Assignment 1

Airline Planning and Optimisation AE4423-20

by

Group 26

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SWEDISH AIRWAYS
flyga framtiden

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1 Introduction

The purpose of this assignment is to develop two different network and fleet plans for a new regional airline called *Swedish Airways*. With its hub located in Gothenburg (ICAO code: ESGG) and 14 other destination airports at which it may operate, the goal is to maximise the profit for the airline.

In the first part of the assignment, a demand forecast is carried out to determine the future demand for all possible routes. Next, a network and fleet plan is developed for direct flights only, considering three different types of aircraft. Finally, another network and fleet plan is developed that also considers routes (i.e. including triangular routes). The latter also consider two additional aircraft types that are fully electric.

For clarity, an overview of the aircraft types is shown in Table 1.1. For the network and fleet plan detailed in Chapter 3, only aircraft types 1 to 3 are considered, while for the one presented in Chapter 4, *all* aircraft types are considered (i.e. aircraft 1 to 5).

Table 1.1: *Aircraft characteristics and costs.*

	Aircraft 1	Aircraft 2	Aircraft 3	Aircraft 4	Aircraft 5
Aircraft characteristics	Regional turboprop	Regional jet	Single aisle twin engine jet	Electric twinprop	Electric regional
Speed [km/h]	550	820	850	350	480
Seats [-]	45	70	150	20	48
Average TAT [min]	25	35	45	20	25
Additional charging time [min]	-	-	-	20	45
Maximum range [km]	1500	3300	6300	400	1000
Runway required [m]	1400	1600	1800	750	950
Weekly lease cost [EUR]	15000	34000	80000	12000	22000
Fixed operating cost C_X [EUR]	300	600	1250	90	120
Time cost parameter C_T [EUR/h]	750	775	1400	750	750
Fuel cost parameter C_F [EUR/h]	1.0	2.0	3.75	-	-
Batteries energy G^k [kWh]	-	-	-	2130	8216

2 Problem 1A: Demand Forecast

The regional airline company Swedish Airways will start flying in 2030. In order to start up operations of this company, it is necessary to determine the demand for all the airports that the company will operate. Unfortunately, the Scandinavian airline possesses only population data from 2020 and demand for 10 airports in the Swedish network, airports which are not the same as the regional airline's network. Based on this data, the demand in the year 2030 is calculated by using the gravity model from Equation 2.1:

$$D_{ij} = k\frac{(\text{pop}_i \text{pop} j)^{b_1}}{(f \cdot d_{ij})^{b_2}} \tag{2.1}$$

where D_{ij} is the demand between airports i and airport j, and pop_i and pop_j are the population in the region of airports i and j, respectively. Furthermore, f = 1.42 [USD/gallon] is the fuel cost in 2020 and d_{ij} is the distance between airports i and j.

To determine the demand for year 2030, the first step is to calibrate Equation 2.1 using the 2020 demand values that are given in Section A.1 and the 2020 population values that are given in Section A.2. The distance between two airports is calculated based on the position of each airport, as shown in Equation 2.2:

$$\Delta\sigma_{ij} = 2\arcsin\sqrt{\sin^2\frac{\phi_i - \phi_j}{2} + \cos(\phi_i)\sin^2\frac{\lambda_i - \lambda}{2}} \qquad d_{ij} = R_E \Delta\sigma_{ij} \tag{2.2}$$

where $\Delta\sigma_{ij}$ is the arc length between airports i and j, ϕ_i and ϕ_j are the latitude of airports i and j respectively, and λ_i and λ_j are the longitude of airports i and j respectively. Finally, $R_E = 6371 km$ is the radius of the Earth in km.

The distances between all the airports analysed in this assignment are illustrated in Section A.3. In order to calibrate the model, it is assumed that the initial condition for the parameters b_1 and b_2, and the scaling factor k, are 0.35 0.25 0.3, respectively. Before finding the best fit for the model, logarithms are applied to the gravity model. The Equation 2.1 now becomes Equation 2.3:

$$D_{ij} = \log k + b_1 \cdot \log(\text{pop}_i \cdot \text{pop}_j) - b_2 \cdot \log(f \cdot d_{ij}) \tag{2.3}$$

Based on Equation 2.3, k must be positive. So, it is assumed that the boundaries for the scaling factor and for the parameters are: $k \in [0.0001; 10]$, $b_1 \in [-5; 5]$, $b_2 \in [-5; 5]$. Using the minimisation of scalar function of more variables function (optimise.minimise), k, b_1 and b_2 are:

$$\begin{aligned} k &= 0.00404348419583168; \\ b_1 &= 0.473249860703695; \\ b_2 &= 0.167219625298232 \end{aligned} \tag{2.4}$$

In order to see if the model is calibrated, it is printed the standard demand and the demand resulted from the gravity model. If the error between values is less than 20%, the gravity model is calibrated well. In this case, the error between the given demand and the demand resulted from the gravity model is less than 20%, so the model is calibrated.
To generate the future demand, the next step is to forecast the population for 2030, based on the data for 2020 and the annual growth per region given in Section A.2. So, the population in 2030 is calculated using the following formula, Equation 2.5:

$$\text{pop}_{2030} = \text{pop}_{2020} \cdot (1 + r_{\text{pop}})^{10} \tag{2.5}$$

where $r_{pop} = 0.8\%$ is the annual population growth. The population forecast in 2030 is shown in Section A.2. Based on these results, the demand for 2030 for the all 15 airports that the Scandinavian airline company will operate is calculated and it is shown in Section A.4.

3 Problem 1B: Network & Fleet Development

Based on an accurate demand data resulted from previous section, Swedish Airways can compute a weekly flight frequency plan. In addition, as the airline is new, the company must acquire new aircraft. The number of aircraft of each type is determined to maximise the profit of the airline. With other words, the fleet is composed of 3 types of aircraft. The aircraft characteristics and costs were already presented in Table 1.1. Note that, for this model, since the unit of average TAT is provided in minutes, it was converted in hours.

To generate the weekly flight frequency plan for the airline, a leg-based mathematical model is implemented in Python-Gurobi. The model is calculating the profit of Swedish Airways per week.

3.1. Objective Function

The first part of setting up the problem is setting up the objective function, which is stated in Equation 3.1

$$\text{Max Profit } = \sum_{i\in N}\sum_{j\in N}\left[\text{ Yield }_{ij} \times d_{ij} \times \left(x_{ij} + w_{ij}\right)\right] - \sum_{i\in N}\sum_{j\in N}\sum_{k\in K}\left(\text{COST}^k_{ij}\right) - \sum_{k\in K}\text{LEASE}^k \tag{3.1}$$

Where x_{ij} is direct flow from airport i to airport j, w_{ij} is flow from airport i to airport j that transfers at the hub. Furthermore, LEASE^k is defined as the cost of leasing an aircraft for 1 week, as speficied in Table 1.1. Within this equation, COST is defined as follows:

$$\text{COST}^k_{ij} = \text{FIXED COST}^k + \text{TIMEBASED COST}^k_{ij} + \text{FUEL COST}^k_{ij} \tag{3.2}$$

With all costs in euros. Furthermore, for this equation, it is taken into account that cost are discounted 30% if they depart from or arrive at the hub, making use of the economies of scale provided at the hub.

Furthermore, YIELD is defined in the following way:

$$\text{Yield}_{\,ij} = 5.9 \cdot d_{ij}^{-0.76} + 0.043 \tag{3.3}$$

In which it is taken into account that for passengers with a transfer, the yield is 10% lower.

3.2. Constraints

With the objective function defined, it is time to look at the constraints that it has to meet, in order for the network to be able to operate.

3.2.1. Demand Constraint

The first constraints that the network has to meet are those on demand:

$$x_{ij} + w_{ij} \leq q_{ij} \quad ,\forall i, j \in \boldsymbol{N} \tag{3.4}$$

$$w_{ij} \leq q_{ij} \times g_i \times g_j, \forall i, j \in \boldsymbol{N} \tag{3.5}$$

Within these equations, q_{ij} is the travel demand between airport i to airport j, and g is a binary variable, which is 0 if a hub is located at the airport, and 1 otherwise.

3.2.2. Capacity Constraint

The next constraint to meet is that the amount of passengers on all flights should not exceed the capacity on those flights:

$$x_{ij} + \sum_{m \in N} w_{im} \times (1 - g_j) + \sum_{m \in N} w_{mj} \times (1 - g_i) \leq \sum_{k \in K} z^k_{ij} \times s^k \times LF \quad ,\forall i, j \in \boldsymbol{N} \tag{3.6}$$

Within this equation, z^k_{ij} is the number of flights from airport i to airport j with aircraft type k. s_k is the number of seats in aircraft type k, as specified in Table 1.1. Lastly, LF is the load factor, specified at 0.8.

3.2.3. Continuity Constraint

The following constraint makes sure that there are no aircraft accumulating at a certain location along the route:

$$\sum_{j \in N} z^k_{ij} = \sum_{j \in N} z^k_{ji} \quad ,\forall i \in \boldsymbol{N}, k \in \boldsymbol{K} \tag{3.7}$$

3.2.4. Time Constraint

The next constraint makes sure that all aircraft are operated no more time than they are available:

$$\sum_{i \in N} \sum_{j \in N} \left(\frac{d_{ij}}{sp^k} + LTO \right) \times z^k_{ij} \leq BT^k \times AC^k, k \in \boldsymbol{K} \tag{3.8}$$

Within this constraint, sp^k is the speed of aircraft type k, as specified in Table 1.1. LTO is the landing and take off time, which is increased with 50% if the aircraft is connecting at the hub. BT^k is the block time of an aircraft, which is given to be 10 hours/day, 7 days a week. Lastly, AC^k is the number of aircraft of type k deployed.

3.2.5. Aircraft Allocation constraints

The last set of constraints is that of aircraft allocation. For this, there are 2 things to take into consideration. The first constraint makes sure that a flight is within an aircraft's range:

$$z^k_{ij} \leq a^k_{ij} \quad \rightarrow \quad a^k_{ij} = \begin{cases} 10000 & \text{if } d_{ij} \leq \text{ Range}^{\,k} \\ 0 & \text{otherwise} \end{cases} \tag{3.9}$$

Within this constraint, a^k_{ij} is an auxiliary matrix to construct this constraint. Similar to this, it should also be true that the aircraft is actually able to land on the length of runway provided. Therefore, a constraint is created to make sure the runway available does not exceed the runway required by the aircraft:

$$z^k_{ij} \leq \text{run}^k_{ij} \quad \rightarrow \quad \text{run}^k_{ij} = \begin{cases} 10000 & \text{if MIN RUNWAY}_{ij} \leq \text{ RUNWAY REQUIRED }^k \\ 0 & \text{otherwise} \end{cases} \tag{3.10}$$

In which run^k_{ij} is again an auxiliary matrix.

3.3. Results

With the problem formulated and solved, it is time to look at the results.

The most important result visible is the obtained profit: **69,405.6 €**. This was achieved by making use of four aircraft of type 1, and one aircraft of type 2. The optimal network was plotted on a map and is shown in Figure 3.1. Furthermore, the flight frequencies networks for both types of aircraft used are shown in Figures 3.2 and 3.3 respectively.

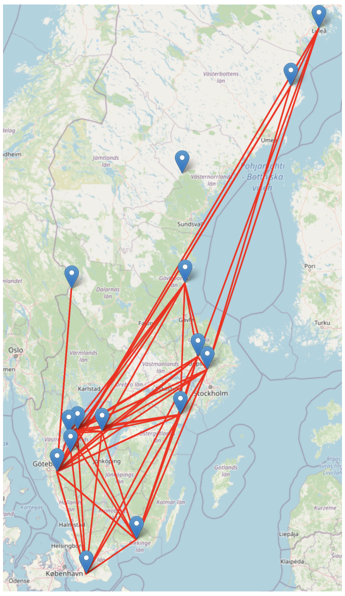

Figure 3.1: *Optimal network for problem 1B.*

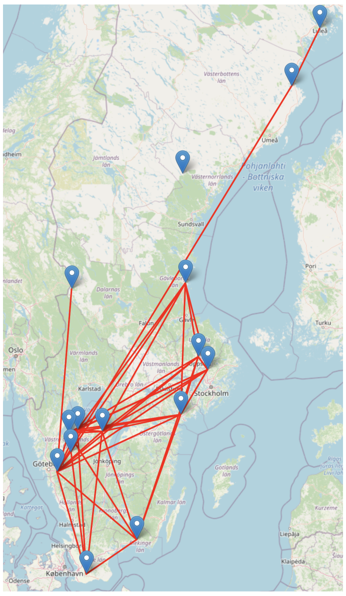

Figure 3.2: *Flight frequencies network for aircraft of type 1.*

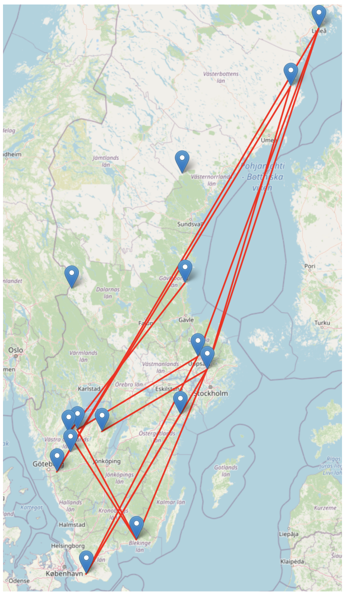

Figure 3.3: *Flight frequencies network for aircraft of type 2.*

The resulting flights can be visualised in a table as well, to show the amount of passengers travelling along each flight leg directly. Table 3.1 shows these values for direct flights x_{ij}, while Table 3.2 gives the transferring flights w_{ij} i.e. those going from airport i to j through the hub.

Table 3.1: *All direct passengers from airport i to airport j.*

x[i,j]	ESGG	ESMS	ESPA	ESSA	ESFR	ESDF	ESIB	SE-0016	ESNS	ESGR	ESNY	ESKN	ESNB	ESCM	ESGO
ESGG	0	365	112	540	173	205	282	16	85	215	106	170	0	203	0
ESMS	365	0	0	392	108	175	178	0	0	144	0	112	0	112	0
ESPA	112	0	0	112	0	0	0	0	36	0	0	0	0	56	0
ESSA	540	392	112	0	180	224	288	0	112	236	144	252	0	393	0
ESFR	173	108	0	180	0	56	108	0	0	72	36	36	0	56	0
ESDF	205	175	0	224	56	0	92	0	0	72	0	72	0	72	0
ESIB	282	178	0	288	108	92	0	0	0	108	56	72	0	107	0
SE-0016	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ESNS	85	0	36	112	0	0	0	0	0	0	0	0	0	0	0
ESGR	215	144	0	236	72	72	108	0	0	0	36	72	0	72	0
ESNY	106	0	0	144	36	0	56	0	0	36	0	36	0	36	0
ESKN	170	112	0	252	36	72	72	0	0	72	36	0	0	72	0
ESNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ESCM	203	112	56	393	56	72	107	0	0	72	36	72	0	0	0
ESGO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3.2: *All indirect passengers from airport i to airport j.*

w[i,j]	**ESGG**	**ESMS**	**ESPA**	**ESSA**	**ESFR**	**ESDF**	**ESIB**	**SE-0016**	**ESNS**	**ESGR**	**ESNY**	**ESKN**	**ESNB**	**ESCM**	**ESGO**
ESGG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ESMS	0	0	0	0	0	0	0	**12**	**4**	0	**2**	0	0	**13**	0
ESPA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ESSA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ESFR	0	0	0	0	0	**3**	0	0	0	0	0	**4**	0	0	0
ESDF	0	0	0	0	**1**	0	0	**7**	**3**	0	0	0	0	0	0
ESIB	0	0	0	0	0	0	0	0	0	0	0	**6**	0	0	0
SE-0016	0	**12**	0	0	0	**7**	0	0	0	**1**	0	0	0	0	0
ESNS	0	**6**	0	0	0	**1**	0	0	0	0	0	0	0	0	0
ESGR	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0
ESNY	0	**2**	0	0	0	0	0	0	0	0	0	0	0	0	0
ESKN	0	0	0	0	**4**	0	**6**	0	0	0	0	0	0	0	0
ESNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ESCM	0	**11**	0	0	**2**	0	0	0	0	0	0	0	0	0	0
ESGO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

After saving the results in an Excel file, namely '*Model_1B_results.xls*', the number of flights made by each type of aircraft per week is determined using the table of frequencies for each aircraft type. To find the average of number of flights made by an aircraft of type k, the total number of flights is divided by the number of aircraft of type k. Additionally, the output illustrates the most frequented flight for every type of aircraft. The 3.3 contains the parameters mentioned above. Note that there are *no* aircraft of type.

Table 3.3: *Flights frequencies.*

	Regional turboprop	Regional jet
Number of aircraft	4	1
Number of flights per week	318	56
Average of number of flights per aircraft per week	78	56
The most frequented flight	Gothenburg - Stockholm	Malmo - Stockholm

Furthermore, the times flown can be visualised, as plotted in Figure 3.4. As can be seen, even though there are a lot of flights per aircraft, they are of short duration, with flights averaging at just short of one hour flight time, including turnaround time. Therefore, if the amount of flights is multiplied with the time flown, the utilisation of an aircraft is estimated at around 67 hours out of the 70 hours of block time available.

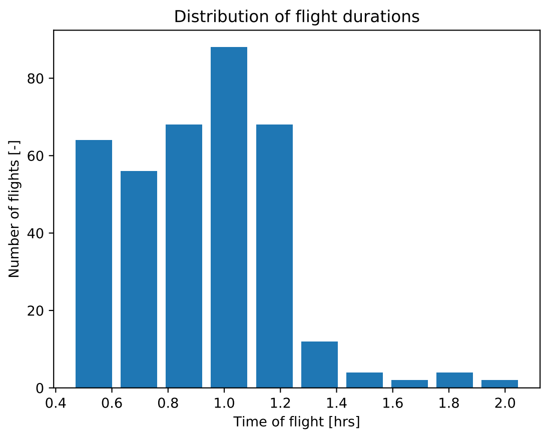

Figure 3.4: *Flight times for network 1.*

4 Problem 2: Regional Network Development Including Electric Aircraft

Problem 2 is attempting to tackle a similar routing problem as already tackled in Problem 1, but now with some new challenges:

- Electrical aircraft are employed, which can charge only at the hub
- Non-electric aircraft can also only refuel at the hub.
- Aircraft either fly from hub to 1 connection, then back to hub, or they fly from hub to 1, to 2, then back to hub

In other words, now the fleet is composed of 5 types of aircraft. The aircraft characteristics and costs are presented in Table 1.1.

With those challenges in mind it is time to set up the model that will be solved. In order to do this, most equations are derived from Lecture 3 from the course '*Airline Planning and Optimisation*'[1].

4.1. Objective Function

The first part of formulating the problem is setting up the objective function. The objective is the same as in problem 1, to maximise the profit. This can be seen in Equation 4.1:

$$\text{Max Profit } = \sum_{r\in R}\sum_{i\in N}\sum_{j\in N}\left[\text{ Yield }_{ij}\times d_{ij}\times\left(x_{ij}^{r}+\sum_{n\in R}w_{ij}^{rn}\right)\right]-\sum_{r\in R}\sum_{k\in K}\left(\text{COST}_{r}^{k}\right)-\sum_{k\in K}\text{LEASE}^{k} \tag{4.1}$$

In this equation, Yield is defined the same as in Problem 1. Furthermore, x_{ij}^{r} is the direct flow of passengers from i to j on route r. w_{ij}^{rn} is the connecting flow at the hub going from i in route r to node j in route n. $COST_{r}^{k}$ is the total cost of operating aircraft type k in route r. It is defined similarly:

$$\text{COST}_{r}^{k}=\text{FIXED COST}^{k}+\text{TIMEBASED COST}_{r}^{k}+\text{FUEL COST}_{r}^{k} \tag{4.2}$$

Within this equation, it is taken into account that most flight legs either depart or arrive at the hub. Therefore, they make use of the economies of scale provided at the hub, receiving a 30% discount on fixed costs, time based costs, and fuel cost if the aircraft is flying on kerosene. For all itineraries between 2 non-hub airports, the costs are not discounted.

4.2. Constraints

Maximising profit is a good goal to have, but in order to actually operate aircraft, it must meet some constraints.

4.2.1. Demand Constraints

The first constraints that have to be met are the constraints on demand. These constraints make sure that there are no more people flying on a route, than there are willing to fly on said route.

$$\sum_{r\in R}\left(x_{ij}^{r}+\sum_{n\in R}w_{ij}^{rn}\right)\le q_{ij}\quad,\forall i,j\in N \tag{4.3}$$

$$x_{ij}^{r}\le q_{ij}\times\delta_{ij}^{r}\quad,\forall r\in R,i,j\in N \tag{4.4}$$

$$w_{ij}^{rn}\le q_{ij}\times\delta_{ih}^{r}\times\delta_{hj}^{n}\quad,\forall r,n\in R,\quad i,j\in N \tag{4.5}$$

Within these constraints, an auxiliary matrix has to be constructed, δ_{ij}^{r}. For every flight route r , δ_{ij}^{r} is only nonzero for all flight legs that can be flown on the route. For route r1 = H -> A -> B -> H, we see therefore that δ_{ij}^{r} is nonzero for the values: $\delta_{HA}^{r1}=1$, $\delta_{HB}^{r1}=1$, $\delta_{AB}^{r1}=1$, $\delta_{AH}^{r1}=1$, $\delta_{BH}^{r1}=1$.

[1] https://brightspace.tudelft.nl/d2l/le/content/398016/viewContent/2296805/View

4.2.2. Flow Constraints

The second set of constraints is the most involved one, which are the flow constraints. For these, there are 3 individual situations:
From the hub node:

$$\sum_{m\in S_H^r} x_{Hm}^r + \sum_{n\in R}\sum_{p\in N}\sum_{m\in S_H^r} w_{pm}^{nr} \leq \sum_{k\in K} z_r^k \times s^k \times LF \quad ,\forall r \in \boldsymbol{R}\left(\text{ with } j = S_H^r(\mathbf{1}) \text{ and } i = H\right) \tag{4.6}$$

Between 2 spokes:

$$\sum_{m\in S_j^r} x_{im}^r + \sum_{m\in P_i^r} x_{mj}^r + \sum_{n\in R}\sum_{p\in N} w_{pj}^{nr} + \sum_{n\in R}\sum_{p\in N} w_{ip}^{rn} \leq \sum_{k\in K} z_r^k \times s^k \times LF, \forall r \in R2 \text{ with } i = S_H^r(1) \text{ and } j = S_H^r(2) \tag{4.7}$$

And to the hub node:

$$\sum_{m\in P_i^r} x_{mH}^r + \sum_{n\in R}\sum_{p\in N}\sum_{m\in P_i^r} w_{mp}^{rn} \leq \sum_{k\in \boldsymbol{K}} z_r^k \times s^k \times LF \quad ,\forall r \in R2 \text{ with } i = S_H^r(2) \& \forall r \in R\backslash R2 \text{ with } i = S_H^r(1) (\text{ and , for both , } j = H) \tag{4.8}$$

Within these equations, z_r^k is the frequency for aircraft type k in route r. Furthermore, there's 2 additional sets used. S^r is the set of nodes following each of the nodes along route r. For route r1 = H -> A -> B -> H this is : $S^{r1} = \{H : (A,B,H); A : (B,H); B : (H)\}$. P^r is the inverse of S^r, as it is all of the nodes preceding one of the nodes, along route r. For completeness, this is therefore for the same route r1: $P^{r1}\{H : (H); A : (A,H); B : (B,A,H)\}$

4.2.3. Utilisation Constraint

The third constraint to be met is the constraint on utilisation. This constraint makes sure that aircraft are not used more than they are available, within the week of operations specified. This is done through the following constraint:

$$\sum_{r\in R}\left(\frac{d_r}{sp^k} + LTO^{rk} + \text{ Charge }_r^k\right) \times z_r^k \leq BT^k \times AC^k, \forall k \in \boldsymbol{K} \tag{4.9}$$

In this constraint, LTO is the turnaround times on a route. For these, it is taken into account that arriving at the hub, these are 50% longer, to facilitate transfers. The only exception to this is for the electric aircraft, the LTO is not taken to be longer, but instead a Charge time is added, which is the time required to charge the aircraft back up to full capacity. Charge time is taken to be 0 for non-electric aircraft.

4.2.4. Aircraft Allocation Constraints

The last set of constraints is that of aircraft allocation. For this, there are 2 things to take into consideration. Firstly, an route should be within an aircraft's range:

$$z_r^k \leq a_r^k \quad \rightarrow \quad a_r^k = \begin{cases} 10000 & \text{if } d_r \leq \text{ Range }^k \\ 0 & \text{otherwise} \end{cases} \tag{4.10}$$

Within this constraint, a_r^k is an auxiliary matrix to construct this constraint. Similar to this, it should also be true that the aircraft is actually able to land on the length of runway provided. Therefore, it needs to be checked that the for the shortest runway on the route, the aircraft is still able to take off and land:

$$z_r^k \leq \text{run}_r^k \quad \rightarrow \quad \text{run}_r^k = \begin{cases} 10000 & \text{if MIN RUNWAY}_r \leq \text{ RUNWAY REQUIRED }^k \\ 0 & \text{otherwise} \end{cases} \tag{4.11}$$

Within this equation, run_r^k is again an auxiliary matrix used to construct this constraint.

4.3. Results

With all constraints set, the model can be run. Now, it is time to look at the results, and draw relevant conclusions.

The first result to look into is the accrued profit: **69,345 €** This is achieved by employing one aircraft of type 1, one aircraft of type 4 and two aircraft of type 5.

The resulting flights can be visualised in tables showing the amount of passengers travelling along each flight leg. Table 4.1 shows these values for direct flights x_{ij}, while Table 4.2 gives the transferring flights w_{ij} i.e. those going from airport i to j through the hub.

Table 4.1: *All direct passengers from different i to j locations*

x[i,j]	**ESGG**	**ESMS**	**ESPA**	**ESSA**	**ESFR**	**ESDF**	**ESIB**	**SE-0016**	**ESNS**	**ESGR**	**ESNY**	**ESKN**	**ESNB**	**ESCM**	**ESGO**
ESGG	0	**364**	0	**552**	**173**	**205**	**282**	0	0	**215**	**106**	**170**	0	**190**	**309**
ESMS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ESPA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ESSA	0	0	0	0	0	0	**266**	0	0	0	0	**10**	0	0	0
ESFR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ESDF	0	0	0	0	0	0	**19**	0	0	0	0	0	0	0	0
ESIB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SE-0016	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ESNS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ESGR	0	0	0	0	0	0	**95**	0	0	0	0	0	0	0	0
ESNY	0	0	0	0	**19**	0	**38**	0	0	0	0	0	0	0	0
ESKN	0	0	0	0	0	0	**76**	0	0	0	0	0	0	0	0
ESNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ESCM	0	0	0	0	0	0	**95**	0	0	0	0	0	0	0	0
ESGO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 4.2: *All indirect passengers from different i to j locations*

w[i,j]	**ESGG**	**ESMS**	**ESPA**	**ESSA**	**ESFR**	**ESDF**	**ESIB**	**SE-0016**	**ESNS**	**ESGR**	**ESNY**	**ESKN**	**ESNB**	**ESCM**	**ESGO**
ESGG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ESMS	0	0	**87**	0	0	0	0	**12**	**64**	0	**79**	0	**53**	**69**	0
ESPA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ESSA	0	**297**	**156**	0	0	0	0	0	**117**	0	0	0	0	0	0
ESFR	0	**57**	**38**	0	0	0	0	0	**28**	0	**36**	0	**23**	0	0
ESDF	0	0	**50**	0	0	0	0	**7**	**37**	0	**45**	0	**30**	**49**	0
ESIB	0	**164**	**59**	**290**	0	0	0	0	**44**	0	**56**	0	**37**	0	0
SE-0016	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ESNS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ESGR	0	**63**	**49**	0	0	0	0	0	**36**	0	**47**	0	**31**	0	0
ESNY	0	**79**	0	0	0	**35**	0	0	0	0	0	0	0	0	0
ESKN	0	**45**	**45**	0	0	0	0	0	**34**	0	0	0	**28**	0	0
ESNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ESCM	0	**88**	**58**	0	0	0	0	0	**44**	0	0	0	0	0	0
ESGO	0	**74**	**59**	**288**	0	0	0	9	**44**	0	**55**	0	**37**	**106**	0

The respective routes flown by the three different aircraft types are shown in the tables below.

(a) *Aircraft type 1*

Route	Frequency
ESGG - ESMS - ESGG	8
ESGG - ESFR - ESGG	4
ESGG - ESDF - ESGG	5
ESGG - ESIB - ESGG	17
ESGG - ESGR - ESGG	1

(b) *Aircraft type 4*

Route	Frequency
ESGG - ESGO - ESGG	42

(c) *Aircraft type 5*

Route	Frequency
ESGG - ESMS - ESGG	2
ESGG - ESSA - ESIB - ESGG	14
ESGG - ESSA - ESKN - ESGG	1
ESGG - ESFR - ESGG	1
ESGG - ESDF - ESIB - ESGG	1
ESGG - ESIB - ESGG	1
ESGG - ESGR - ESIB - ESGG	5
ESGG - ESNY - ESFR - ESGG	1
ESGG - ESNY - ESIB - ESGG	2
ESGG - ESKN - ESIB - ESGG	4
ESGG - ESCM - ESIB - ESGG	5

Finally, the optimal network was plotted on a map and is shown in Figure 4.1. Furthermore, the flight frequencies networks for aircraft types 1, 4, and 5 are shown in Figures 4.2, 4.3, 4.4 and respectively.

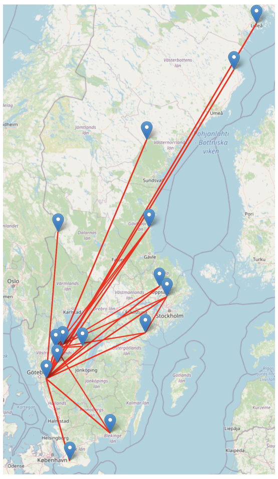

Figure 4.1: *Optimal network for problem 2.*

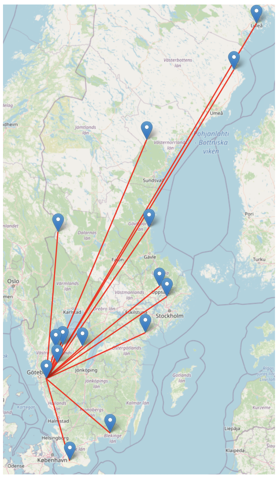

Figure 4.2: *Flight frequencies network for aircraft of type 1.*

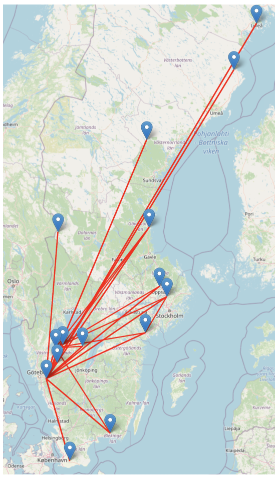

Figure 4.3: *Flight frequencies network for aircraft of type 4.*

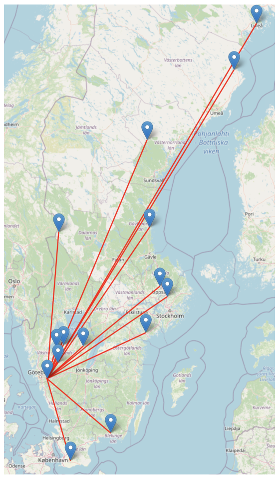

Figure 4.4: *Flight frequencies network for aircraft of type 5.*

5 Results Comparison

Now that both models have been presented, it is time to have a look at the differences between them, and how these differences might be taken into account. First of all, let us look at the overall profit and aircraft deployment:

For problem 1B, the total profit was 69,406 €, using four aircraft of type 1, and one aircraft of type 2. For problem 2, the total profit was 69,345 €, using one aircraft of type 1, one aircraft of type 4 and two aircraft of type 5. Clearly, the network developed in problem 1B gives slightly more profit, so if the overall goal of the airline is to maximise profit, and real life is as simple as the models dictate, then this would be the model to go for.

However, there are certain things that must be taken into account. First of all, there are differences imposed by the model constraints. Within problem 1B, more use is made of flights between nodes, not connecting to the hub. This occurs less often in problem 2, as routes are defined as triangular. Therefore, even though some flight legs in between more nodes might be profitable, they cannot be generated. The reason why this formulation makes sense is that the range of the electric aircraft is fairly limited, so for them triangular routes are the only sensible option. It would likely be more profitable to employ a hybrid network, where the aircraft flying on kerosene fly freely between the nodes, and the electric aircraft are constraint to short range, high frequency routes, coming back to the hub often to charge.

5.1. Key Performance Indicators

Aside from the obvious conclusions, it is valuable to look at some more in depth performance indicators. The first performance indicator is the **Available Seat Kilometer (ASK)**, which is the number of seats available per flown kilometer. This is defined as shown in Equation 5.1.

$$\text{ASK} = \sum_{i \in N} \sum_{j \in N} \sum_{k \in AC} \left(d_{ij} * s^k \right) \tag{5.1}$$

Then, the **Revenue Passenger Kilometer (RPK)**, which is the number of revenue passengers transported per flown kilometer. This is defined as in Equation 5.2.

$$\text{RPK} = \sum_{i\in N}\sum_{j\in N}\sum_{r\in R}\left(x^{r}_{ij} * d_{ij}\right) \tag{5.2}$$

With these two traffic based indicators, Swedish Airways now have an idea of the capacity offered, the number of passengers transported, and the distance travelled.

Then, some financial based indicators are constructed, in order to get an idea of the revenue and operating expenses. The first of these is is the **Revenue per ASK (RASK)**, described in Equation 5.3.

$$\text{RASK} = \frac{\text{REV}}{\text{ASK}} \tag{5.3}$$

In the above, REV is the total revenue, which is equal to the total cost summed with the profit. Furthermore, **Cost per ASK (CASK)** is defined as shown in Equation 5.4.

$$\text{CASK} = \frac{\text{COST}}{\text{ASK}} \tag{5.4}$$

In the latter, COST is the total cost. Then, the **Load Factor (LF)** can be defined as given by Equation 5.5.

$$\text{LF} = \frac{\text{RPK}}{\text{ASK}} \tag{5.5}$$

The load factor refers to the ratio of the number of seats taken and the number of seats available. In this case, the load factor taken is the **Average Leg Load Factor (ALLF)**, which is the mean of load factors over all flights. Lastly, **Unit Profit** can be found in Equation 5.6.

$$\text{Unit Profit} = \text{RASK} - \text{CASK} \tag{5.6}$$

These performance indicators can finally be compared, as seen in Table 5.1.

Table 5.1: *Key Performance Indicators*

KPI	Network 1	Network 2	Unit
ASK total	11121638.08	1758899.89	[km seats]
ASK mean	99300.34	103464.64	[km seats]
RPK total	8526110.55	2697582.08	[km pax]
RPK mean	76125.99	44021.00	[km pax]
RASK mean	0.05133	0.1456	[€ / (km pax)]
CASK mean	0.04509	0.1062	[€ / (km pax)]
LF mean	0.7778	0.45049	[-]
Profit	69405	69345	[€]
Unit profit mean	0.006241	0.03942	[€ / (km pax)]

It can be observed that even though the profit of both networks is about the same, their way of achieving this profit is vastly different. Network 1 offers almost 10 times more ASK, has a significantly lower mean RPK, and far lower RASK and CASK. The Load Factor of network 2 is far lower, which is expected, as some of the return trips from nodes to hubs are a necessity. The unit profit is 5 times higher for network 2. This shows that the airline is further away from the edge of profitability, which indicates a healthier airline.

Lastly, there are some assumptions made in the model development that are not reflective of real life. For example, it is likely that people are more willing to fly electric aircraft, as the environmental impact will be far less. Therefore, these flights likely see an increased demand.
Furthermore, the model developed now is for a single moment in time, but fleet development is done taking into account many years of operation. A network based on kerosene aircraft will likely become increasingly expensive in the coming decades, as fuel prices go up due to scarcity and increased environmental taxes. Therefore, it might be even more attractive to focus the network on electrical aircraft, as the analysis has shown that they are currently slightly less profitable, but will likely grow to be more profitable in the years to come.

A Appendix

All data presented in this appendix is used as input for the development of both network and fleet plans described in Chapters 3 and 4. Section A.5 contains the workload distribution of the group members.

A.1. Demand Data (2020)

Table A.1: *Demand per week (2020)*

2020 demand	ESGG	ESPA	ESMS	ESSA	ESTA	ESNZ	ESNX	ESGJ	ESQO	ESKV
ESGG	0	134	310	520	204	140	24	386	142	162
ESPA	110	0	74	134	44	40	10	52	72	32
ESMS	292	76	0	444	254	80	16	196	106	72
ESSA	546	130	456	0	318	172	28	308	184	158
ESTA	228	50	274	392	0	56	8	118	60	52
ESNZ	122	40	88	156	52	0	8	72	54	36
ESNX	22	12	16	26	10	8	0	12	14	6
ESGJ	362	60	184	276	104	60	12	0	96	68
ESQO	142	74	98	158	76	58	14	90	0	36
ESKV	142	28	66	140	48	40	6	86	36	0

A.2. Population Data (2020 and 2030)

Table A.2: *Population data in 2020 and 2030*

ICAO Code	Population 2020	Population 2030
ESGG	579281	627328
ESMS	344166	372712
ESPA	48728	52770
ESSA	975551	1056466
ESFR	51846	56147
ESDF	100593	108937
ESIB	138979	150507
SE-0016	510	553
ESNS	24802	26860
ESGR	90728	98254
ESNY	31940	34590
ESKN	72892	78938
ESNB	14904	16141
ESCM	117462	127205
ESGO	138979	150507
ESTA	136208	147506
ESNZ	50444	54628
ESNX	1869	2025
ESGJ	171592	185825
ESQO	98857	107057
ESKV	31252	33845

A.3. Distances Between Airports

Table A.3: *Distances between airports*

Distance	ESGG	ESMS	ESPA	ESSA	ESFR	ESDF	ESIB	SE-0016	ESNS	ESGR	ESNY	ESKN	ESNB	ESCM	ESGO
ESGG	0	245.834	1016.61	393.8644	103.3869	238.3885	88.65171	389.9672	904.8724	133.0279	483.7086	298.6284	664.2988	393.9266	51.55938
ESMS	245.834	0	1208.628	531.4756	329.9486	143.0592	323.8838	625.9506	1095.324	326.7352	672.3221	419.7143	872.9492	545.4323	280.6496
ESPA	1016.61	1208.628	0	689.1926	913.2317	1094.665	929.3939	671.0207	113.3266	893.9621	537.4745	797.7301	361.3265	668.6293	965.7296
ESSA	393.8644	531.4756	689.1926	0	306.1351	407.609	327.3176	325.0984	576.6105	261.8374	184.524	111.7968	394.4479	32.95493	345.1815
ESFR	103.3869	329.9486	913.2317	306.1351	0	281.2797	21.25692	296.0449	801.5447	53.65712	381.1454	225.5806	561.3625	301.3987	53.29578
ESDF	238.3885	143.0592	1094.665	407.609	281.2797	0	284.7137	561.534	981.5419	255.5082	565.3178	297.1421	773.7083	426.1233	247.2632
ESIB	88.65171	323.8838	929.3939	327.3176	21.25692	284.7137	0	303.8682	818.0246	73.30305	399.0343	246.412	575.9296	322.2828	43.25298
SE-0016	389.9672	625.9506	671.0207	325.0984	296.0449	561.534	303.8682	0	567.2301	307.0112	228.1954	347.312	310.2977	294.9981	346.8295
ESNS	904.8724	1095.324	113.3266	576.6105	801.5447	981.5419	818.0246	567.2301	0	781.3346	424.481	684.7146	257.2023	555.6076	853.8365
ESGR	133.0279	326.7352	893.9621	261.8374	53.65712	255.5082	73.30305	307.0112	781.3346	0	357.3445	174.1336	548.9708	260.9252	83.35594
ESNY	483.7086	672.3221	537.4745	184.524	381.1454	565.3178	399.0343	228.1954	424.481	357.3445	0	275.1696	212.4308	154.0293	432.2473
ESKN	298.6284	419.7143	797.7301	111.7968	225.5806	297.1421	246.412	347.312	684.7146	174.1336	275.1696	0	487.3386	129.1074	254.1364
ESNB	664.2988	872.9492	361.3265	394.4479	561.3625	773.7083	575.9296	310.2977	257.2023	548.9708	212.4308	487.3386	0	365.4387	614.5612
ESCM	393.9266	545.4323	668.6293	32.95493	301.3987	426.1233	322.2828	294.9981	555.6076	260.9252	154.0293	129.1074	365.4387	0	343.9206
ESGO	51.55938	280.6496	965.7296	345.1815	53.29578	247.2632	43.25298	346.8295	853.8365	83.35594	432.2473	254.1364	614.5612	343.9206	0

A.4. Demand Forecast (2030)

Table A.4: *Demand forecast for 2030*

2030 demand	ESGG	ESMS	ESPA	ESSA	ESFR	ESDF	ESIB	SE-0016	ESNS	ESGR	ESNY	ESKN	ESNB	ESCM	ESGO
ESGG	0	365	115	552	173	205	282	16	85	215	106	170	70	203	309
ESMS	365	0	87	411	111	175	178	12	64	145	79	126	53	150	182
ESPA	115	87	0	156	38	50	59	5	38	49	33	45	24	58	59
ESSA	552	411	156	0	184	240	290	21	117	246	159	256	98	393	288
ESFR	173	111	38	184	0	64	115	6	28	80	36	57	23	68	98
ESDF	205	175	50	240	64	0	102	7	37	85	45	75	30	88	104
ESIB	282	178	59	290	115	102	0	9	44	121	56	89	37	107	162
SE-0016	16	12	5	21	6	7	9	0	4	7	5	6	3	8	9
ESNS	85	64	38	117	28	37	44	4	0	36	25	34	19	44	44
ESGR	215	145	49	246	80	85	121	7	36	0	47	78	31	91	119
ESNY	106	79	33	159	36	45	56	5	25	47	0	44	22	61	55
ESKN	170	126	45	256	57	75	89	6	34	78	44	0	28	92	89
ESNB	70	53	24	98	23	30	37	3	19	31	22	28	0	37	37
ESCM	203	150	58	393	68	88	107	8	44	91	61	92	37	0	106
ESGO	309	182	59	288	98	104	162	9	44	119	55	89	37	106	0

A.5. Workload Distribution

The workload distribution of the group members for problems 1 and 2 can be seen in Table A.5 respectively. The latter contain an overview of the contributions to the problems that have been detailed in this report, as well as their respective aspects i.e. mathematical modelling, programming, and reporting.

Table A.5: *Workload distribution per team member.*

Student names	Mathematical modelling (30%)	Programming (50%)	Reporting (20%)
Menno Berger	1/3	1/3	1/3
Andrada Gheorghe	1/3	1/3	1/3
Ioana Toanchină	1/3	1/3	1/3