rather than sticking to the actual distance itself, however, destination countries were listed. Each country would then be allocated to one of the three tax tiers, depending on its relative distance to Germany. Furthermore, akin to the Netherlands, only departing passengers would be subject to the fee, with transferring passengers exempted from the excise duty. When introduced in 2011, the short-haul flights were taxed at €8.00 per departing passenger, medium-haul flights at €25.00, and long-haul flights at €45.00 [34]. Over the years, the tax charges fluctuated, first decreasing somewhat, only to be subject to larger hikes in recent years. The three different tax brackets remained, however.

In 2024, the German government raised the air passenger tax to €15.53 for OD passengers on short-haul flights, €39.34 for medium-haul flights and €70.83 for long-haul flights[10]. Those numbers closely resemble the figures proposed for 2027 by the Dutch legislators. This decision, however, received heavy criticism in Germany as the country was thought to be losing its competitive status, with many potential business partners as well as tourists actively avoiding the country due to the consistently higher airfares since the introduction of the tax in 2011 [35]. As a result, the new German government decided to roll back the increase and bring the air taxes back down in mid-2026[11]. As such, the new tax rates, which will be fully in force in 2027, will amount to €12.73 for short-haul flights, €32.25 for medium-haul flights and €58.06 for long-haul flights. A comparison of the recent and future tax rates has been presented in Table 2.4 located below.

Table 2.4: German Air Passenger Tax (2024 - 2027)

Passenger Type	Distance	2024	2027
OD passengers	EU flights + Morocco, Tunisia, Algeria	€15.53	€12.73
OD passengers	Middle East, Central Asia, Central Africa	€39.34	€32.25
OD passengers	Other directions (> 6000 km)	€70.83	€58.06
Transfer	All distances	€0.00	€0.00

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[10] https://www.iata.org/en/pressroom/2024-releases/2024-05-02-01/

[11] https://euroweeklynews.com/2025/11/17/germany-cuts-aviation-tax-prices-to-drop-fast/

Although the new rates will still be very costly to the German travellers, they will become somewhat lower than for their Dutch counterparts.

A stark comparison to the air passenger taxes in Germany or the Netherlands can be observed in Belgium. Although the country has, just like the rest of the region, also introduced an air passenger tax (Embarkation tax), its rate is much lower than that of its neighbours. The tax itself is also much newer, having only been implemented in 2022. Just like in the rest of the region, its aim was to incentivise more sustainable means of transport, while also raising the governmental budget[12]. Unlike its neighbours, however, Belgium wanted to disincentivise travel on shorter routes, where other modes of transport can be a realistic alternative to flying. Although the tax rates have somewhat changed since their introduction, the country has mostly stuck to that principle. As such, in 2024, the air passenger tax amounted to €10.00 for short-haul flights of less than 500 kilometres. For longer flights, however, a lower €5.00 tax rate applied. Furthermore, just like in other countries, only departing OD passengers were subject to the fee, with transfer passengers being exempted[13].

Similar to its neighbours, though, the Embarkation tax is to undergo a significant increase in Belgium[14]. First, in 2027, the tax is to equate to €10.00 regardless of the flight distance. Subsequently, in the following years, the short-haul flights, which are less than 500 kilometres in length, will be subject to 50-cent increases both in 2028 and 2029. As such, the tax rate will then reach €11.00 per departing passenger on short-distance routes. The full comparison of the tax can be observed in Table 2.5, which can be found below.

Table 2.5: Belgian Air Passenger Tax (2024 - 2029)

Passenger Type	Distance	2024	2027	2028	2029
OD passengers	< 500 km	€10.00	€10.00	€10.50	€11.00
OD passengers	≥ 500 km	€5.00	€10.00	€10.00	€10.00
Transfer	All distances	€5.00	€0.00	€0.00	€0.00

While these changes represent a significant increase, which already sparked sharp criticism from the representatives of the aviation industry[15], this remains vastly below the tax rates observed in the neighbouring countries.

2.4.3. Comparison of tax rates in the region

If the airfares remain lower in Belgium compared to the German and Dutch counterparts, the country's airports of Brussels Zaventem (BRU) and Brussels Charleroi (CRL) may observe a significant influx of other residents, especially from the well-connected Netherlands. This becomes even more apparent when directly comparing the tax levels between the three countries, depending on the respective flight distances, as depicted by Table 2.6 - Table 2.8.

Table 2.6: Air Passenger Taxes on short-haul flights for OD passengers

Origin Country	2024	2025	2026	2027	2028	2029
Netherlands (EU flights)	€29.05	€29.40	€30.25	€29.40		
Germany (EU/EEA flights)	€15.53	€15.53	€12.73	€12.73		
Belgium (< 500 km)	€10.00	€10.00	€10.00	€10.00	€10.50	€11.00

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[12] https://www.ejustice.just.fgov.be/cgi/article_body.pl?language=fr&caller=summary&pub_date=2022-03-31&numac=2022031434

[13] https://www.fccaviation.com/regulation/belgium/embarkation-tax

[14] https://newmobility.news/en/2025/11/25/belgian-air-passenger-tax-to-double-from-2027-for-flights-over-500-km/

[15] https://www.aviation24.be/miscellaneous/environment/belgiums-eco-tax-on-flights-hike-sparks-backlash-led-by-ryanair/

Table 2.7: Air Passenger Taxes on medium-haul flights for OD passengers

Origin Country	2024	2025	2026	2027	2028	2029
Netherlands (< 5500 km)	€29.05	€29.40	€30.25	€47.24		
Germany (Middle East, Central Asia)	€39.34	€39.34	€32.25	€32.25		
Belgium (≥ 500 km)	€5.00	€5.00	€5.00	€10.00	€10.00	€10.00

Table 2.8: Air Passenger Taxes on long-haul flights for OD passengers

Origin Country	2024	2025	2026	2027	2028	2029
Netherlands (≥ 5500 km)	€29.40	€29.40	€30.25	€70.86		
Germany (> 6000 km)	€70.83	€70.83	€58.06	€58.06		
Belgium (≥ 500 km)	€5.00	€5.00	€5.00	€10.00	€10.00	€10.00

As can be observed from the three tables, the Netherlands is set to become the most expensive country to fly from, regardless of the distance. For passengers with competitive access to German and especially Belgian airports, this will present an opportunity to fly from abroad in order to save additional funds. As a result, the occurrence of passenger leakage among Dutch residents may well be exacerbated given the lower airfares offered at nearby foreign airports such as BRU, NRN or DUS.

Lastly, it is to be noted, however, that aviation taxes do not fully determine the differences in airfares for flights from different airports. Several other factors are also included. Each airport charges departing aircraft different types of fees. Those may be related to the ground handling of an aircraft, its take-off weight, generated noise, or the number of passengers onboard. In light of the strive for sustainability, they can also correspond to the NO_x or CO_2 emissions associated with the given aircraft/engine type[16]. All those charges differ between airports and countries. For the purpose of this study, however, those have been disregarded, as it is assumed that the relative differences in airport fees are not affecting the relative airfares to a large extent, with a heavier focus placed on the air passenger taxes themselves. This, however, should be further explored in the future so as to enhance the findings in the area of passenger leakage.

2.5. Preferences of different travel groups

Different travel groups may have varying preferences regarding air travel. Although it is difficult to group every traveller by their habits and likings, the most basic categorisation can still be made. When booking a flight, very often a passenger will be asked to check one of two boxes as the purpose of their travel: business or leisure. This is important for the aviation industry as almost every aspect of air travel is approached differently by those two groups. Although the differences between the two groups are substantial, they are mainly related to the relative value of time and money.

Making up only 12% of total air passengers, but a much larger portion of total airline revenue[17], business travellers are extremely crucial for the airlines. One of the main reasons for that is related to business travellers not paying for the flights themselves. As such, the costs of getting to the airport as well as the flight itself are not a factor, given that someone else is covering the bill. Business trips also tend to be quite busy in terms of schedules. As a result, the main aspect that business travellers will focus on is time. For that reason, they will be much more likely to fly from an airport that offers the fastest overall itinerary to their desired destination, at the most preferable time [36, 37, 38].

Leisure passengers, on the other hand, focus much more on the incurred costs. As such, their relative value of time will be considerably diminished, up to three times lower than in the case of business trav-

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[16] `https://media.brusselsairport.be/bruweb/default/0001/39/d96fce90431fe6e443ad1b3a4b35a3b139d9ee63.pdf`
[17] `https://financesonline.com/business-travel-statistics/`

ellers [38]. For that reason, they will also be more likely to use public transport in order to access the desired airport, as well as fly from a further airport in order to save additional funds. The time-money trade-off for that group will vastly differ between individuals, however, largely depending on their income [2, 9].

Based on the differing preferences of the two travel groups, some travellers might be considerably more likely to fly from airports located further away from their homes than others. Given that passengers going away on business trips do not spend their own money, they will not place much value on the additional costs associated with the to-be-taken journey. Leisure travellers, on the other hand, will consider the savings potential to a much greater degree. If the additional costs associated with flying from their closest airport were to greatly exceed their tolerable amount, they would be very likely to consider alternatives located further away [29].

2.6. Modelling the passenger choices

The strive to model airport selection has already been subject to extensive research in the past [2, 29, 39]. Although different models were utilised, in almost all instances, they could be categorised under the category of logistic regression (logit) models. Logit models themselves have several different types, such as nested, multinomial, or mixed, which will all be explained in this section. All types of logit models, however, aim to estimate the probability of an event occurring based on several factors that may or may not be independent from one another[18]. This, in turn, facilitates the modelling of the airport selection in numerous scenarios, which can even incorporate the influence of an aviation tax on some of the considered airports.

2.6.1. Types of logit models

Logit models themselves are statistical models. They are mainly created in order to predict the probabilities of discrete, binary outcomes. At its core, the model itself combines several parameters that may influence the final decision, also called the explanatory variables. It then links those parameters to the probabilities of different outcomes, Y, occurring. Rather than providing the probabilities themselves, though, it expresses them as log-odd values of the outcome. This is visualised by means of Equation 2.1, in the case of the outcome, Y, being a binary variable.

$$\text{logit}(P(Y=1)) = \log\left(\frac{P(Y=1)}{1-P(Y=1)}\right) \tag{2.1}$$

As can be observed, the probabilities are converted into values belonging to $(-\infty, +\infty)$. Computing the probabilities themselves, however, vastly depends on the type of model used. Irrespective of the utilised model type, though, all probability functions use utility functions, which capture the relative attractiveness of each alternative.

The expression for a given utility function, defining the attractiveness of alternative j for individual i, U_{ij}, can be described by means of Equation 2.2:

$$U_{ij} = V_{ij} + \varepsilon_{ij} = X_{ij}\beta + \varepsilon_{ij} \tag{2.2}$$

where V_{ij} is the deterministic part of the utility j based on individual i and X_{ij} is a deterministic parameter related to an individual i, affecting utility j. Furthermore, β is a coefficient defining the marginal effect of the parameter on a given utility, whereas ε is the (unobserved) random utility term. The utility functions themselves capture all factors that may affect the to-be-made choices, such as airport selection. Moreover, the models assume that an alternative j rather than alternative k will be chosen by individual $i \iff$ the value of utility U_{ij} will exceed the value of utility U_{ik} ($U_{ij} \geq U_{ik} \quad \forall k \neq j$). The calculation of probabilities based on the obtained utility functions, however, varies with different types of logit models. The most common model types will be introduced and subsequently compared in the remainder of this section.

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[18] `https://www.sciencedirect.com/topics/economics-econometrics-and-finance/logit-model`

Multinomial Logit

The Multinomial Logit model (MNL) is the most popular type of logit model. One of the main reasons behind it is its relative straightforwardness and efficiency. It does present several weaknesses, however. Firstly, the model assumes that the random error, ε_{ij}, follows an independent and uniform distribution. The model itself also considers the ratio of probabilities of any two alternatives to be fully independent of any other alternative (IIA). As such, the addition of a new alternative is assumed to affect the existing ones in a proportional manner. Unfortunately, this assumption is often unrealistic when considering real-life scenarios. As such, although the model is very efficient in terms of modelling straightforward choices, such as selecting an airport access mode, it does not reflect real-life situations in the most versatile manner.

The probability of an individual i choosing a utility j can be expressed by means of Equation 2.3.

$$P_{ij} = \frac{e^{(V_{ij})}}{\sum_{k=1}^{J} e^{(V_{ik})}} \tag{2.3}$$

where the value of an exponential of a given utility function is divided by the sum of all exponentials of all utility functions across the total number of alternatives, J.

Nested Logit

One of the models, which relaxes some of the constraints posed by the Multinomial Logit model, is the Nested Logit model. Within the model, each alternative j belongs to exactly one nest, m, $j \in m$. Furthermore, similar alternatives are grouped into the same nest, which, in turn, allows for correlation across similar options within distinct nests.

On a nest-specific scale, a correlation within a given nest, m, is also defined by means of a parameter λ_m, $0 < \lambda_m \leq 1$. The lower the value of λ_m, the stronger the correlation within the nest. In case of $\lambda_m = 1$, the model simplifies to a standard MNL.

As a result, assuming the nesting structure was completed correctly, groupings of similar alternatives can be efficiently handled. This could entail, for example, first choosing which airport to access, and only afterwards deciding which access mode (public transit, private vehicle) to choose from. The probability of selecting a given alternative can be expressed by:

$$P_{ij} = P_{j|m} \cdot P_m \qquad \text{, where } j \in m \tag{2.4}$$

while the probability of selecting an alternative within a nest, $P_{j|m}$, is calculated using:

$$P_{j|m} = \frac{e^{V_{ij}/\lambda_m}}{\sum_{k \in m} e^{V_{ik}/\lambda_m}} \tag{2.5}$$

The probability of selecting a given nest, m, on the other hand, is obtained by means of:

$$P_m = \frac{e^{\lambda_m I_m}}{\sum_n e^{\lambda_n I_n}} \tag{2.6}$$

where the inclusive log-sum, I_m, summarising the expected utility across all alternatives in a given nest, m, is equal to:

$$I_m = \log\left(\sum_{k \in m} e^{\left(\frac{V_{ik}}{\lambda_m}\right)}\right) \tag{2.7}$$

Cross-Nested Logit

A variation of the Nested Logit model is a Cross-Nested Logit model (CNL). This type of logit model is used when several decisions are made simultaneously. This can include a situation where the airport selection as well as the airport access mode choices are made jointly. In such a case, each alternative j may belong to multiple nests m at the same time. Each alternative would then have a nest-membership parameter $\alpha_{jm} \in [0, 1]$ defining its degree of membership to a given nest m. This would then be subject to a normalisation $\sum_{m \in \mathcal{M}} \alpha_{jm} = 1 \quad \forall j$ so as to ensure that each alternative is fully distributed across the possible nests.

On a nest-specific scale, just like in the case of a regular nested logit model, a correlation within a given nest, m, is also defined by means of a parameter λ_m, $0 < \lambda_m \leq 1$. The lower the value of λ_m, the stronger the correlation within the nest. In case of $\lambda_m = 1$, the model again simplifies to a standard MNL.

Calculating the cross-nested logit choice probability of an alternative j can be done by means of Equation 2.8:

$$P_{ij} = \sum_{m \in \mathcal{M}} \left[\frac{\alpha_{jm}^{\lambda_m} \exp\left(\frac{V_{ij}}{\lambda_m}\right)}{\sum_{k=1}^{J} \alpha_{km}^{\lambda_m} \exp\left(\frac{V_{ik}}{\lambda_m}\right)} \right] \cdot \frac{\exp(\lambda_m I_m)}{\sum_{n \in \mathcal{M}} \exp(\lambda_n I_n)} \tag{2.8}$$

In the above equation, the probabilities are summed across all nests, while also taking into account the weights of each nest based on their relevance to an alternative j. Finally, the inclusive value I_m can be calculated by means of:

$$I_m = \log\left(\sum_{k=1}^{J} \alpha_{km}^{\lambda_m} \exp\left(\frac{V_{ik}}{\lambda_m}\right)\right) \tag{2.9}$$

Mixed Logit

The next type of logit model is the Mixed Logit model. Its main differentiator, when compared to previous types, is that it allows parameters, $\beta = \beta_i$, to vary between individuals, i. As such, β_i becomes a parameter unique to each individual, in turn, making the utility also vary per individual, i. As a result, the utility function becomes:

$$U_{ij} = V_{ij} + \varepsilon_{ij} = X_{ij}\beta_i + \varepsilon_{ij} \tag{2.10}$$

The above modification results in $\beta = \beta_i \sim f(\beta \mid \theta)$, where θ represents the distribution parameters of a considered density function affecting β. This, in turn, allows one to capture differentiators between individuals in a given group. One of the most prominent examples of this could be an income distribution among residents of a given country.

The probability of a given choice then becomes conditional on β_i:

$$P_{ij}(\beta_i) = \frac{e^{(X_{ij}\beta_i)}}{\sum_{k=1}^{J} e^{(X_{ik}\beta_i)}} \tag{2.11}$$

Equation 2.11 can then be integrated over the distribution of β coefficients to become:

$$P_{ij} = \int \frac{e^{(X_{ij}\beta)}}{\sum_{k=1}^{J} e^{(X_{ik}\beta)}} f(\beta \mid \theta)\, d\beta \tag{2.12}$$

Although the Mixed Logit model allows for the approximation of any random utility model, it is extremely heavy in terms of required computational power, given the extensive needs for integration in order to obtain the desired probabilities.

2.6.2. Comparison of logit models

Each of the four distinct types of logit models can be characterised by distinct features and applications. Furthermore, each type also has its own set of relative advantages and drawbacks. In order to better visualise those, Table 2.9 has been made comparing the four model types with one another, as depicted below.

Table 2.9: Comparison of discrete-choice logit models

Model Type	Key Feature	Strengths	Weakness	Probability Function
MNL	Errors are uniformly distributed, simple	Easy, fast	Unrealistic random error distribution	$P_i = \frac{e^{V_i}}{\sum_j e^{V_j}}$
Nested Logit	Correlation within nests	Handles grouping	Requires correct nesting structure	$P_{ij} = P_{ij\|m} \cdot P_m$
CNL	Alternatives belong to multiple nests	Very flexible	Complex estimation	$P_{ij} = \sum_m P_{ij\|m} \cdot P_m$
Mixed Logit	Captures differences between individuals	Very robust	Heavy computation	$P_{ij} = \int \frac{e^{(X_{ij}\beta)}}{\sum_{k=1}^{J} e^{(X_{ik}\beta)}} f(\beta\|\theta)\, d\beta$

As can be observed from the above table, each model has its distinct advantages, but also its own set of drawbacks. For the purpose of this project, however, it has been determined that the Nested Logit will be the best choice. This is due to it having the required balance between accuracy and the required computational power [16]. Such a selection still allows for correlation, for example, within airports, allowing for the grouping of similar alternatives.

2.6.3. Data required for logit models

In order to properly design a logit model, several steps need to be undertaken. First, the parameters, which are to be analysed, need to be selected. This step heavily depends on which factors are to be included in the model and which are to be omitted. This is done during the conceptual design of the model, which will take place during the project. Alongside the selection of the desired parameters, another aspect needs to be considered. When designing the utility functions, each parameter has its own utility coefficient, β. In order to estimate its value when calibrating the model, different datasets need to be utilised. In many papers [15, 40, 41], this is most often achieved by means of surveying participants. To obtain the desired data, surveyors would often ask questions regarding the choices made by participants. The questions would then often pertain to hypothetical scenarios and how their choices would be affected in case a given alternative were to be introduced. Their answers, also known as stated preferences (SP), would then be quantified and, subsequently, used for model calibration [15]. What also often happened, however, was that the SP data was compared with actual observations of passenger behaviour, known as revealed preferences (RP) [11, 40]. While the RP data was used for modelling the current scenario, the SP data was utilised for modelling hypothetical improvements/additions to the existing alternatives. Combining the two data sources then allows for a detailed understanding of factors driving individuals' decisions and, as such, the proper calibration of the model [40].

As part of this project, no surveys will be performed, however. This is due to such an endeavour taking a very extensive amount of time [42], hence not being a viable solution for an MSc Thesis. As such, alternative data sources will be used. Although the official list of data files will be finalised during the project itself, it will include, among others, a dataset of airport accessibility metrics and temporal distances, as well as flight schedules. This will, in turn, allow for bypassing the need for surveys with the usage of publicly available data [42].

2.6.4. Gravity models

Apart from logit models, there is one more model type, which is widely incorporated in the aviation industry, a gravity model [43, 44, 45]. This model type allows for analysing, among others, the demand between two locations based on their attractiveness and the distance between them. The gravity models, however, can also be used to determine demand for flights between two airports, G_{ab}, depending on the population of a given region and the distance of that region from the said airport. This can be modelled by means of Equation 2.13, which has been presented below.

$$G_{ab} = K \cdot \frac{(A_a A_b)^{\delta}}{d_{ab}^{\gamma}} \tag{2.13}$$

where K is a scaling constant, A_a and A_b represent the attractiveness of the two locations, d_{ab} relates to the distance between locations a and b, while γ and δ are calibration parameters.

A special type of gravity model can be used to define the catchment areas and market shares of airports, depending on their location [14, 46]. The model used for this analysis is a modified probabilistic gravity model, known as a Huff model. The model determines the probability (H_{ab}) of a given airport b being chosen by residents of region a, depending on the size of the airport, S_b and the temporal distance from region a to that airport, T_{ab}.

$$H_{ab} = \frac{\dfrac{S_b}{T_{ab}^{\Lambda}}}{\sum_{b=1}^{n} \dfrac{S_b}{T_{ab}^{\Lambda}}} \tag{2.14}$$

where Λ is the sensitivity parameter. The Huff model is very good at analysing the spheres of influence of different airports, while also capturing their respective sizes. It fails, however, to incorporate the differences in airline schedules, airfares and service frequencies, for which logit models are much more appropriate [39].

2.7. Research gap

Based on the conducted literature study, it can be observed that the area of the impact of aviation taxes on passengers' choices presents significant research potential. This is especially true in the case of the Netherlands, a very small, affluent country with a large, mobile population. The country used to have an air passenger tax in place more than 15 years ago [28]. In light of the Global Financial Crisis as well as the heavy pushback from both the aviation industry and the citizens themselves, the tax was revoked less than a year after its introduction [28]. In recent years, however, the tax was reintroduced, with its rate systematically being raised every year. Although the direct neighbours of the Netherlands, Germany and Belgium, also have aviation taxes in place, in the coming years, they will not be as high as in the case of their Dutch counterparts. Furthermore, Germany, the country with the higher tax rate, is focusing on reducing the tax burden as opposed to the Netherlands, which aims to further increase it.

Given the higher costs of flying from the Netherlands, many of its residents may choose to go abroad and fly from a foreign airport in order to save extra money. As such, they could contribute to a phenomenon of passenger leakage. This is already present with Dutch travel agencies, such as Corendon, offering some travel package holidays with departures from DUS or BRU[19] rather than a Dutch airport. Those situations are only poised to gain popularity, as the taxes in the Netherlands continue to rise.

The phenomenon of Dutch passenger leakage has already been rather extensively analysed in 2010 [28]. As part of the study, it has been observed that 7% of surveyed Dutch residents chose to fly from a foreign airport [28]. The findings from that time period cannot be translated into current or future simulations, however. This is due to two very important factors. First, the effects of the tax in 2008

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[19] `https://nltimes.nl/2025/09/23/corendon-expanding-german-airports-dutch-avoid-pricey-tickets-netherlands`

were heavily distorted due to the Global Financial Crisis. Furthermore, the neighbouring countries of Germany and Belgium, which could serve as viable alternatives for Dutch residents, did not have any aviation taxes in place, hence potentially skewing the results. What can be extracted from the analysis, however, is the estimation of the impact that a unit tax increase will have on the choices among Dutch residents. This, however, requires a further analysis of the topic. In order to quantify the potential passenger leakage depending on the aviation tax rates in different countries, a mathematical logit model is to be created. The findings of the model will then be used to identify the potential mitigations of the passenger leakage phenomenon amid more complex taxation measures. As such, the following Research Objective has been identified:

Research Objective: ***“To develop a model that can quantify the influence of Dutch aviation tax on the propensity of Dutch residents to fly from foreign airports and evaluate passenger sensitivity to changes in the taxation structure.”***

In order to effectively address the research objective, the following Research Question (RQ) has been formulated:

RQ: ***To what extent does the Dutch aviation tax contribute to the phenomenon of passenger leakage among Dutch residents, and how sensitive is passenger behaviour to changes in the tax levels?***

To support this research, several sub-questions (SQ) have also been formulated, which will be answered throughout the remainder of the project.

- **SQ1:** *How does the Dutch aviation tax affect the catchment areas of Dutch airports compared to their foreign counterparts?*
- **SQ2:** *Which regions of the Netherlands are the most sensitive to the airfare increases associated with the aviation tax?*
- **SQ3:** *Which parameters have the highest impact on the selection of the departure airport under the influence of the aviation tax?*
- **SQ4:** *Which foreign airports are the most desirable for Dutch residents, contributing to the passenger leakage phenomenon?*
- **SQ5:** *How do the changes to the Dutch aviation tax affect passenger leakage to foreign airports?*

3

Planning

To facilitate the laid-out plan, extensive planning has been undertaken. Given the scale of the project and its projected total duration of 32 work weeks, a breakdown into smaller segments has been proposed. As such, the Thesis itself has been divided into four distinct phases, with each phase representing a different part of the entire project. Finally, contingencies had to be allocated. To accommodate this, for each phase, a 10% contingency has been scheduled for each task to account for any potential difficulties and/or unexpected hurdles. Furthermore, the to-be-performed work is to be truncated at 31 weeks, creating an additional one-week buffer to be incorporated if needed. This chapter will briefly describe each phase, whereas the project plan itself will be presented in Appendix A by means of a Gantt Chart. The first phase, scheduled to last a total of eight weeks, including contingencies, is to be related to the literature review of existing research. Throughout the phase, scientific papers are to be reviewed in detail so as to develop a deep understanding of the state-of-the-art situation of airport catchment areas, passenger leakage and multi-airport systems. The obtained findings will be summarised in a Literature Review chapter, with the phase concluding with a Literature Review milestone meeting.

The second phase of the project, once again scheduled to last eight weeks, is to focus on the methodology aspect. Throughout its duration, the relevant project data will be obtained and processed. Based on the obtained dataset, the definitive modelling approach is to be agreed upon. Afterwards, the entire model will be conceptualised, along with the methodology chapter of the thesis being drafted during this phase. The phase will conclude with a Midterm Review, during which a preliminary model will be presented.

In the third phase of the Thesis, the expansion of the model will occur. This includes the analysis of the obtained results as well as the corresponding sensitivity analysis investigating the outcomes of the model. All of the results will also be documented in this phase. Given that the tasks in this phase are the most time-demanding, a total of 11 weeks has been scheduled for the work. After the documentation of the findings, the completed work is to be presented. For that, the Greenlight Review milestone meeting will be scheduled, concluding the phase.

The final phase of the project will focus on the finalisation of the Thesis itself. In the remaining four weeks of the work, the Thesis document will be finalised. This is to be combined with the preparation for the following Thesis Defence. The defence will also mark the end of the phase. Unlike in previous phases, however, the end of this portion of the project will also conclude the entire Thesis. This, in turn, results in the project lasting a total of 31 work weeks, including contingencies, with an additional one-week buffer to be incorporated if needed.

4

Conclusion

The aim of this document was to present the reader with an MSc Research Proposal addressing the topic of "*Evaluating passenger leakage of Dutch travellers to foreign airports under the influence of the aviation tax*". The project aims to quantify and evaluate the role of Dutch aviation taxes in the selection of foreign airports among Dutch residents. Given the lack of publicly available analysis for the upcoming increase in the tax levels, there is a broad research gap to be addressed by the project. Through the formulation of a discrete choice logit model, the research question and corresponding sub-questions shall be addressed, with the project contributing to the ongoing analysis of multi-airport systems and passenger behaviour.

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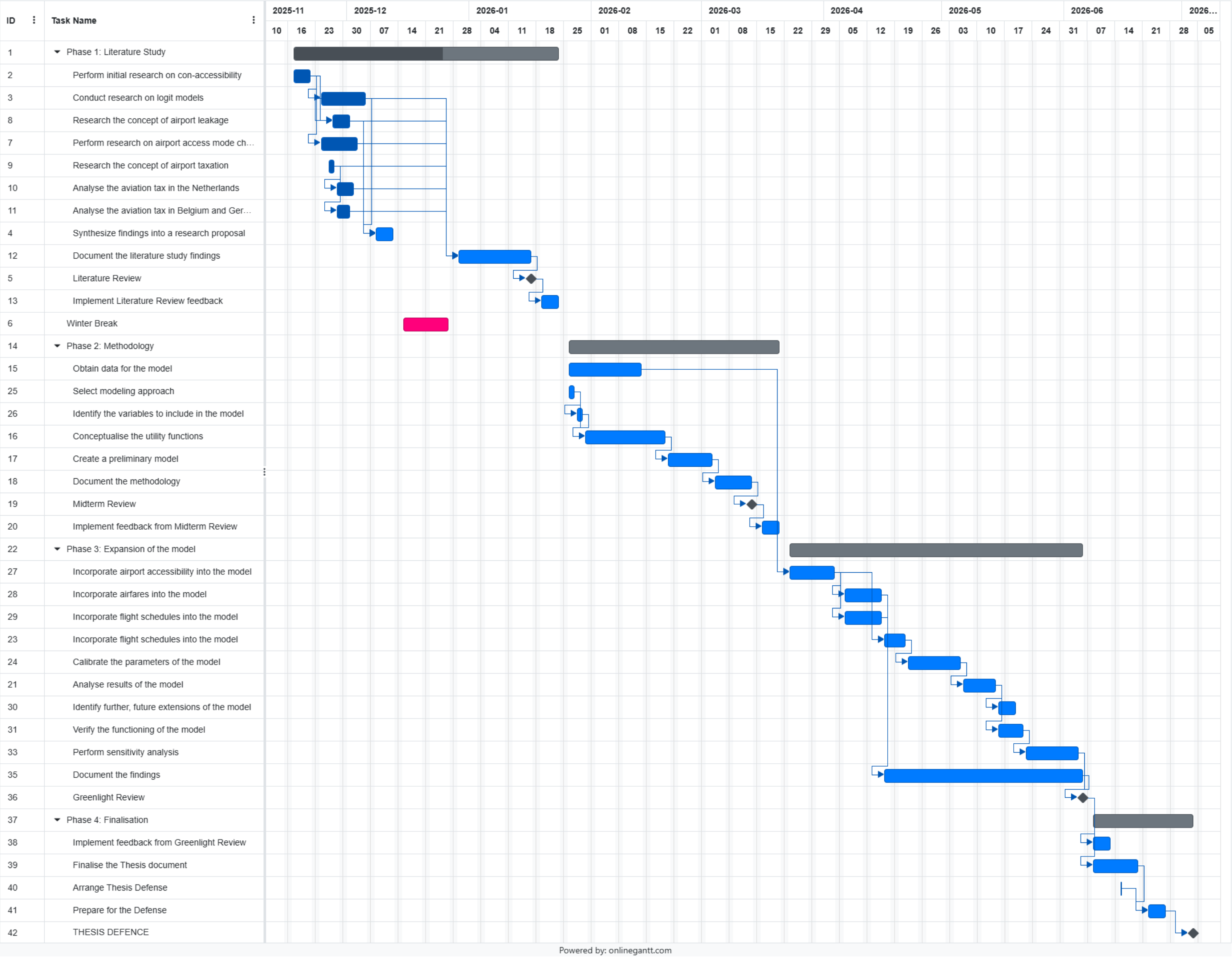
A

Gantt Chart

As part of the planning of the MSc Thesis, a detailed project plan was to be created. In this plan, different phases of the Thesis were proposed, along with the distinct tasks corresponding to each phase. Furthermore, dependencies between tasks were also identified. As such, a Gantt Chart has been created, which can be observed on the following page.



ID	Task Name
1	Phase 1: Literature Study
2	Perform initial research on con-accessibility
3	Conduct research on logit models
8	Research the concept of airport leakage
7	Perform research on airport access mode ch…
9	Research the concept of airport taxation
10	Analyse the aviation tax in the Netherlands
11	Analyse the aviation tax in Belgium and Ger…
4	Synthesize findings into a research proposal
12	Document the literature study findings
5	Literature Review
13	Implement Literature Review feedback
6	Winter Break
14	Phase 2: Methodology
15	Obtain data for the model
25	Select modeling approach
26	Identify the variables to include in the model
16	Conceptualise the utility functions
17	Create a preliminary model
18	Document the methodology
19	Midterm Review
20	Implement feedback from Midterm Review
22	Phase 3: Expansion of the model
27	Incorporate airport accessibility into the model
28	Incorporate airfares into the model
29	Incorporate flight schedules into the model
23	Incorporate flight schedules into the model
24	Calibrate the parameters of the model
21	Analyse results of the model
30	Identify further, future extensions of the model
31	Verify the functioning of the model
33	Perform sensitivity analysis
35	Document the findings
36	Greenlight Review
37	Phase 4: Finalisation
38	Implement feedback from Greenlight Review
39	Finalise the Thesis document
40	Arrange Thesis Defense
41	Prepare for the Defense
42	THESIS DEFENCE

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Part III

Supporting Work

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1

Introduction

Although the Scientific Article provided a comprehensive overview of the project, it did not mention every aspect. To support the presented work, additional tasks were performed. Among these, the two main supporting components are to be presented in this document. First, in Chapter 2, the data acquisition and subsequent processing of the files will be described. This was a lengthy, albeit required, undertaking when preparing the dataset that was to be used in the model. In the chapter, the entire process of acquiring separate types of data will be explained, together with the presentation of the relationships between different files. Lastly, the structure of the actual dataset incorporated into the model will also be described.

Subsequently, in Chapter 3, the verification process will be presented. This includes the verification of the completeness of the created dataset as well as the verification of the mathematical model itself. The purpose of these steps was to ensure the correctness of the implemented methods along with the reliability of the results obtained from the analysis.

2

Data collection and processing

In order to address the described research questions, a discrete-choice model was conceived. This allowed for a detailed analysis of airport selection in a multi-airport region, with the model capturing different factors affecting passengers' choices by means of utility functions [1]. For the model to work, however, the acquisition and processing of the data had to occur. This proved to be a lengthy process due to the size and complexity of the required data. As such, various data processing methods were applied to different parts of the dataset.

This chapter will aim to present the reader with the methods undertaken to obtain the dataset used for the model, along with the presentation of the respective data files. For that, first, the data regarding the aviation taxes will be discussed in Section 2.1. Afterwards, the dataset containing the geographical locations will be introduced in Section 2.2. This will then be followed by the data regarding airport ground accessibility, as presented in Section 2.3. The section will also introduce the Dijkstra algorithm, the aim of which was to obtain the airport temporal distances. Afterwards, Section 2.4 will aim to expand on the airport ground access times by discussing the costs associated with reaching an airport, depending on the selected access mode. The dataset related to the airside travel components will then be introduced. First, Section 2.5 will discuss the flight schedules across the analysed airports. Afterwards, in Section 2.6, the corresponding airfare calculation will be presented. Finally, the overview of the data files will be provided in Section 2.7.

2.1. Aviation taxes data

To obtain the dataset, first, the data files regarding aviation taxes in the Netherlands, Belgium and Germany were collected by means of web scraping and literature research, as extensively described in the Literature Review in the Scientific Article and Thesis Proposal documents. The aim of this analysis was to quantify the relative differences in airfares between the three countries, both in the past and in the near future. The obtained data was subsequently stored as .csv files in order to be later utilised in the created model.

2.2. Geographical locations data

Apart from the aviation taxes, other data had to be obtained, though. In order to model and compare the accessibility of competing airports, their temporal distances to each segment of the Netherlands had to be calculated. For that, it was determined that using the Dutch postcodes would yield the most comprehensive coverage. A trade-off between computational time and accuracy had to be made, however. In case the most accurate dataset were to be used, the full PC6 postcodes, the total number of locations would reach in excess of $460,000$ distinct postcodes[1]. As such, the PC4 postcodes, the four digits describing each postcode in the Netherlands, were used. This yielded a total of 4072 distinct postcode

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[1] `https://www.cbs.nl/nl-nl/dossier/nederland-regionaal/geografische-data/gegevens-per-postcode`

locations, providing an accurate representation of the country. Those were obtained from the Publieke Dienstverlening Op de Kaart (PDOK)[2], which contains geographical datasets of the entire Netherlands. After obtaining the dataset, the geographical centroid of each PC4 postcode was calculated. This was done in order to aggregate the location of the origin from a given postcode. To accomplish that, the Quantum Geographic Information System (QGIS) software[3], a public, open-source program, was used. Finally, the obtained dataset was converted into a .csv file. For each PC4 postcode, the number of inhabitants, $n_{\text{residents}}$, as well as the longitude and latitude of the centroid of the postcode, were included. The sample of the dataset can be observed in Table 2.1, which is located below.

Table 2.1: PC4 geographical locations

PC4	$n_{\text{residents}}$	Longitude [°]	Latitude [°]
1011	10010	4.9058	52.3725
1012	9120	4.8960	52.3745
1013	23020	4.8745	52.3969
1014	4950	4.8786	52.3956
1015	14965	4.8840	52.3783
1016	11355	4.8899	52.3731
1017	13550	4.8929	52.3629
1018	23430	4.9179	52.3678
1019	20630	4.9378	52.3753

2.3. Airport ground accessibility data

With the geographic locations of the trip origins obtained, the airports and their temporal distances had to be mapped. In order to facilitate that, the OpenStreetMap (OSM)[4] data was used. First, the geographical coordinates of the analysed airports were extracted into a .csv file. Afterwards, an Application Programming Interface (API) request was used by means of the Open Source Routing Machine (OSRM) engine[5], given its open-source nature. This allowed for the extraction of both spatial and temporal driving distances from each PC4 postcode to each of the considered airports, with the obtained results stored as a .csv file, with the entire request being created by means of a Python[6], .py, script.

Similar to the driving distances, the travel time to each airport was also obtained for individuals arriving by public transit. This required a more complicated approach, however, as the OSRM engine does not support public transit data. As such, the distances had to be calculated manually. In order to accomplish that, first, a dataset containing train operations in the Netherlands (including international service from/to the country) was obtained from Nationale Data Openbaar Vervoer (NDOV-loket)[7] for the month of September 2025. The obtained .csv file contained every train service in the country, together with stations served by the train, as well as the corresponding timetables. Based on the file, a Python script was created with the aim of obtaining temporal distances between each of the served stations. In order to accomplish that, a Dijkstra algorithm was used, as described below.

Let $G = (V, E, w)$ be a weighted graph, where:

- V is the set of vertices (stations),
- $E \subseteq V \times V$ is the set of edges,
- $w : E \to \mathbb{R}_{\geq 0}$ is a weight function assigning a non-negative weight to each edge.

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[2] `https://www.pdok.nl/`

[3] `https://qgis.org/?lang=en`

[4] `https://www.openstreetmap.org/`

[5] `https://project-osrm.org/`

[6] `https://www.python.org/`

[7] `https://ndovloket.nl/`

Furthermore, a distance function can be defined as $d : V \to [0, \infty]$ such that:

$$d(v) = \begin{cases} 0, & \text{if } v = s \\ \infty, & \text{if } v \neq s \end{cases}$$

where $s \in V$ is the source vertex. Furthermore, the algorithm itself creates a priority queue:

$$Q = \{(0, s)\}$$

where, while $Q \neq \emptyset$, closest vertices are considered:

$$u = \arg \min_{(v, d(v)) \in Q} d(v)$$

Moreover, for every edge $(u, v) \in E$, a relaxation is performed in order to update the distance in case a shorter path is found.

$$\text{If } d(u) + w(u, v) < d(v), \text{ then}$$
$$d(v) \leftarrow d(u) + w(u, v)$$
$$Q \leftarrow Q \cup \{(d(v), v)\}$$

The algorithm terminates when the priority queue is empty. Based on that, the resulting function $d(v)$ then represents the shortest-path distance, $d(v) = \delta(s, v)$, $\forall v \in V$ where $\delta(s, v)$ denotes the length of the shortest path from s to v. It is important to note, however, that only the edge distances were incorporated into the total temporal distance. As such, the connection times between trains were disregarded, along with the stop times at stations.

In order to connect the temporal distance matrix with the PC4 postcodes, the geographical data of the stations also had to be obtained. For that, the dataset from Rijden de Treinen[8] was used, as it contained a list of all stations, together with their geographical coordinates. A Python script was then created in order to find the closest train station to each PC4 postcode. Furthermore, for the stations located in proximity to airports, but not at the airport itself, the travel distances to the corresponding airports from those stations were manually added based on the data provided by Google Maps[9]. The additional temporal distances were then subsequently implemented into the dataset. Finally, a separate Python code calculated the total temporal distance to each of the considered airports per PC4 postcode. The results would then be stored as a separate .csv file, together with the driving distances, a snippet of which can be observed in Table 2.2.

Table 2.2: Travel times from 1011 postcode to the analysed airports

PC4	Closest station ID	Airport	Driving time (min)	Public transit time (min)
1011	ASD	AMS	24.70	14
1011	ASD	BRU	151.65	137
1011	ASD	CGN	187.14	166
1011	ASD	CRL	195.48	169
1011	ASD	DTM	173.90	220
1011	ASD	DUS	156.19	131
1011	ASD	EIN	99.86	89
1011	ASD	MST	162.47	143
1011	ASD	NRN	139.32	137
1011	ASD	RTM	61.36	60

where ASD stands for Amsterdam Sloterdijk station, and the airport codes represent all of the airports considered in the Scientific Article. As can be seen from the above table, the obtained dataset contains

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[8] `https://www.rijdendetreinen.nl/en/open-data`

[9] `https://maps.google.com`

information on temporal distances to each airport from each PC4 postcode, both by means of driving and public transit. This, in turn, allows for the analysis of the temporal distances to every airport while also accounting for different potential transport modes used.

2.4. Airport ground access costs data

An important aspect affecting passenger choices regarding airport selection is ground accessibility. Although the temporal distance to a given airport is an important aspect, so are the costs of reaching it, c_{drive}. In order to obtain those, several aspects need to be considered [2]. The main factors include the cost of fuel, $c_{\text{fuel}} = €1.85$[10], the fuel burn (in litres per 100 kilometres), $f_f = 6.5$[11], as well as general usage costs, $c_{\text{use}} = 0.08 \cdot d_{\text{total}}$[12], represented as a function of the covered distance, d_{total}. Moreover, the individuals driving the car, after reaching the airport, need to store their vehicle at a car park. Not all passengers opting for accessing the airport by car park their vehicle at the airport, however. As evaluated by Zijlstra [3], only 40.9% of individuals not arriving by public transport to AMS leave their car at the car park. In the case of other airports, this figure increases to 54.7%. This, however, needs to be incorporated into the cost function as the probability of parking, P_{park}, with the remaining passengers being either brought to the airport by car or by means of a taxi. Furthermore, the costs of parking are also airport-dependent. As such, additional research was performed to identify the aggregate daily expenditures associated with storing a personal vehicle at each of the considered airports, with the obtained results presented in Table 2.3.

Table 2.3: Aggregate daily parking costs at the considered airports

Netherlands		**Germany**		**Belgium**	
Airport	Parking cost (€)	Airport	Parking cost (€)	Airport	Parking cost (€)
AMS	30[a]	CGN	30[e]	BRU	25[i]
EIN	25[b]	DTM	20[f]	CRL	15[j]
MST	25[c]	DUS	35[g]		
RTM	35[d]	NRN	20[h]		

[a] `https://www.schiphol.nl/en/parking/`
[b] `https://shop.eindhovenairport.nl/book/EIN/Parking?parkingCmd=collectParkingDetails&lang=en-gb`
[c] `https://www.maa.nl/en/parking/`
[d] `https://www.rotterdamthehagueairport.nl/en/parkeertarieven/`
[e] `https://parking.koeln-bonn-airport.de/`
[f] `https://www.dortmund-airport.com/en/parking`
[g] `https://www.dus.com/en/parking`
[h] `https://airport-weeze.com/wp-content/uploads/2025/06/Parking-fees-as-from-01.07.2025.pdf`
[i] `https://www.brusselsairport.be/en/passenger/mobility/parking`
[j] `https://www.brussels-charleroi-airport.com/en/parking-access`

Lastly, an average trip duration had to be identified. In the Netherlands, according to Zijlstra [3], the average trip duration of the trips taken by the Dutch residents equals $t_{\text{trip}} \approx 4$ days. Based on that data, the total round-trip cost of driving per individual could finally be obtained. This was calculated by means of Equation 2.1, which has been presented below.

$$c_{\text{drive}} = \frac{2 \cdot \left(c_{\text{fuel}} \, \frac{f_f}{100} \, d_{\text{total}} \; + \; c_{\text{use}}\right) \; + \; P_{\text{park}} \, c_{\text{park}} \, t_{\text{trip}}}{n_{\text{travellers}}} \tag{2.1}$$

where $n_{\text{travellers}} = 1.3$ represents the average number of travellers that are to share the costs between each other [3].

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[10] `https://www.fuel-prices.eu/Netherlands(NL)/`; the numerical value used represents the long-term average rather than the current value

[11] `https://fuelconsumption.co.za/what-is-a-good-fuel-consumption-per-100km/`

[12] `https://www.wat-kost-het.nl/wat-kost-het-onderhouden-van-een-auto/`

When accessing the airport by means of public transit, the modelling of the charged fares becomes rather different. To accomplish that, the NS unit fare matrix had to be utilised as it contained the unit distances between all train stations served by NS within the Netherlands. The relevant data was once again obtained from Rijden de Treinen[13] while the conversion of fares corresponding to the distances was extracted from the online data[14]. As such, the fares between all stations in the Netherlands were calculated. The obtained travel costs, however, lacked the data for journeys to the neighbouring countries. To account for that, an extrapolation was to be performed. For that, the public transit travel times, as calculated in Section 2.3, were utilised, given that they also included foreign train stations. The domestic part of the travel time (`pt_time` [min]) matrix was then compared with the obtained cost (`pt_cost` [€]) matrix to identify a correlation between the two. The cost was assumed to be a linear function of time, prompting a linear regression model to create a fit by means of `sklearn.linear_model.LinearRegression()` function in Python. This, in turn, resulted in the following function.

$$\texttt{pt\_cost} = 0.1707 \cdot \texttt{pt\_time} + 9.243 \tag{2.2}$$

Equation 2.2 estimates the potential cost of public transport trips from each PC4 postcode to any station, with $R^2 = 0.77$. It is important to note, however, that the ground access costs calculated by means of the above equation were only used for international routes. As such, for travel within the Netherlands, the cost matrix obtained from unit fare data was kept.

Lastly, as described in Section 2.3, not all of the considered airports have direct access to a train station. As such, just like the additional time, the extra travel costs had to be manually extracted. This was done by means of the 9292 website[15]. As such, based on the performed research, the cost of accessing each airport from each PC4 postcode has been calculated. Furthermore, the snippet of the obtained results has been visualised and presented in Table 2.4, which can be observed below.

Table 2.4: Airport ground access costs from 1011 postcode

PC4	Closest station ID	Airport	Driving cost (€)	Public transit cost (€)
1011	ASD	AMS	44.79	11.20
1011	ASD	BRU	103.49	79.06
1011	ASD	CGN	131.68	83.84
1011	ASD	CRL	104.23	87.42
1011	ASD	DTM	108.25	105.08
1011	ASD	DUS	125.17	63.22
1011	ASD	EIN	79.09	56.50
1011	ASD	MST	104.00	65.20
1011	ASD	NRN	83.56	71.20
1011	ASD	RTM	81.56	44.60

The above table showcases the different airport ground access costs from the 1011 PC4 postcode. As can be observed, in the vast majority of cases, the public transit option is considerably cheaper than driving. This, in turn, could prompt many travellers to consider both airport ground access modes before deciding on the final alternative.

2.5. Flight schedules data

In order to complete the data acquisition process, one more dataset had to be extracted, namely the flight schedules. To accomplish that, the Rapid API[16] program was used. As a sample dataset, flight

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[13] `https://www.rijdendetreinen.nl/open-data/tariefafstanden`

[14] `https://www.ns.nl/`

[15] `https://9292.nl/`

[16] `https://rapidapi.com/hub`

schedules spanning one entire day (24 hours) were extracted, with the selected date being 19 January 2026. As such, for the given date, flight schedules were extracted for each of the considered airports. Furthermore, given that only departing passengers are subject to the analysis, only departing flights were extracted by the Rapid API software. Based on the obtained .csv files, Python scripts were developed in order to process the data. Furthermore, the schedules were analysed in terms of the destinations served. Doing so would then allow for the analysis of which airports serve a given destination (Dest.), as depicted below for the case of Alicante Airport (ALC).

Table 2.5: Scheduled ALC-bound flights

Dest.	Origin	Local departure time	Aircraft	Airline	Local arrival time
ALC	AMS	19/01/2026 06:50	Boeing 737-800	Transavia	19/01/2026 09:30
ALC	AMS	19/01/2026 12:30	Boeing 737-800	Transavia	19/01/2026 15:10
ALC	AMS	19/01/2026 14:40	Airbus A320	Vueling	19/01/2026 17:20
ALC	AMS	19/01/2026 17:00	Airbus A321 NEO	Transavia	19/01/2026 19:40
ALC	BRU	19/01/2026 06:05	Boeing 737-800	TUI Belgium	19/01/2026 08:30
ALC	BRU	19/01/2026 07:30	Boeing 737-800	Transavia	19/01/2026 10:00
ALC	BRU	19/01/2026 09:45	Airbus A320 NEO	Brussels	19/01/2026 12:15
ALC	BRU	19/01/2026 15:05	Airbus A320	Vueling	19/01/2026 17:30
ALC	CGN	19/01/2026 15:40	Boeing 737-800	Ryanair	19/01/2026 18:25
ALC	CRL	19/01/2026 09:00	Boeing 737 MAX 8	Ryanair	19/01/2026 11:35
ALC	CRL	19/01/2026 12:40	Boeing 737-800	Ryanair	19/01/2026 15:15
ALC	EIN	19/01/2026 13:05	Boeing 737 MAX 8	Ryanair	19/01/2026 15:45
ALC	EIN	19/01/2026 16:15	Boeing 737-800	Transavia	19/01/2026 18:45
ALC	EIN	19/01/2026 20:20	Boeing 737-800	Ryanair	19/01/2026 23:00
ALC	NRN	19/01/2026 06:20	Boeing 737-800	Ryanair	19/01/2026 09:05
ALC	RTM	19/01/2026 07:00	Boeing 737-800	Transavia	19/01/2026 09:25
ALC	RTM	19/01/2026 16:15	Boeing 737-800	Transavia	19/01/2026 18:40

As can be observed, there are numerous ALC-bound flights departing from the region on the same day. This, in turn, presents passengers with ample choice regarding departure airport, airline, and departure time.

The obtained dataset was subsequently combined with the temporal distances from each PC4 postcode. The aim of that was to obtain the closest airports per postcode that would serve a given destination. In the case of most PC4 postcodes, for a given destination, this was AMS, RTM or EIN. In case of regions located closer to the country's borders, however, those were also BRU, NRN, or, in some cases, CGN. Furthermore, the data was also combined with the different tax levels depending on the departure airport, as well as the airport access costs. This, in turn, showcased how many aspects may affect passenger choices and how some may be inclined to fly from foreign airports in search of lower prices or simply a shorter trip duration.

2.6. Airfares data

Finally, after obtaining the flight schedules for the considered airports, the corresponding airfares had to be assigned to each flight. This, in turn, entailed obtaining the flight distances, estimating the approximate airline airfares based on their service offerings and lastly adding aviation taxes onto the charged amounts.

Before the flight distances could be calculated, the geographical coordinates of all arrival airports had to be obtained. For that, a dataset with coordinates of all airports across the world was extracted from

OurAirports[17]. Based on the obtained document, a Python script was developed in order to calculate the corresponding flight distances. For that, first, the latitude and longitude for both the origin (lat_1, lon_1) and destination (lat_2, lon_2) for each flight were converted from degrees to radians:

$$\phi_1 = \mathrm{rad}(\text{lat}_1), \quad \phi_2 = \mathrm{rad}(\text{lat}_2)$$

where ϕ_1 and ϕ_2 are the latitudes of origin and destination airports expressed in radians. Furthermore:

$$\Delta\phi = \mathrm{rad}(\text{lat}_2 - \text{lat}_1), \quad \Delta\lambda = \mathrm{rad}(\text{lon}_2 - \text{lon}_1)$$

where $\Delta\phi$ is the difference in latitudes and $\Delta\lambda$ the difference in longitudes. Afterwards, the Haversine parameter, a, was computed by means of Equation 2.3:

$$a = \sin^2\left(\frac{\Delta\phi}{2}\right) + \cos(\phi_1)\cos(\phi_2)\sin^2\left(\frac{\Delta\lambda}{2}\right) \tag{2.3}$$

Furthermore, the central angle returning a positive angle between the positive x-axis and the point (x,y), c, was also computed by means of Equation 2.4:

$$c = 2\arctan 2\left(\sqrt{a}, \sqrt{1-a}\right) \tag{2.4}$$

Lastly, the great-circle distance, d, corresponding to the flight distance, was obtained:

$$d = R \cdot c \tag{2.5}$$

where R denotes the Earth's radius in kilometres, $R = 6371$ km. Based on the described procedure, the flight distances were calculated for each flight in the dataset, the sample of which can be observed in Table 2.6.

Table 2.6: Overview of flight distances

Destination	Origin	Aircraft	Airline	Distance (km)
AAL	AMS	Embraer 195	KLM	624.13
ABJ	BRU	Airbus A330-300	Brussels Airlines	5134.85
ACC	AMS	Boeing 777-300	KLM	5212.86
AGP	BRU	Airbus A320	Brussels Airlines	1735.48
ALC	AMS	Airbus A321 NEO	Transavia	1613.15
ARN	AMS	Airbus A321 NEO	KLM	1152.37
ATH	BRU	Airbus A320 NEO	Aegean	2101.43
ATL	AMS	Boeing 787-10	KLM	7065.79
BCN	AMS	Boeing 737-800	KLM	1241.14
BKK	AMS	Boeing 777-300	KLM	9207.55

where the airport codes representing destination airports refer to Aalborg Airport (AAL), Félix-Houphouët-Boigny International Airport (ABJ), Kotoka International Airport (ACC), Malaga-Costa del Sol Airport (AGP), Alicante Airport (ALC), Stockholm Arlanda Airport (ARN), Athens International Airport (ATH), Atlanta Hartsfield-Jackson International Airport (ATL), Barcelona-El Prat International Airport (BCN) and Bangkok Suvarnabhumi Airport (BKK).

Apart from the flight distance for each route, the airline operating it was also found to be of relevance. In the age of low-cost carriers becoming very prominent in the aviation industry, different airlines tend to charge different airfares despite operating on the same route. As such, each airline was categorised into one of four categories, depending on its services. This was done based on real-life analysis of airline services and the charged airfares[18], with the results of the categorisation presented in Table 2.7.

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[17] `https://ourairports.com/data/`

[18] `https://www.skyscanner.com/`

Table 2.7: Classification of airlines by service model

Category	Count	Airlines
ULC	7	AJet, Air Arabia Maroc, Laudamotion, Pegasus, Ryanair, Wizz Air, Wizz Air Malta
LC	18	Condor, Dan Air, easyJet, Enter Air, Eurowings, FlyOne, FlyOne Armenia, IndiGo, Norwegian Air Shuttle, Norwegian Air Sweden, Sky Alps, Sky Express, SmartWings, Transavia, Transavia France, TUIfly, Vueling
FC	65	Aegean, Aer Lingus, Aeromexico, Air Algeria, airBaltic, Air Belgium, Air Canada, Air Dolomiti, Air Europa, Air France, Air India, Air Serbia, American Airlines, ASL Airlines Ireland, Austrian Airlines, Avanti Air, British Airways, Brussels Airlines, Bulgaria Air, China Eastern, China Southern, Corendon Dutch, Corendon Europe, Croatia Airlines, Cygnus Air, Delta Air Lines, EgyptAir, El Al, Ethiopian, Finnair, Garuda Indonesia, Georgian, Hainan Airlines, Iberia, Icelandair, ITA Airways, Kenya Airways, KLM, KM Malta, LOT Polish Airlines, Lufthansa, Lufthansa CityLine, Royal Air Maroc, Royal Jordanian, SAR, SAS, Sichuan Airlines, Sprint Air, Star Air A/S, Sun Express, SWISS, Swiftair, TAP Air Portugal, TAROM, Thai International, TUI Belgium, TUI Nederland (Netherlands), Tunisair, United Airlines, Wideroe, Xiamen Air
Premium	6	Cathay Pacific, Emirates, Etihad, Qatar, Singapore Airlines, Turkish Airlines

where ULC implies an ultra-low-cost carrier, LC a low-cost carrier, FC a full-service airline and Premium represents a premium-service airline.

Depending on the corresponding category, each airline group was assumed to be charging distinct airfares[19]. Those were dependent on the quality of services offered, but also on the flight distances, as presented in Table 2.8, located below.

Table 2.8: Base airfares charged by the airlines

Category	Short-haul ($<$ 2500 km)	Medium-haul (2500 - 5500 km)	Long-haul ($>$ 5500 km)
ULC	€100	€200	€400
LC	€150	€300	€600
FC	€200	€400	€800
Premium	€250	€500	€1000

The airfares presented in the above table represent assumed round-trip airfares. The actual average airfares per flight were not implemented, however, due to the lack of publicly available data. As such, the above-presented values were assumed. To further resemble the real-life scenarios, the flight departure times were analysed. If a flight were to take off early in the morning (before 7 am) or late in the evening (after 8 pm), it would be subject to a 10% reduction in the charged fare, based on real-life observations of Skyscanner data[18]. This is because those hours are not very desirable to passengers and, as such, require a financial stimulus in order to be more appealing.

Furthermore, it is to be noted that the discussed airfares are not the total amount charged. They only represent the base fare, $Fare_b$. Given that not all charges are absorbed by the airlines, the `Tax` needs to be added to the ticket price in order to obtain the total airfare. This, however, differs per country of origin, affecting the final ticket prices. As described in the Scientific Article, the Netherlands and Belgium impose their own distance-based taxation structures, with a different amount charged depending on the distance travelled. Germany, on the other hand, envisioned a different approach, where countries are more arbitrarily classified into the taxation tiers, while also considering the flight distances. As such, the aviation tax for flights out of Germany had to be assigned not only based on the distances, but also on the destination countries, with the exact structure of the tax explained in Appendix A.

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[19] `https://www.google.com/travel/flights`

To visualise the differences in airfares, the ALC-bound flights were again compiled, along with their flight distances, base airfares, imposed aviation taxes (for the year 2027, denoted by $\texttt{Tax}_{27}$) and the total airfares. The overview of such a comparison can be found in Table 2.9:

Table 2.9: Airfares for ALC-bound flights

IATA	Origin	Dep. time	Airline	Dist. (km)	Cat.	$\texttt{Tax}_{27}$ (€)	$Fare_b$ (€)	$Fare_{tot}$ (€)
ALC	AMS	06:50	Transavia	1613.15	LC	29.40	135.00	164.40
ALC	AMS	12:30	Transavia	1613.15	LC	29.40	150.00	179.40
ALC	AMS	14:40	Vueling	1613.15	LC	29.40	150.00	179.40
ALC	AMS	17:00	Transavia	1613.15	LC	29.40	150.00	179.40
ALC	BRU	06:05	TUI Belgium	1458.01	FC	10.00	180.00	190.00
ALC	BRU	07:30	Transavia	1458.01	LC	10.00	150.00	160.00
ALC	BRU	09:45	Brussels	1458.01	FC	10.00	200.00	210.00
ALC	BRU	15:05	Vueling	1458.01	LC	10.00	150.00	160.00
ALC	CGN	15:40	Ryanair	1524.41	ULC	32.25	100.00	132.25
ALC	CRL	09:00	Ryanair	1410.99	ULC	10.00	100.00	110.00
ALC	CRL	12:40	Ryanair	1410.99	ULC	10.00	100.00	110.00
ALC	EIN	13:05	Ryanair	1535.76	ULC	29.40	100.00	129.40
ALC	EIN	16:15	Transavia	1535.76	LC	29.40	150.00	179.40
ALC	EIN	20:20	Ryanair	1535.76	ULC	29.40	90.00	119.40
ALC	NRN	06:20	Ryanair	1570.44	ULC	32.25	90.00	122.25
ALC	RTM	07:00	Transavia	1569.31	LC	29.40	150.00	179.40
ALC	RTM	16:15	Transavia	1569.31	LC	29.40	150.00	179.40

where IATA represents the destination airport code, Cat. depicts the airline category, and $Fare_{tot} = Fare_b + \texttt{Tax}_{27}$ describes the total airfare as a summation of the base fare and the imposed aviation tax.

2.7. Overview of data files

The obtained data files provide a quantitative measure of aspects affecting passenger choices upon airport, airline and flight selection. While the impacts of aviation taxes are an important metric, the particular location of a given resident and their temporal distance from different airports are relevant factors as well. This, in turn, results in numerous data files needing to be obtained, the overview of which can be found in Table 2.10 located below.

Table 2.10: Overview of data analysis files

Type of data	**How was data collected?**	**Purpose of processing**	**File name(s)**
Aviation taxes	Web scraping	To quantify the differences in aviation taxes between the Netherlands, Belgium and Germany	`airport_coordinates`
Geographic locations	QGIC, PDOK, OurAirports	To obtain the geographical location of every airport and every PC4 postcode in the Netherlands	`airport_coordinates`, `pc4_centroids`, `train_stations`
Airport driving accessibility	OpenStreetMap	To model the airport temporal driving distances	`OSRM driving data`
Train operations	NDOV	To extract temporal distances between each PC4 postcode and the considered airports	`train_stations`, `NS_services`

Type of data	How was data collected?	Purpose of processing	File name(s)
Airport ground access costs	Web scraping	To model the costs of accessing airports by car or public transit	-
Flight schedules	Airport timetables	To quantify the attractiveness of different routes and airport competition	`flight_overview_19.01.2026`
Calibration data	Findings presented in [3, 4]	To calibrate the utility coefficients of the model based on real, observed airport market shares data	`model_benchmark_data`
Data analysis & processing	Python (Visual Studio Code)	To process the obtained .csv files into model-ready format	-
Model inputs	Python (Visual Studio Code)	To quantify and evaluate passenger leakage to foreign airports	`model_input_data`, `pc4_centroids`, `model_benchmark_data`

The data obtained from the performed research was subsequently incorporated into the data analysis process. The aim of this was to prepare a dataset that could be used in the model itself. To accomplish that, the acquired data was transformed into separate files ("Sourced files"), with each file relating to a different aspect of the dataset. Those included:

Table 2.11: Sourced files used in the data processing

Sourced file	Description of the file
`pc4_centroids`	Geographical coordinates of the centroid of each PC4 postcode, together with the corresponding population numbers.
`OSRM driving data`	Driving spatial and temporal distances between different coordinates, based on OSRM API requests.
`train_stations`	Geographical locations of all train stations located in the Netherlands or being served by trains departing from the Netherlands.
`NS_services`	All rail services of all rail operators that at any point traversed through the Netherlands. The services were extracted for the month of September 2025 and also included the unit fare distances used for calculating ticket prices.
`flight_overview_19.01.2026`	Concatenated departures of all commercial aircraft departing from each of the ten considered airports (AMS, BRU, CGN, CRL, DTM, DUS, EIN, MST, NRN, RTM). The data includes the departure and arrival airports, the time of departure, and the airline operating the flight.
`airport_coordinates`	Geographical coordinates of all commercial airports in the world, together with the corresponding IATA codes.
`model_benchmark_data`	Airport market shares of the considered airports for the year 2024 [3]. Furthermore, the file also contains data regarding the incremental leakage experienced due to the introduction of the aviation tax in 2008 [4].

Based on the above data files, several Python files were created. The aim of those was to process the obtained data into files that could be used in the actual mathematical model in a straightforward manner. The overview of the created files can be observed in Table 2.12, which is located below.

Table 2.12: Python files used in the data processing

Python file(s)	**Description of the file**
`airport_distances.py`	Calculation of the driving temporal and spatial distances from each PC4 postcode to each of the considered airports.
`PC4_closest_stations.py`	Calculation of the closest railway station to each PC4 postcode based on the respective geographical coordinates.
`NS_temporal_distances.py`	Calculation of the temporal distances between all station combinations served by trains operating in the Netherlands by means of the created Dijkstra algorithm, as explained in Section 2.3.
`flight_distances.py`	Calculation of the distances covered by the operated flights as described in Section 2.6.
`NS_costs_1/2.py`	Calculation of the public transport travel costs between any NS station and each of the considered airports.
`airport_access_times.py` + `access_costs.py`	Calculation of the temporal distances between each PC4 postcode and each of the considered airports, both in the case of driving and taking public transit. Performed in accordance with the procedure described in Section 2.4.
`airfares.py`	Calculation of the base airfares as well as the charged taxes depending on the flight distance, departure country, time of departure, and the airline operating the flight, as described in Section 2.6.
`MODEL - dataset.py`	Merging of the data files together with the preparation of the dataset to be used in the model (`model_input_data`).

The relationships between each of the described files have also been documented and can be observed in Figure 2.1.

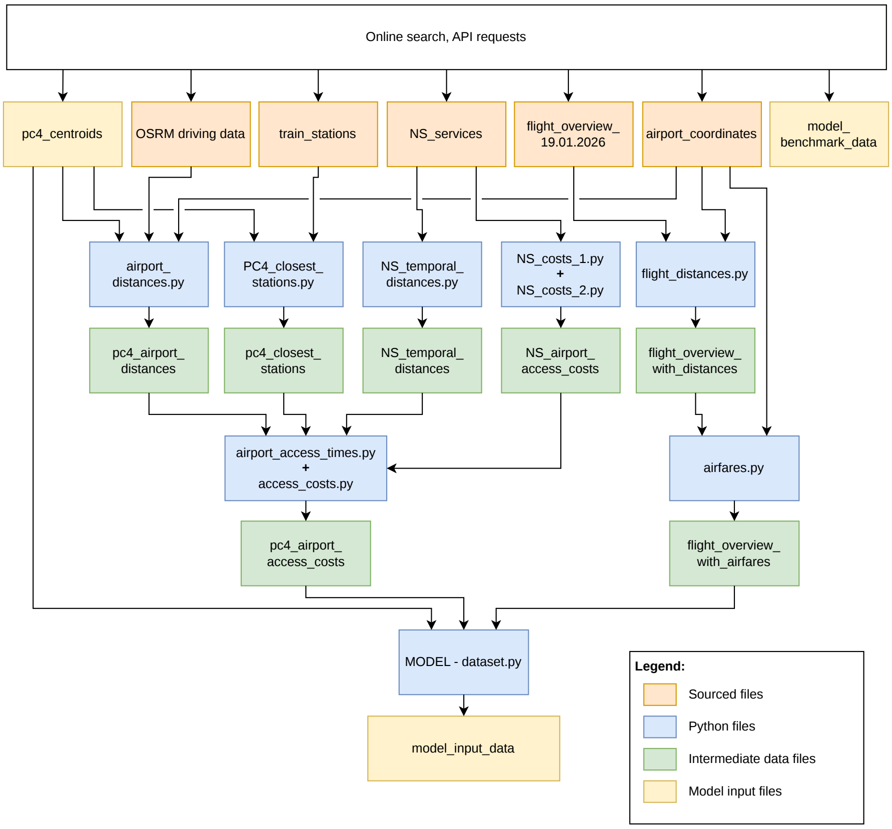

Figure 2.1: Data processing flowchart

Based on the presented procedure, a total of three model input files were created, namely: `pc4_centroids`, `model_benchmark_data` and `model_input_data`. The last of those files was used to present a complete list of alternatives that were evaluated by the model. For each of the 4072 PC4 postcodes, a set of 1162 distinct flights that could be selected was listed. Furthermore, each flight can be accessed by one of two possible access modes, p, namely public transit or personal car. This, in turn, provides a total of 9.46 million alternatives in the entire dataset, the sample of which can be observed in Table 2.13 and Table 2.14.

Table 2.13: Sample version of the `model_input_data` file (Part 1)

$pc4$	x	y	p	$Fare_b$	Tax_{2007}	Tax_{2008}	Tax_{2024}	Tax_{2027}	$\cdots$
1058	AMS	ZRH	car	200	0	11.25	29.05	29.40	$\cdots$
9172	DTM	STN	pt	150	0	0.00	15.53	12.73	
1454	BRU	MUC	pt	200	0	0.00	5.00	10.00	
4751	DUS	MUC	pt	200	0	0.00	39.34	32.25	
4103	AMS	LHR	pt	200	0	11.25	29.05	29.40	
6281	AMS	LBA	pt	200	0	11.25	29.05	29.40	
6704	DUS	DOH	pt	500	0	0.00	39.34	32.25	
6999	AMS	FCO	pt	200	0	11.25	29.05	29.40	
6981	EIN	OSL	pt	150	0	11.25	29.05	29.40	
4835	BRU	HEL	car	200	0	0.00	5.00	10.00	

Table 2.14: Sample version of the `model_input_data` file (Part 2)

$pc4$	x	y	p	$\cdots$	T^{GA}	C^{GA}	ST	$FREQ$	$TYPE$	BUS	n_{res}
1058	AMS	ZRH	car	$\cdots$	15.6	34.9	0	11	FC	0.12	15750
9172	DTM	STN	pt		220.0	115.0	0	1	LC	0.12	1825
1454	BRU	MUC	pt		147.0	78.5	0	6	FC	0.12	550
4751	DUS	MUC	pt		153.0	81.5	0	12	FC	0.12	7440
4103	AMS	LHR	pt		44.0	27.0	0	16	FC	0.12	1450
6281	AMS	LBA	pt		144.0	77.0	0	3	FC	0.12	1720
6704	DUS	DOH	pt		97.0	53.5	0	1	Premium	0.12	1020
6999	AMS	FCO	pt		80.0	45.0	0	6	FC	0.12	1600
6981	EIN	OSL	pt		103.0	56.5	0	1	LC	0.12	4445
4835	BRU	HEL	car		70.9	65.3	0	3	FC	0.12	6825

Each alternative can be characterised by the four digits corresponding to the PC4 postcode, the departure airport, x, the destination airport, y, and the airport access mode, p. Moreover, the destination airports presented in the table represent Zurich Airport (ZRH), London Stansted Airport (STN), Munich Airport (MUC), London Heathrow Airport (LHR), Leeds Bradford Airport (LBA), Doha Hamad International Airport (DOH), Rome Fiumicino Airport (FCO), Oslo Gardermoen Airport (OSL) and Helsinki Airport (HEL). Furthermore, for each alternative, several characteristics have been included. Those are: the base airfare, $Fare_b$ (€), dependent on the airline and the time of departure of the aircraft, as well as the aviation taxes (€) for the years 2007, 2008, 2024 and 2027. Furthermore, the airport access time (min) and round-trip cost (€) from a given postcode area to the given airport by a given access mode have also been included. The next characteristics are related to the flights themselves. ST determines whether the given flight departs at the undesired early morning/late evening hours, in which case its value is equal to one, zero otherwise. Furthermore, $FREQ$ and $TYPE$ provide the daily frequency on the given route and the airline type operating the flight, respectively. BUS characteristic, on the other hand, defines the share of business travellers on a given route who also reside in the given postcode. The last column of the table is related to the inherent characteristic of the alternative itself, where n_{res} provides the number of residents in a given postcode. This is important when quantifying the aggregate leakage in the entire country by means of the weighted average. Lastly, it should be noted that the data directly serving as input to the utility function, namely $Fare$, Tax, T^{GA}, C^{GA} and $FREQ$ values, were all standardised in their respective categories to showcase their relative attractiveness on the $[-1, 1]$ scale.

The model input files were subsequently used in the created model. The model itself, however, also contained several Python files, the description of which can be observed in Table 2.15.

Table 2.15: Python files used in the mathematical model

Python file	Description of the file
`MODEL.py`	Calculation of the utility functions and the corresponding airport selection probabilities (`model_results_with_probabilities`). The script also computes both the aggregate leakage (`aggregate_leakage`) and the leakage for each PC4 postcode (`leakage_by_pc4`).
`calibration.py`	Calibration of the coefficients in the utility function based on the real-life observed benchmark data (`model_benchmark_data`), with the file updating the coefficients in the model environment.
`leakage_plot.py`	Plotting of the leakage experienced in each PC4 postcode across the map of the Netherlands.
`airport_probabilities.py`	Plotting of the airport market shares across the map of the Netherlands.
`ALC_probabilities.py`	Plotting of the probabilities of a given airport being selected for each PC4 postcode, assuming that a given airport, such as ALC, is the final destination.

All of the above files are related to each other. In order to properly visualise those relations, a flowchart of the model has been created and can be observed in Figure 2.2, which is located below.

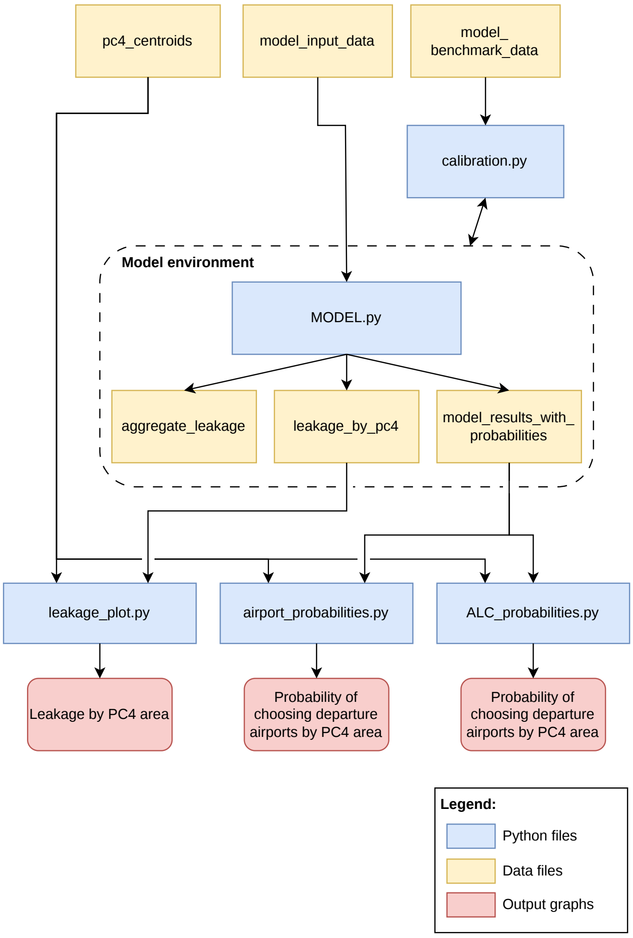

Figure 2.2: Mathematical model flowchart

3

Verification

A crucial aspect related to academic research is verification. Its main aim is to evaluate whether or not the created files perform correctly and contain accurate data [5]. For that reason, extensive work is often performed so as to confirm that the project files are performing as desired. This was also the case for this Thesis, where extensive verification of the files was performed. This included both the obtained data files and the created model. This chapter will aim to familiarise the reader with the performed verification steps as well as the resulting outcomes.

3.1. Verification of the dataset

To ensure both the completeness and the correctness of the dataset, verification was performed on each of the sourced files as well as each data processing script. This was required to ensure that the dataset used in the model is representative of the real-life data and that the Python code performs as expected.

In the case of the sourced files, the verification process analysed the completeness of the files. To accomplish that, the data was manually compared to online sources. One of the prime examples of this was the `flight_schedules_19.01.2026` file, containing departures from each of the considered airports. Completeness of the dataset was verified by checking the number of daily departures at each airport, based on real-life schedules[1,2]. This, in turn, confirmed, among others, that 567 departures from AMS airport present in the dataset were indeed all commercial departures from AMS on 19 January 2026. The same approach was performed for the remaining files, one of which was `airport_coordinates`. To verify the correctness of the geographical coordinates of the airports, a selection of 10 airports from the dataset was analysed manually. This entailed comparing the coordinates in the data file against real-life values[3]. All of the files passed the verification tests, as no errors were observed among the analysed samples. This, in turn, completed the verification process of the sourced data files.

Afterwards, the verification of the data processing scripts had to occur. This included the scripts presented in Table 2.12. In order to verify them, two separate approaches were utilised. First, the functions responsible for modifying the datasets were analysed. One of those entailed evaluating a function assigning IATA airport codes to the flight schedules data. The correct functioning of this part of the Python script was verified by means of unit testing. Similarly, other functions, such as the assignment of a tax level depending on a given route, were verified by means of extensive unit testing as well as through visual inspection. Not all scripts could be verified this way, however. One of those was `flight_distances.py`, which entailed extensive calculation, where the flight distances were obtained

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[1] https://www.flightradar24.com/

[2] https://www.schiphol.nl/en/

[3] https://www.google.com/maps

based on the geographic coordinates of two airports, as described in Section 2.6. To verify the correct functioning of this file, the results of ten sample calculations were compared to the calculations obtained by hand. The results of the Python code perfectly matched those of the manual calculation. This, in turn, resulted in the respective Python scripts passing the verification process. Based on the performed verification, all data files and Python scripts were deemed complete and functioning as intended, in turn, providing the desired dataset for the mathematical model.

3.2. Verification of the mathematical model

After verifying the correctness of the dataset, which serves as the input to the model, the mathematical model itself also had to be verified. This was a more complicated task, however, as the model contained several mathematical functions, which were closely related to one another. To account for that, print statements were added to each function. Their aim was to allow for visual inspection of the code throughout its execution. Furthermore, every function was subjected to unit testing to determine whether the code was functioning correctly. This included the calculation of the utility functions, the marginal and conditional probabilities, as well as the passenger leakage.

Given the several functions forming the mathematical model, system testing was also incorporated in order to verify the relations between the functions. This was combined with the visual inspection of the plotting of the airport selection probabilities. For this, Doha Hamad International Airport (DOH) was considered. The reason for that is that there is only one airline, Qatar Airways, serving the BE, DE, and NL region from DOH. As such, there are fewer aspects affecting airport selection, and the distribution between departure airports becomes more dependent on the geographical location of the residents. This is what was indeed observed in the plots, verifying the correct functioning of the mathematical model.

3.3. Verification of the calibration of the model

The last part of the verification process revolved around verifying the correctness of the calibration process. To accomplish that, the verification of the optimiser was to be conducted. This was necessary so as to confirm that the values of the utility coefficients are indeed modified with each iteration and that the associated loss is computed correctly. This was achieved by, among others, inserting numerous print statements into the Python script. This, in turn, provided the necessary visual information on the state of the coefficients throughout the calibration process. Furthermore, the calibration file was run several times so as to ensure that the obtained results are the same every time. Apart from that, unit tests were also incorporated with the aim of verifying the distinct mathematical operations performed by the Python file. Finally, the results obtained based on the calibrated parameter coefficients were visually inspected to confirm that they are as expected. All of the designed tests were ultimately passed, concluding the verification of the file. This, however, also marked the completion of the entire verification process, with all of the project files being verified.

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German aviation taxes

For flights originating from Germany, the tax rate is determined per destination country. Countries located within the EU are all subject to the lowest taxation fee. Apart from those, however, there are 23 more countries which fall into the same tax bracket. Those were listed by the German authorities in the Luftverkehrsteuergesetz Annex1[1] and can also be observed in Table A.1, which can be found below.

Table A.1: Annex 1 Countries

Count	Countries
23	Albania, Algeria, Andorra, Bosnia and Herzegovina, Iceland, Kosovo, Liechtenstein, Libya, Moldova, Monaco, Montenegro, Morocco, North Macedonia, Norway, Russian Federation, San Marino, Serbia, Switzerland, Tunisia, Turkey, Ukraine, United Kingdom, Vatican City

Destinations in all remaining countries fall into the higher taxation tiers. All destinations, whose countries were not explicitly listed in Annex1, but are at a distance of up to 6000 km, are subject to the middle taxation tier, with further destinations falling into the highest taxation level.

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[1] `https://www.gesetze-im-internet.de/luftvstg/anlage_1.html`