Delft University of Technology

Airline Planning and Optimization
AE4423

Airline Optimization - Network and Fleet Development

Authors:
Pieter Becking 4685377
Sam Edmonds 4552253
Max Hendriks 4694333

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1 Introduction

1.1 Assignment Outline

This report presents a study on the optimization of the planning of an airline operating in Italy with Rome Ciampino as its main hub airport. The main objective of the study is to maximize the total profit of the airline.

To achieve this goal, it is necessary to forecast the demand for air travel between different airports in Italy in 2030. The gravity model will be used to make these predictions, taking into account the populations and distances between the airports, as well as the expected growth of the population and other relevant variables.

Based on the demand forecast, a network and fleet plan for the airline will be developed. This will involve determining the optimal routes and schedules for the airline's flights, as well as the number and type of aircraft needed to operate these routes. The leasing of a fleet of 5 aircraft types to operate the airline's network will be considered. This will involve analyzing the costs and benefits of leasing different types of aircraft and determining the optimal mix of aircraft to maximize the total profit of the airline.

The Gurobi software is used for the Mathematical optimization this Gurobi Dual Simplex algorithm makes use of the power of math to find the best solution to a complex, real-world problem. This algorithm is implemented in the python environment in order to insert the airlines details of the problem into the Gurobi algorithm, likewise the goals the airline want to achieve, the limitations the airline is facing, and the variables they control are inserted in the Gurobi optimizer. Having received all this information from and the mathematical optimization solver will calculate your optimal set of decisions.

Overall, the goal of this report is to develop a comprehensive plan for the optimization of the airline's operations, taking into account the demand forecast, network and fleet development, and aircraft leasing decisions. By applying these methods and using the appended scripts, it is expected that the total profit of the airline will be maximized and its competitiveness in the airline environment improved.

1.2 Key Performance Indicators

The metrics to evaluate the performance of the airline are based on real life KPIs:

- *Operating profit* is used to measure the financial performance of an airline. It represents the profit the company generates from its core business operations, after subtracting operating expenses.
- *Fraction of transported passengers from total available passenger demand.* This gives an indication of how much of the demand the airline able to satisfy. A higher percentage will also result in better publicity for reliability

2 Demand Forecast

2.1 Calibrating Gravity Model

The gravity model is a widely used model for predicting the flow of goods or people between two locations. It is based on the idea that the flow between two locations is proportional to the size of the locations and inversely proportional to the distance between them. In this chapter, we will discuss the process of calibrating the gravity model using the ordinary least squares (OLS) method with the given demands for legs between ten airports.
The gravity model for the demand in this assignment is shown below.

$$D_{ij} = k \cdot \frac{(pop_i \cdot pop_j)^{b_1} \cdot (GDP_i \cdot GDP_j)^{b_2}}{(f \cdot d_{ij})^{b_3}} \tag{1}$$

where D_{ij} is the demand for travel from airport i to airport j, pop_i and pop_j the populations of the departure and arrival airport regions respectively, GDP_i and GDP_j the Gross Domestic Product of the departure and arrival airport regions respectively, f the fuel price, and d_{ij} the distance between airport i and airport j.
Using the OLS method gives the values for coefficients k, b_1, b_2 and b_3 as shown in table 1. The results of the OLS method are visualized in Fig. 1, where the red line represents the situation where the predicted demand corresponds exactly to the given demand.

Table 1: Coefficients of the gravity model

Coefficient	Value
k	0.004127176700191273
b_1	0.34683447685180807
b_2	0.12476859271230578
b_3	0.2777469849212998

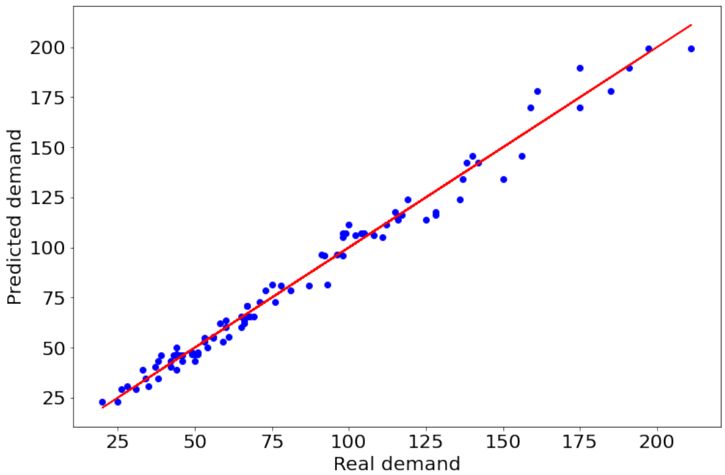

Figure 1: Regression of the 2020 demands by OLS method

2.2 Demand forecast for 2030

A yearly increase in population of 1% is expected over the next 10 years. Using the gravity model and its calculated coefficients, we can predict the demand for air travel between airports in 2030 based on this growth rate and the other known variables. Each population is multiplied by 1.01^{10} to represent the population in the year 2030, ten years later. Keeping all other variables constant, the gravity model in equation 1 yields the demands as visualized in figure 2, where the varying opacity represents varying demands.

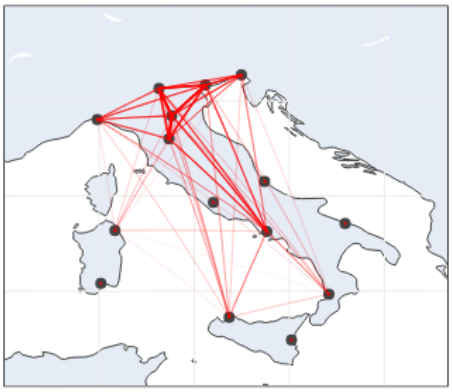

Figure 2: Visualized demand of each route in 2030

The values for the demand forecast for 2030 are appended in Appendix A

3 Leg-Based Model

3.1 Network and Fleet Development

Equipped with accurate demand data, the goal was to generate the weekly flight frequency plan for an airline. As the airline is new, new aircraft must be acquired. For this first model, the fleet selection is limited to 3 kerosene fueled aircraft. Thus, it needs to be determined how many aircraft should be leased to maximize the profit. To achieve this goal several steps need to be taken to start of with defining the objective function.

The network and fleet model has an objective function maximize the profit of the airline, by weighing the costs and yields of flying the planned routes. In order for this model to function properly constraints need to be taken into account.

Table 2: Constraints Fleet and network model

Constraint	Description	Equation
C1	Demand verification	Number of passengers $\leq$ demand
C2	Capacity	Number of passengers in each leg $\leq$ seat available per leg
C3	Continuity constraint	Aircraft inbound = Aircraft outbound (per airport, per aircraft type)
C4	Aircraft Productivity	Hours of operation $\leq$ Aircraft avg. utilization time $\times$ number of aircraft
C5	Range Constraint	Range $\leq$ distance $\rightarrow$ no flights

3.1.1 Mathematical Model

In order to understand the mathematical model the variables used need to be defined:

Table 3: Notation Fleet and network model

Sets	N:	Set of airports (where h is the hub)
	K:	Set of aircraft types
Decision Variables	w_{ij}:	Flow of passengers from airport i to airport j that transfers at the hub
	x_{ij}:	Flow of passengers from airport i to airport j that do not go through the hub
	z_{ij}^k:	number of flights from airport i to airport j with aircraft type k
	AC^k:	Number of aircraft type k
Parameters	q_{ij}:	Travel demand between airport i to airport j
	g_h:	0 if a hub is located at airport h, otherwise equal to 1
	d_{ij}:	Distance between airports i and j found in the Airport data file.
	$Y_{EUR_{i,j}}$:	Revenue per passenger per km flown on leg i to j
	s^k:	Number of seats per aircraft found in Appendix D.
	$CASK^k$:	Unit operation cost per available seat per km flown. Dependent on aircraft.
	sp^k:	Speed of the aircraft found in Appendix D.
	LF:	Average load factor: assumed to be 80% of cabin capacity
	R^k:	Range of aircraft found in Appendix D.
	LTO^k:	Landing and take-off time (including Turn-Around-Time) of each aircraft
	TAT:	Parameter for Turn-Around-Times: equals 1.5 if aircraft travels to Hub else equal to 1
	BT^k:	Aircraft avg. utilisation time: assumed to be 10 hours per day
	C_L^k:	Cost of leasing aircraft type k found in Appendix D.
	C_T^k:	Time cost parameter for aircraft type k found in Appendix D.
	C_F^k:	Cost of fuel for aircraft type k found in Appendix D.
	C_x^k:	Cost of operating aircraft type k found in Appendix D.
	f:	Fuel price equal to 1.42 USD/gallon
	$z_{hub_{i,j}}$:	Effect of hub on operation costs: 0.7 if the airport i or j is the hub else equal to 1
	V^k:	Speed per aircraft type k found in Appendix D.

The Variables $Y_{EUR_{i,j}}$ and $CASK^k$ are defined as followed:

$$Y_{EUR_{i,j}} = 5.9 \cdot d_{ij}^{-0.76} + 0.043 \tag{$Y_{EUR_{i,j}}$}$$

$$CASK^k = \frac{C_T^k}{V^k \cdot s^k} + \frac{C_F^k \cdot f}{1.5 \cdot s^k} \tag{$CASK^k$}$$

The variables Turn-Around-Times (TAT), and landing and take-off times (LTO) are depended on the aircraft type and the route operated. The assumption was made that the TAT for flights to the hub are 50% longer than the normal TAT. Typical TATs per aircraft type can be found found in Appendix D.

The yield, $Y_{EUR_{i,j}}$, is calculated in the same manner as in question 1 and is depended on a specific leg (leg between airport i and j).

Leading to the objective function written using the explained notation:

$$Max\ Profit = \sum_{i\epsilon N}\sum_{j\epsilon N}\left[Y_{EUR_{i,j}} \times d_{ij}(x_{ij} + w_{ij} * 0.9) - \sum_{k\epsilon K}((CASK^k \times d_{ij} \times s^k + C_X^k) \times z_{ij}^k \times z_{hub_{i,j}})\right] \tag{Objective Function}$$

The w_{ij} is multiplied by 0.9 due to the revenue generated by passengers connecting at the hub being 10% lower. This is a realistic assumption as passengers tend to have a lower willingness to transfer between flights. The objective function has to keep the constraints in mind, which can be written using the notation as follows:

$$x_{ij} + w_{ij} \leq q_{ij}, \forall i, j\epsilon N \tag{C1}$$

$$w_{ij} \leq q_{ij} \times g_i \times g_j, \forall i, j\epsilon N \tag{C1*}$$

$$x_{ij} + \sum_{m\epsilon N} w_{im}(1 - g_j) + \sum_{m\epsilon N} w_{mj} \times (1 - g_i) \leq \sum_{k\epsilon K} z_{ij}^k \times s^k \times LF, \forall i, j\epsilon N \tag{C2}$$

$$\sum_{j\epsilon N} z_{ij}^k = \sum_{j\epsilon N} z_{ji}^k, \forall i\epsilon N, k\epsilon K \tag{C3}$$

$$\sum_{i\epsilon N}\sum_{j\epsilon N}(\frac{d_{ij}}{sp^k} + LTO^k \cdot TAT_{ij}) \times z_{ij}^k \leq BT \times AC^k, k\epsilon K \tag{C4}$$

$$z_{ij}^k \leq a_{ij}^k \rightarrow a_{ij}^k \begin{cases} 10000 & if\ d_{ij} \leq R^k and\ Runway_{max_r} \leq Runway_{req}^k \\ 0 & otherwise \end{cases} \tag{C5}$$

3.2 Results

With the data available in the Excel file supplied with the assignment and the aircraft data shown in Appendix D, the network to be operated and the corresponding flight frequency is determined assuming one standard week of operations. furthermore it is determine how many aircraft of each type will be leased in the most optimal solution.

The modeling optimization problem is solved and the optimal routes are visualized in the figure below.

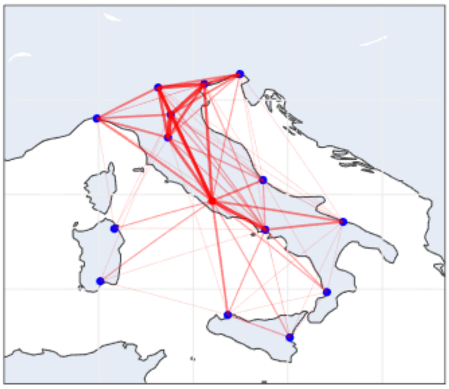

Figure 3: Visualized Results for the Leg-Based Model

It was concluded that the total number of flights flown is 134 in total. The optimal amount of aircraft and corresponding type are found to be 3 Turbo Props aircraft, 1 Regional Jet aircraft and 0 Single Isle Twin Jet aircraft. These aircraft combined transferred 18 passengers through the hub and 11756 passengers in total. As the total demand between the cities is 16773, this schedule will satisfy 70.1% of the market. This model assumes an average load factor of 80% on there flights. This leads to the total profit on a weekly basis to be $52,929.96$ *Euro*.

These results are in line with what was expected from the results. As the model allows the airline to fly all possible legs, the model should get close to satisfying the total demand. As the averge load factor is set at 80%, the maximum demand to satisfy should also be close to that. At 70.1% this is close.

KPI	Value
Operating profit	€ 52,929.26
Fraction of transported passengers	70.1%

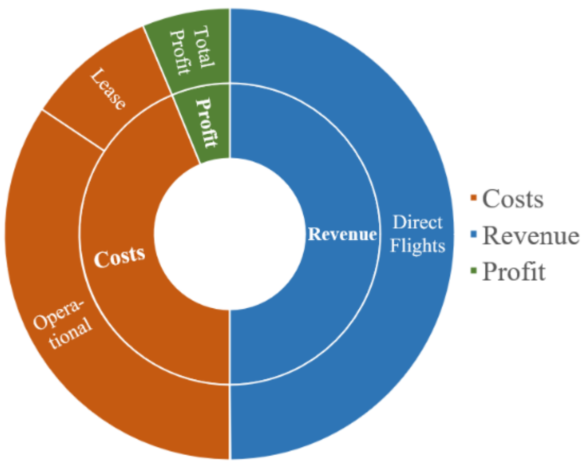

Figure 4: KPI Values and Financial Analysis for the Leg-Based Model

4 Route-Based Model

4.1 Network and Fleet Development

Due to the environmental goals, the airline is considering the option of operating electric aircraft. In order to investigate the potential of electric aircraft as a replacement for kerosene a network and fleet development problem is solved. As a charging station would be located at the hub airport. The network and fleet development problem analyses the possible triangular routes, in which the aircraft will fly to a maximum of two airports before returning to the hub airport. The possible options are considered for both kerosene and electric aircraft to determine how many aircraft for each type will be leased in the most optimal solution. The results are compared with the results from Problem 1 and used to determine the best strategy for the airline.

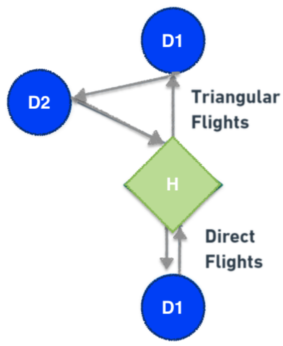

Figure 5: Network and Fleet Development model

4.1.1 Mathematical Model

In order to understand the mathematical model, the variables used are defined in Table 4.

The parameter $CASK^k$ is defined as follows:

$$CASK^k = \frac{C_T}{V^k \cdot s^k} + \frac{C_F \cdot f}{1.5 \cdot s^k} + \frac{G^k \cdot e}{s^k R^k} \qquad (CASK^k)$$

The variables Turn-Around-Times (TAT), and landing and take-off times (LTO) are depended on the aircraft type and the route operated in the same means as the first problem. Leading to the objective function written using the explained notation:

$$Max\ Profit = \sum_{r \epsilon R} \sum_{i \epsilon N} \sum_{j \epsilon N} \left[Y_{EUR_{i,j}} \times d_{ij}(x_{ijr} + \sum_{n \epsilon R} w_{ij}^{rn} \times 0.9) \right] \qquad \text{(Objective Function)}$$

$$- \left[\sum_{r \epsilon R} \sum_{k \epsilon K} ((CASK^k \times d_r \times s^k + C_{x_{freq},r} \cdot C_X^k) \times z_r^k \times z_{hub_r}) + \sum_{k \epsilon K} C_L^k \times AC^k \right]$$

The objective function has to keep the constraints in mind, which can be written using the notation as follows:

Demand constraints:

$$\sum_{r \epsilon R} \left(x_{ij}^r + \sum_{n \epsilon R} w_{ij}^{rn} \right) \leq q_{ij}, \forall i, j \epsilon N \qquad \text{(C1)}$$

$$x_{ij}^r \leq q_{ij} \times \delta_{ij}^r, \forall i, j \epsilon N \qquad \text{(C1*,1)}$$

$$w_{ij}^{rn} \leq q_{ij} \times \delta_{ih}^r \times \delta_{hj}^n, \forall r, n \epsilon R, i, j \epsilon N \qquad \text{(C1*,2)}$$

Flow Constraints: From the hub node (H):

$$\sum_{m \epsilon s_H^r} x_{Hm}^r + \sum_{n \epsilon R} \sum_{p \epsilon N} \sum_{m \epsilon s_H^r} w_{pm}^{nr} \leq \sum_{k \epsilon K} z_r^k \times s^k \times LF \quad \forall r \epsilon R\ (with\ j = S_H^r(1)\ and\ i = H) \qquad \text{(C2, 1)}$$

Table 4: Notation Fleet and network model

Sets	N:	Set of airports (where h is the hub)
	R:	Set of all possible routes
	K:	Set of aircraft types
Decision Variables	w_{ij}^{rn}:	Flow of passengers from airport i to airport j that transfers at the hub from route r to n
	x_{ij}^{r}:	Flow of passengers flying a direct route from airport i to airport j on route r
	z_r^k:	Number of flights flown on route r with aircraft type k
	AC^k:	Number of aircraft type k
Parameters	q_{ij}:	Travel demand between airport i to airport j
	d_r:	Distance of the route.
	d_{ij}:	Distance between airports i and j found in the Airport data file.
	$Y_{EUR_{i,j}}$:	Revenue per RPK flown (average yield)
	s^k:	Number of seats per aircraft found in Appendix D.
	$OperatingCost_r^k$:	Unit operation cost per route flown
	sp^k:	Speed of the aircraft found in Appendix D.
	LF:	Average load factor: assumed to be 80% of cabin capacity
	R^k:	Range of aircraft found in Appendix D.
	LTO^k:	TAT of aircraft including Landing and take-off time
	TAT_r:	Parameter for Turn-Around-Times equals 3.5 if route of aircraft had a spoke else equal to 2.5
	TAT_{elec_r}:	Parameter for Turn-Around-Times of electric aircraft equals 3 if route of aircraft had a spoke else equal to 2
	BT^k:	Aircraft avg. utilization time: assumed to be 10 hours per day
	C_L^k:	Cost of leasing aircraft type k found in Appendix D.
	C_T^k:	Time cost parameter for aircraft type k found in Appendix D.
	C_F^k:	Cost of fuel for aircraft type k found in Appendix D.
	C_x^k:	Cost of operating aircraft type k found in Appendix D.
	e:	Price of energy equal to 0.07 Euro/kWh
	G^k:	Energy in fully recharged aircraft of type k found in Appendix D.
	$Charge^k$:	Time to fully recharged aircraft of type k found in Appendix D.
	f:	Fuel price equal to 1.42 USD/gallon
		Equal to 0.7 if the airport flies route H-A-H else $= \frac{2 \cdot 0.7+1}{3}$
	$Runway_{max}$:	Parameter to determine shortest runway in a route
	$Runway_{req}^k$:	Parameter to determine required runway distance for aircraft k found in Appendix D.
	$\delta_{i,j,r}$:	Parameter to determine if a leg is in specific route
	V^k:	Speed per aircraft type k found in Appendix D.

Between the spokes:

$$\sum_{m\epsilon s_j^r} x_{im}^r + \sum_{m\epsilon P_i^r} x_{mj}^r + \sum_{n\epsilon R}\sum_{p\epsilon N} w_{pj}^{nr} + \sum_{n\epsilon R}\sum_{p\epsilon N} w_{ip}^{rn} \leq \sum_{k\epsilon K} z_r^k \times s^k \times LF, \tag{C2, 2}$$

$$\forall r\epsilon R2 \ with \ i = S_H^r(1) \ and \ j = S_H^r(2)$$

To the hub node (H):

$$\sum_{m\epsilon P_i^r} x_{mH}^r + \sum_{n\epsilon R}\sum_{p\epsilon N}\sum_{m\epsilon P_i^r} w_{mp}^{rn} \leq \sum_{k\epsilon K} z_r^k \times s^k \times LF, \tag{C2,3}$$

$$\forall \ r\epsilon R2 \ with \ i = S_H^r(2) \ and \ \forall r\epsilon R/R2 \ with \ i = S_H^r 1 \ (and \ for \ both \ j = H)$$

Aircraft Utilization constraint

$$\sum_{r\epsilon R}\left(\frac{d_r}{V^k} + LTO^k \times TAT_r + Charge^k\right) \times z_r^k \leq BT \times AC^k, \ \forall k\epsilon K \tag{C4}$$

Aircraft allocation constraints:

$$z_r^k \leq a_r^k \rightarrow a_r^k \begin{cases} 10000 & if \ d_r \leq R^k \ and \ Runway_{max_r} \leq Runway_{req}^k \\ 0 & otherwise \end{cases} \tag{C5}$$

4.1.2 Route Generation

First, the code generates all possible routes between airports and stores them in a list *AllRoutes*. Each route is given a unique route ID and stored in a dictionary *Route*. The keys of the dictionary are the route IDs and the values are the routes themselves. The number of routes is denoted by R.

Next, the code creates a new dictionary $Runway_{max}$ which stores the shortest runway for each route. This is done by looping over all routes in *Route* and checking the length of the route. The shortest runway may not exceed the minimum required runway for an aircraft flying that route.

The code also creates a new dictionary d which stores the total distance of each route. This is done by looping over all routes in *Route* and calculating the total distance using the distances between the airports stored in the distance dictionary (from the provided Excel file). If the route has length 3, the total distance is the sum of the distances between the origin and destination airports, and the destination and return airports. If the route has length 4, the total distance is the sum of the distances between the origin and destination airports, the destination and transfer airports, and the transfer and return airports.

Finally, the code loops over all aircraft types k in the set K and adds constraints to the model to ensure that the utilization of each aircraft type does not exceed a given maximum utilization BT, and that the range and required runway length of each aircraft type are sufficient for each route. The utilization constraint is given by:

$$\sum_{r=1}^{R}\left(\frac{d_r}{sp_k} + LTO_k \cdot TAT_r + Charge_k\right) \cdot z_{r,k} \leq BT \cdot AC_k$$

The range and runway constraint is given by Equation C5, where d_r is the total distance of route r, sp_k is the speed of aircraft type k, LTO_k is the time required for takeoff and landing for aircraft type k, TAT_r is the time required for the route r, $Charge_k$ is the time required for refueling for aircraft type k, AC_k is the number of aircraft of type k, R_k is the range of aircraft type k, and $runway_{req,k}$ is the required runway length for aircraft type k. The variables $z_{r,k}$ are binary variables indicating whether or not aircraft type k is used on route r, and the constants BT and 10000 are non-negative constants.

The following represents the first and last five keys and values in the dictionary *Route*:

```
{0:(0,1,0),1:(0,2,0),2:(0,3,0),3:(0,4,0),4:(0,5,0), ...
 191:(0,9,14,0),192:(0,10,14,0),193:(0,11,14,0),194:(0,12,14,0),195:(0,13,14,0)}
```

Whereas the following represents the corresponding distances in list d. For the purpose of representation, the values in this list have been rounded to two decimal places.

```
[(0, 707.84), (1, 824.00), (2, 809.52), (3, 501.29), (4, 825.21), ...
 (191, 1045.17), (192, 1026.23), (193, 1722.52), (194, 1257.30), (195, 924.06)]
```

And the following represents the shortest runway in the corresponding routes:

```
[(0, 2208), (1, 2208), (2, 2208), (3, 1750), (4, 2208), ...
 (191, 2208), (192, 2208), (193, 2208), (194, 2208), (195, 2208)]
```

4.2 Results

Using the same input data from the problem provided in Section 3 and the available aircraft data from Appendix D, the network to be operated and the corresponding flight frequency is determined assuming one standard week of operations. Furthermore it is determined how many aircraft of each type will be leased in the most optimal solution in order to determine if its more lucrative to use electric aircraft for some scenarios.

The modeling optimization problem is solved and the optimal routes are visualized in the figure below.

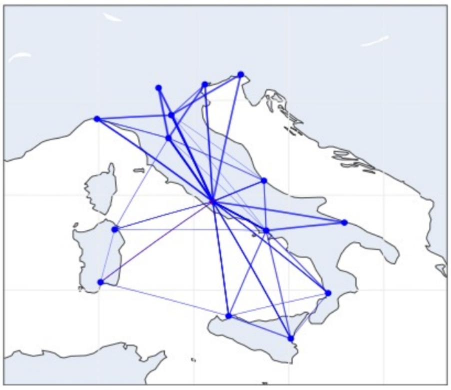

Figure 6: Visualized Results for the Network-Based Model

It was concluded that the total number of routes flown is 77 in total. The optimal amount of aircraft and corresponding type are found to be 1 Turbo Props aircraft, 0 Regional Jet aircraft and 0 Single Isle Twin Jet aircraft, 0 Electric twinprop aircraft, and 3 Electric regional aircraft. These aircraft combined transfer 7264 passengers of which 1368 transfer through the hub with an average load factor of 80% on there flights. The solutions shows that no electric aircraft are leased. As the optimal routes served 7264 out of a possible 16773 passengers to serve, 43.3% of the total possible passengers are served. This results to the total profit on a weekly basis to be $39,496.26$ *Euro*.

This is also in line with what is expected from the model. As the airline is no longer free to fly any route it wants to, the profit should be lower than the first model. The resulting profit of $39,496.26$ *Euro* is therefore a feasible solution.

KPI	Value
Operating profit	€ 36,545.80
Fractiom of transported passengers	28.4%

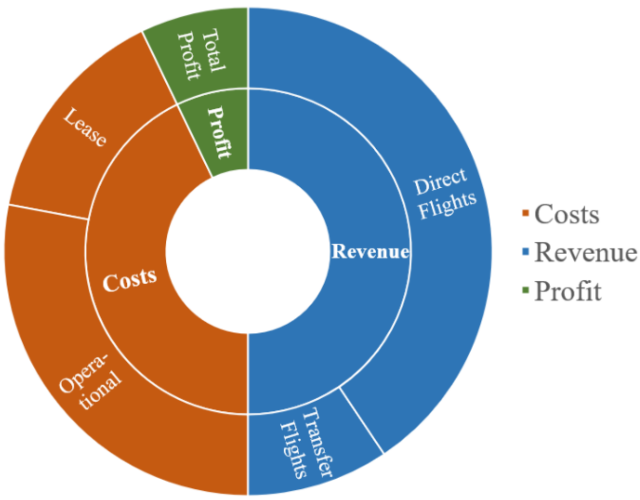

Figure 7: Financial Analysis for the Route-Based Model

5 Discussion and Conclusion

This section describes discussion points and assumptions regarding this subject.

- The gravity model is a commonly used approach for calculating the demand for travel between two regions. However, this model can contain errors for a number of reasons. First, the model does not consider the availability of alternative forms of transportation, such as trains or buses, which can impact the demand for air travel. Second, the model does not account for the presence of natural barriers between the new airport pairs, such as mountains or pressure belts, which can make air travel more difficult or costly. Finally, the model does not consider the effects of external factors, such as political and touristic instability, which can impact the demand for air travel. In order to improve the accuracy of the model, these and other factors could be considered in order to obtain a more comprehensive and accurate estimate of the demand for air travel between airports.

- The OLS (Ordinary Least Squares) method is a widely used statistical technique for forecasting demand. However, it is not without its limitations and can sometimes produce inaccurate results. One potential source of error in the 2030 forecast for demands is the assumption of linearity, which is built into the OLS method. This means that the model assumes that the relationship between the dependent and independent variables is linear, which may not always be the case in real-world situations. Additionally, the OLS method relies on the assumption of homoscedasticity, which means that the error term is constant across all observations. However, this is often not the case, and the presence of heteroscedasticity can lead to biased and inefficient estimates. Finally, the OLS method assumes that there is no multicollinearity, which means that the independent variables are not highly correlated with each other. However, in practice, multicollinearity is often present, and it can lead to unstable and unreliable results. Overall, these limitations of the OLS method can lead to errors in the 2030 forecast for demands.

- It is important to note that the python scripts and Gurobi Optimizer, like any optimization solvers, are only as good as the data that are provided to it. It is therefore important to consider improving the accuracy and quality of the input data like demands to obtain reliable and meaningful results.

- The leg-based model does not take into account the leasing of electric aircraft. If this were the case, the profit to the airline would be larger. This is however assuming that every airport would have a charging station.

- Some of the assumptions made may not be entirely accurate. For example, transfer passenger may not be willing to pay just 10% less, but maybe 30% less to transfer, instead of flying a direct route. Also, the fuel price is bound to increase in the next 10 years, which will also make flying electrically more profitable for the airline. It is important to know that these assumptions were made to get an estimate for the future, but that the reality may be very different.

5.1 Conclusion

The main goal of this assignment was to determine what would be the best strategy for the airline to pursue. Following the results for this specific situation from the KPIs, it must be concluded that the Leg-Based Model is a more beneficial strategy for the airline to follow because it results in a higher operational profit and higher fraction of transported passengers. Also, for a starting airline, supplying flights to a higher fraction of the demand will give the airline a good branding, which may result in better future sales.

A Demand Forecast 2030

For the purpose of representation, the values in this appendix have been rounded to one decimal place.

Figure 8: Values for the Demand Forecast in 2030

	LIRA	LIBD	LIPZ	LICJ	LIRQ	LIEE	LIRN	LICC	LIEO	LIBP	LIPX	LICA	LIPQ	LIPE	LIMJ
LIRA	-	103,4	137,0	87,0	152,5	61,8	171,5	96,5	59,3	103,2	133,4	73,0	98,2	158,0	98,9
LIBD	103,4	-	84,8	58,0	84,6	36,9	112,1	70,1	32,7	61,3	80,7	58,8	62,9	92,1	58,0
LIPZ	137,0	84,8	-	68,1	152,3	49,8	119,2	78,5	46,3	76,6	182,0	58,9	143,9	190,6	103,4
LICJ	87,0	58,0	68,1	-	70,4	38,3	87,2	76,9	31,5	44,9	66,6	49,6	49,5	75,8	49,9
LIRQ	152,5	84,6	152,3	70,4	-	52,9	124,3	79,8	51,2	79,7	156,2	59,6	102,6	213,5	112,8
LIEE	61,8	36,9	49,8	38,3	52,9	-	55,5	40,7	28,3	30,8	49,7	28,5	35,8	56,6	38,8
LIRN	171,5	112,1	119,2	87,2	124,3	55,5	-	98,5	50,0	92,9	114,8	78,1	87,0	132,9	84,1
LICC	96,5	70,1	78,5	76,9	79,8	40,7	98,5	-	34,1	51,5	76,4	66,2	57,5	86,5	56,7
LIEO	59,3	32,7	46,3	31,5	51,2	28,3	50,0	34,1	-	28,5	46,6	24,6	32,9	53,8	37,0
LIBP	103,2	61,3	76,6	44,9	79,7	30,8	92,9	51,5	28,5	-	72,5	40,0	56,0	85,2	51,6
LIPX	133,4	80,7	182,0	66,6	156,2	49,7	114,8	76,4	46,6	72,5	-	56,9	113,6	203,3	114,8
LICA	73,0	58,8	58,9	49,6	59,6	28,5	78,1	66,2	24,6	40,0	56,9	-	43,3	64,7	41,8
LIPQ	98,2	62,9	143,9	49,5	102,6	35,8	87,0	57,5	32,9	56,0	113,6	43,3	-	122,2	70,4
LIPE	158,0	92,1	190,6	75,8	213,5	56,6	132,9	86,5	53,8	85,2	203,3	64,7	122,2	-	126,3
LIMJ	98,9	58,0	103,4	49,9	112,8	38,8	84,1	56,7	37,0	51,6	114,8	41,8	70,4	126,3	-

B Frequencies of Leg-Based Model

Figure 9: Frequencies Flights in Leg-Based Model

	LIRA	LIBD	LIPZ	LICJ	LIRQ	LIEE	LIRN	LICC	LIEO	LIBP	LIPX	LICA	LIPQ	LIPE	LIMJ
LIRA	-	3	4	3	4	2	5	2	2	3	4	2	2	5	3
LIBD	3	-	1	1	1	1	3	1	1	1	1	1	1	1	1
LIPZ	4	1	-	1	4	1	2	1	1	1	5	1	4	5	1
LICJ	3	1	1	-	1	1	2	2	1	1	1	1	1	1	1
LIRQ	4	1	4	1	-	1	2	1	1	2	4	1	2	6	3
LIEE	2	1	1	1	1	-	1	1	1	1	1	1	1	1	1
LIRN	5	3	2	2	2	1	-	1	1	2	2	2	1	2	2
LICC	2	1	1	2	1	1	1	-	1	1	1	1	1	1	1
LIEO	2	1	1	1	1	1	1	1	-	1	1	1	1	1	1
LIBP	3	1	1	1	2	1	2	1	1	-	1	1	1	1	1
LIPX	4	1	5	1	4	1	2	1	1	1	-	1	1	1	1
LICA	2	1	1	1	1	1	2	1	1	1	1	-	1	1	1
LIPQ	2	1	4	1	2	1	1	1	1	1	1	1	-	1	1
LIPE	5	1	5	1	6	1	2	1	1	1	1	1	1	-	1
LIMJ	3	1	1	1	3	1	2	1	1	1	1	1	1	1	-

C Frequencies of Route-Based Model

Table 5: Frequencies of Flights in Route-Based Model

Departure Airport	Transfer Airport	Arrival Airport	Frequency
LIRA	—	LIEE	1
LIRA	LIPE	LIPZ	2
LIRA	LIEE	LICJ	1
LIRA	LICC	LICJ	2
LIRA	LICA	LICJ	1
LIRA	LIPX	LIRQ	1
LIRA	LIMJ	LIRQ	1
LIRA	LICJ	LIEE	1
LIRA	LICC	LIRN	2
LIRA	LICJ	LICC	2
LIRA	LIRN	LICC	2
LIRA	LICA	LICC	1
LIRA	LIEE	LIEO	1
LIRA	LICJ	LICA	1
LIRA	LICC	LICA	1
LIRA	LIPZ	LIPE	1
LIRA	LIRN	LIBD	3
LIRA	LIRQ	LIPZ	3
LIRA	LIRN	LICJ	2
LIRA	LIPZ	LIRQ	3
LIRA	LIRN	LIRQ	1
LIRA	LIEO	LIRQ	1
LIRA	LIBP	LIRQ	1
LIRA	LIPX	LIRQ	3
LIRA	LIMJ	LIRQ	1
LIRA	LIBD	LIRN	3
LIRA	LICJ	LIRN	2
LIRA	LIEO	LIRN	1
LIRA	LIBP	LIRN	2
LIRA	LICA	LIRN	2
LIRA	LIRQ	LIEO	1
LIRA	LIRN	LIEO	1
LIRA	LIRQ	LIBP	2
LIRA	LIRN	LIBP	2
LIRA	LIRQ	LIPX	4
LIRA	LIRN	LICA	2
LIRA	LIPE	LIPQ	3
LIRA	LIRN	LIPE	1
LIRA	LIBP	LIPE	1
LIRA	LIPQ	LIPE	3
LIRA	LIMJ	LIPE	3
LIRA	LIRQ	LIMJ	2
LIRA	LIPE	LIMJ	3

D Aircraft Data

Aircraft type	Aircraft 1: Regional tuboprop	Aircraft 2: Regional jet	Aircraft 3: Single aisle twin engine jet	Aircraft 4: Electric twinprop aircraft	Aircraft 5: Electric regional aircraft
Aircraft characteristics					
Speed [km/h]	550	820	850	350	480
Seats	45	70	150	20	48
Average TAT [mins]	25	35	45	20	25
Additional charging time[1] [mins]	--	--	--	20	45
Maximum range [km]	1,500	3,300	6,300	400	1,000
Runway required [m]	1,400	1,600	1,800	750	950
Cost					
Weekly lease cost [€]	15,000	34,000	80,000	12,000	22,000
Fixed operating cost C_X [€]	300	600	1250	90	120
Time cost parameter C_T [€/hr.]	750	775	1400	750	750
Fuel cost parameter C_F[gallon/km]	1.0	2.0	3.75	--	--
Batteries energy G^k[kWh]	--	--	--	2130	8216

Figure 10: Aircraft Data