THE GREENLAND AIR TRANSPORT MODEL SYSTEM

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ABSTRACT

The paper presents the use of ArcGIS in the Greenland Transport study. Being the worlds largest island, but with only 56,000 inhabitants in a mountainous arctic area with no possibilities for interurban road transport, air plays a central role for the society. However, the present system needs large public subsidies yet having very high ticket costs and often inconvenient transfers for the users.

ArcGIS and the Geoprocessing Framework was used to create a complex model for air transport, which in an interactive process describe passenger and freight flows, design the service network, schedules flights (time-table optimization), decide on airplane types considering cost and capacity, and finally creates airplane schedules.

The model is going to be used by the Greenland Home Rule to decide upon the new airport structure in Greenland (change of main airports and creation of new airports), policies to obtain more competition and to liberalise the market, and to design the main air system.

1. INTRODUCTION

Greenland is the largest Island of the world (see Figure 1), but since it is located in the arctic, it is very thinly populated. Greenland is part of Denmark, but has Home Rule and is not part of the European Union (as Denmark is). Being a very large Island, but with a very small population, set up some very difficult challenges concerning the transportation system. Some key figures are;

Distances;

- North-South; 2,700 km.
- East-Vest; 1,300 km.
- Inland ice at main East-Vest corridor; 500 km.

Area and population;

- 2.2 Mio. Km2
- 410,449 km2 without ice-cover.
- 56,854 inhabitants.

Even though about 80% of Greenland is covered by ice, the part not covered by ice is still pretty large, e.g. 10 times the size of the Netherlands or Denmark (which has 16 and 5.5 Million inhabitants respectively). Alone the area around the capital Nuuk (15,000 inhabitants) has the same size as the mainland of Denmark.

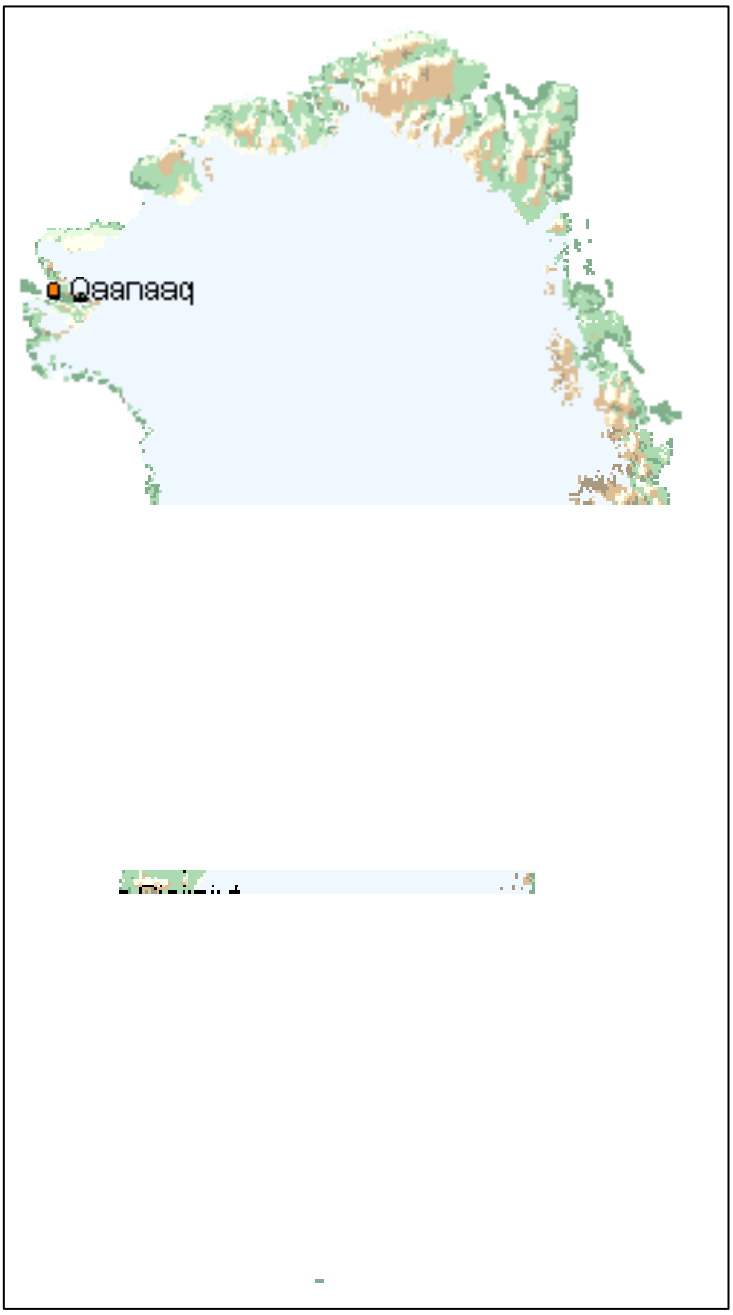

Figure 1 *Greenland with its main cities.*

1.1 Background

The main airport of Greenland is not located at the Capital (Nuuk), but at the location "Kangerlussuaq" at the bottom of the fjord "Sønderstrøm" more or less in the middle of no-where. This location was originally chosen of historical reasons, since the US built the runway and airfield during the Second World War. At that time it was an ideal stop-over between US and UK, since the location had sea access, allowing easy access for building material by ship, yet being at the bottom of a 200 km. long narrow fjord, whereby access by German submarines easily could be controlled (and presented). The far distance from

the main sea also makes the location almost without fog or rain. Furthermore, there is a long and wide plane section of land on a former riverbed, which is unique in the by far very mountainous Greenland.

However, in a modern civilian passenger and freight air transport system, a hub located in the middle of no-where is quite inconvenient. Furthermore, the former riverbed has started to melt (permafrost) due to the global heating. In practice, this makes repair and operations expensive;

- There have to be many flights between Nuuk (The capital and Kangerlussuaq) by the small DASH 7 airplanes (50 seat max) that are the largest plain that can land and take-off in Nuuk. To compare, the 4½ hour flights from Kangerlussuaq to Copenhagen are presently done by 245 seats Airbuses.
- There have to be an "Artificial community" in Kangerlussuaq to support the operation of the airport.
- There have to be hotel capacity in Kangerlussuaq to accommodate passengers if delays or cancellations occurs (which are frequent in the arctic - especially in the wintertime).
- For domestic flights, a Dash7 air network has Nuuk as hub. Therefore, the Island operates with two hubs (see Figure 2, even though the population is only 56,854 inhabitants.

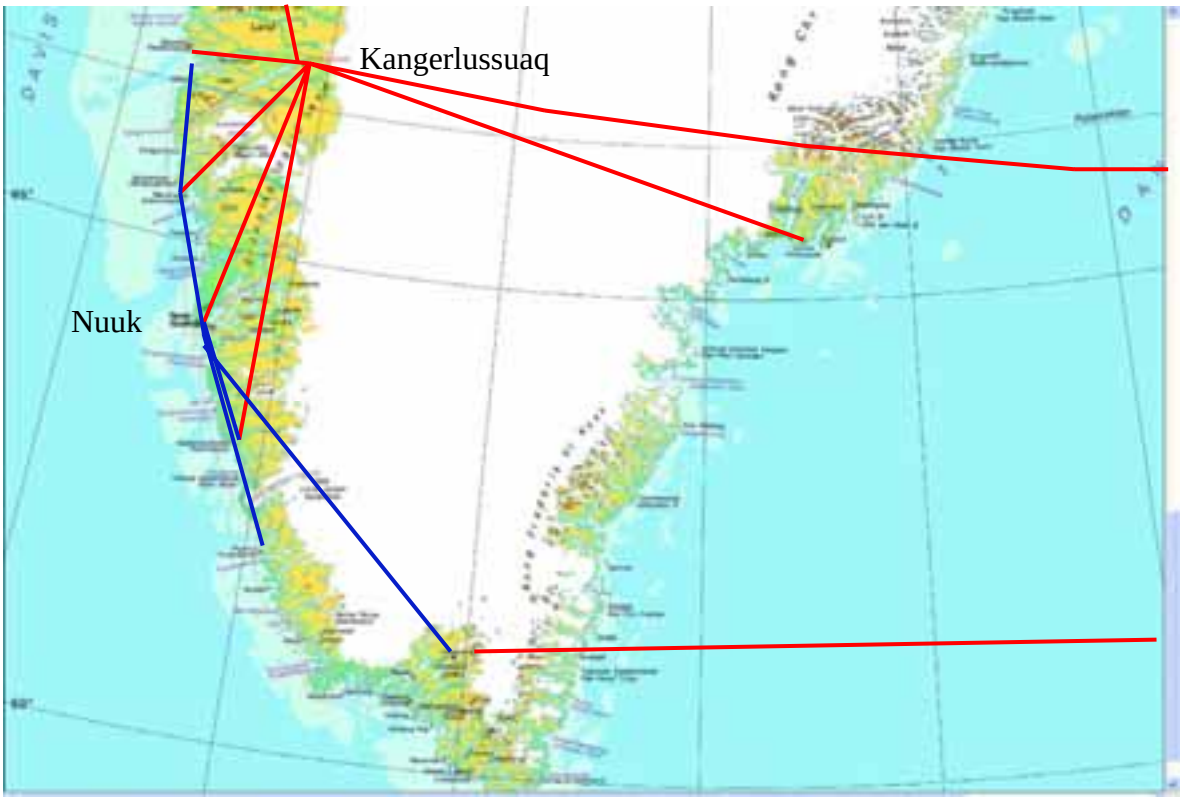

Figure 2 *The two-hub network structure in Greenland.*

Even though it might seem very obvious to build an "Atlantic" airport in Nuuk, the decision is not trivial;

- The Runway in Nuuk is expensive to extent, since it is located on a mountain. The alternative locations in the Nuuk region are expensive to connect with road to Nuuk, and it is also expensive to build a new airport there. Both in absolute numbers, and especially by comparing the size of the population.
- The climate is much more foggy and windy in Nuuk, which is a problem concerning the small feeder airplanes and helicopters that are used to many of the smaller airports (there are 25 airports and heliports in total in the network)
- TheDash7 planes are very robust in Arctic climate compared to jet-plains, whereby the operations run pretty stable today.

Facing on these difficult decisions, the Greenland Home Rule has asked the Technical University of Denmark (DTU) to develop an integrated system of a transport model, an air network optimization model, and a socio-economic decision support model. The model demands were very complex in terms of causal relationships, yet it was also a demand that the model should be user friendly and possible to run by employees at the Home Rule. It was therefore decided to implement the model in ArcGIS based on the Model Builder and Geoprocessing framework. DTU therefore hired Rapidis Ltd. As sub-contractors for the work. Rapidis is a specialist in making ArcGIS applications for the domain of transport.

1.2 Decision to be supported with the new model

Examples on strategic scenarios to be supported by the model system are;

- A new ”Atlantic” airport in Nuuk
    - Direct connections from Copenhagen
    - Number of transfers in Greenland are reduced
    - Less need for domestic flights
    - A certain reduction in prise, due to more direct flights and lower costs of operations (e.g. extra hotels and crews in Kangerlussuaq)
    - Number of forced night stopovers in Copenhagen is reduced
- A new ”Atlantic” airport combined with direct flights to USA
- More connections to Keflavik (Iceland)
    - Cheaper prises from Europe
    - Much more legs from USA
- Importance for tourism

This may result in large changes in tourism. An example is a tourist journey from San Fransisco to Greenland today (one US$ is about 6 DKK);

- San Fransisco->Copenhagen, 18 hours, 2 legs, 5,500 DKK
- Overnight stay Copenhagen, 1,000 DKK
- Copenhagen->Kangerlussuaq, 4,500 DKK (cheapest flight) – 7 hours
- Kangerlussuaq->Nuuk, 4,000 DKK
- i.e. 2 full days, 15,000 DKK

With a new airport in Nuuk and connection via Keflavik (Island), the journey time and cost will be reduced with about 2/3 to.

- San Fransisco->Nuuk, 14 hours, 2 legs, 5,000 DKK

The model is also envisioned to be used to evaluate tactical scenarios and decisions, e.g;

- Other new airports. Typically replace heliports with small short runways. As helicopters are very expensive per passenger kilometre, slow and have a short range, this may led to benefits even though the construction costs are high.
- Upgrade existing airports. This is mainly under consideration for the 3 largest cities in Greenland that have short runways today. Upgraded airports may open up for access by jet-plains and by other air companies that the present Air Greenland (who have a de facto monopoly, although the Home Rule welcome competition)
- Use as a tool to design and evaluate tenders for routes that are subsidised, and to analyses bids
- Analyses of need for subsidies or taxation
- Air network design
- Schedule planning

1.3 Overall transport modelling system

The overall transport modelling system consists of two main parts (se Figure 2);

- Demand models provide traffic to route choice models
- Route choice models deliver networks and LoS to demand models

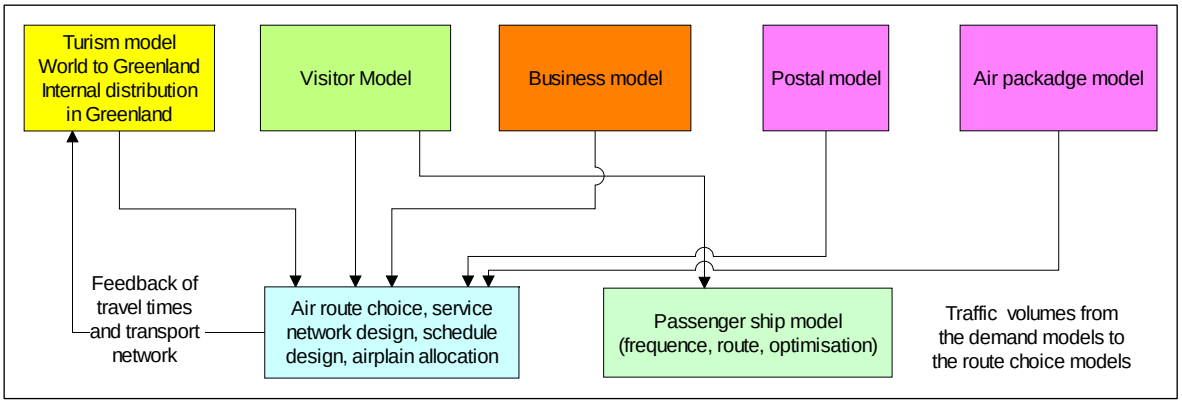

Figure 3 *Main model components.*

The demand models are segmented into tourism, visitors, business, letters and air packages (cargo). The tourism model is further segmented into a "World model" describing demand for tourism from the world (this is split into 43 regions). The demand is calculated for a standard week (since the network is very infrequent) and split into the 7 week days (according to a sub-model), and then into 7 different period during each the day, i.e. 49 time periods for a week.

The route choice model assigns passengers onto the air network. The model operates on the exact timetables, and takes capacity (seat restrictions) into account. The model is ac-

cordingly a stochastic (Mixed Probit) multi-class user equilibrium model. A special consideration is that post (letters) have the highest priority, and that postal sacks literally can replace passengers. Passengers then have higher priority than freight.

Finally, the model consist of an optimization model, that design the overall air transportation network, leg structure (departure time), chooses plain types, and calculates the costs of operations including the necessary number of aircrafts.

The optimization model uses the following optimization criteria;

- *β1·passanger(dis)utility + β2·cost_of_operation + β3·fare_revenue*

This may be used to an air company specific optimisation, i.e.

- *Min[cost_of_operation -·fare_revenue]*

Or a socio-economic optimisation

- *Min[passenger(dis)utility + β2·cost_of_operation]*

Furthermore, the traffic model and the optimisation models have different object functions;

- *The traffic model object function describes passengers preferences (e.g. value of times) and includes a stochastic error term and stochastic coefficients (describing variation of their preferences)*
- *The optimisation models object function include socio-economic criteria (e.g. value of times) and is deterministic*

1.4 Implementation

The model was implemented in ArcGIS using the ArcGIS Model Builder and Geoprocessing Framework.

The demand models where estimated by the SAS statistical software, and the parameter values were then applied mainly in the Traffic Analyst (TA) package by Rapidis (www.rapidis.com) or in special procedures implemented in the Geoprocessing Framework.

The route choice model was a modified version of the timetable-based model developed jointly by the technical university of Denmark and Rapidis in C#.

A number of exchanged routines and queries were implemented in scripts and by SQL-queries. The whole model system was also supported by scripts, due to the missing loop-feature in ArcGIS Model Builder.

1.5 About the Paper

Section 2 describe the data foundation for the model, section 3 the traffic model, section 4 the route choice model and section 5 the network design model. This is followed by a few examples of results by running the model and a summary and conclusions.

2. DATA FOUNDATION

The model covers all towns with airports in Greenland (including heliports). This resulted in a total of 25 airports (see Figure 4), and 2 port zones – i.e. Kastrup and Keflavik representing the only international flights (to Denmark and Iceland respectively).

The airports are defined by;

- Type (airport/heliport)
- Length of runway
- Service restrictions (minimum allowed frequency per week)
- Opening times (e.g. from 8.00 to 20.00 or 6.00 to 22.00).

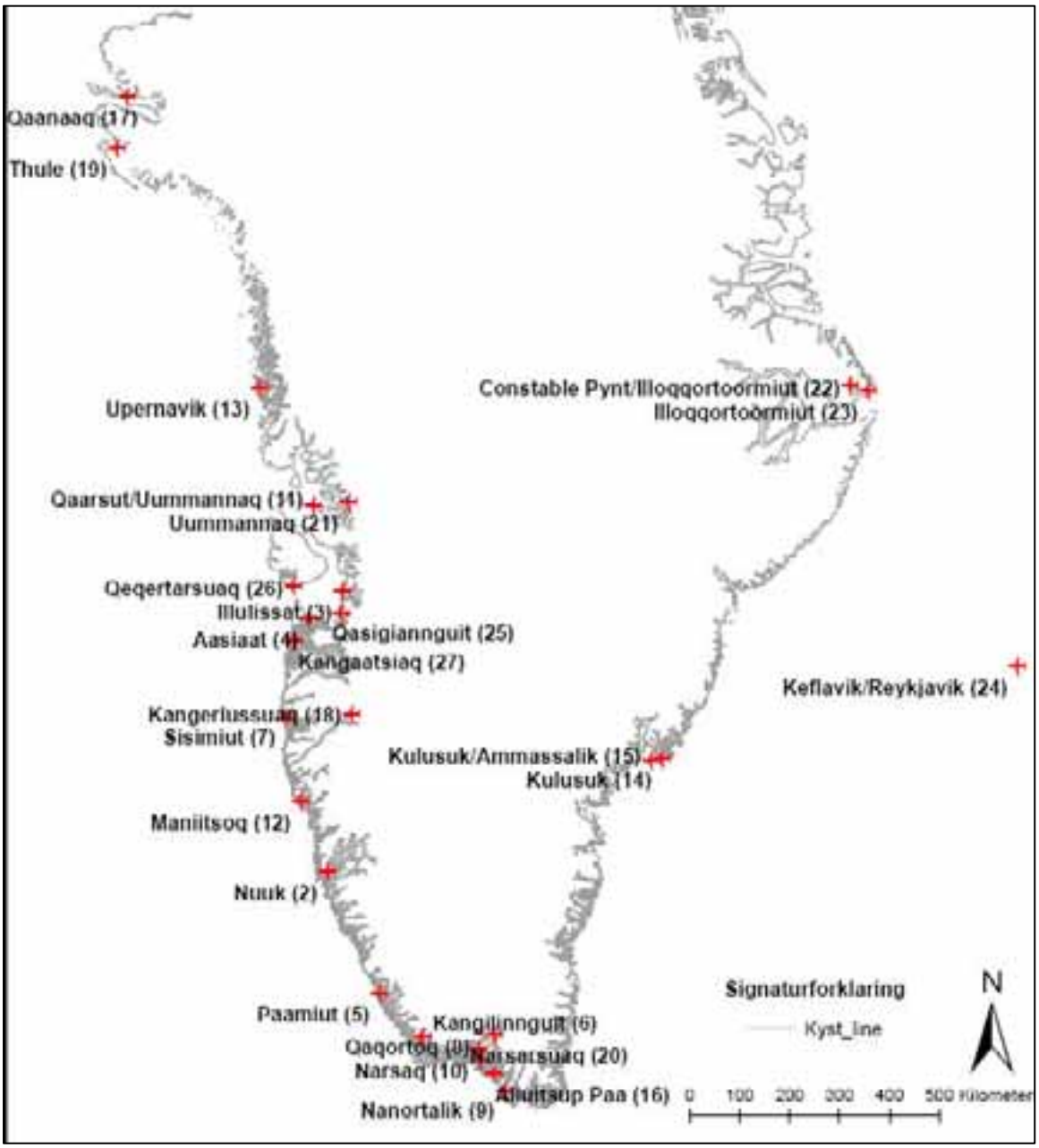

Figure 4 *Airports in the Greenland model.*

Other data includes collected fares from various air companies and airports, and low-price homepages, data on the air links from Keflavik and Kastrup to the rest of the world (again using various home-pages), socio-economic data (hinterland to the airports), data on air-planes, traffic counts on legs and airports, statistical information on tourism, and various travel behaviour surveys.

3. TRAFFIC DEMAND MODELS

The demand models are pretty conventional, as they – with some modifications – follow a traditional 4-step model structure of demand modelling (trip frequency), destination choice (gravity models), mode choice and route choice (see Figure 5).

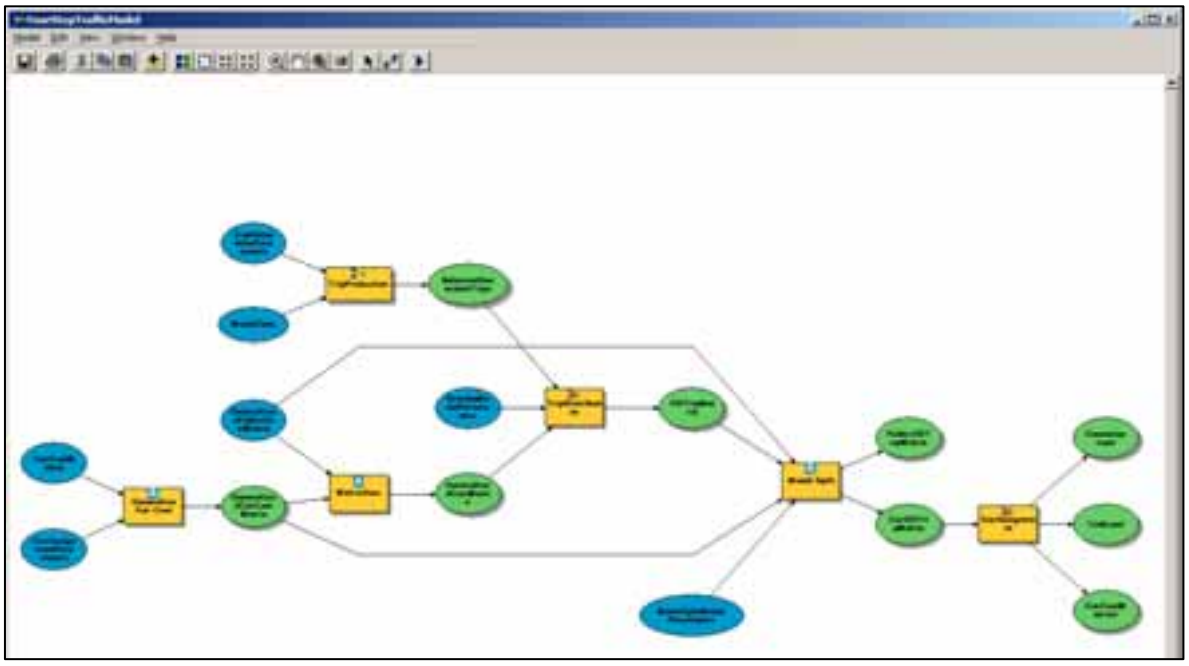

Figure 5 *Example on 4-step model in ArcGIS model builder using Rapidis Traffic Analyst tools (refer to www.rapidis.com)*

The model system runs – as mentioned – with 5 different trip purposes, i.e. tourist trips, private visitor trips, business trips, letters and packages.

3.1 The Tourism model

This model consists of two main models – a growth model for international tourism, and a distribution model for the tourists' use of domestic flights.

The international growth model consists of the following

1. A choice model from each of the 43 World regions, between port zones, i.e. Kastrup and Keflavik, and to 3 regions within Greenland (East, West and South). The model type was a Multinomial Logit model.
2. Calculation of average Level of Service (travel times and costs) weighted with the choice probability from the region in consideration.

3. Calculation of induced transport by a GLM poisson regression model, which was estimated in SAS.

The international tourism model was estimated to fit the base year data. This model was implemented as a spread sheet model due to many exceptions and special considerations, as well as uncertainty of stability in elasticities, whereby the user may want to "overrule" these specific values, e.g. to conduct sensitiveness analyses,

The domestic tourism model was defined as follows;

1. The growth was assumed to be proportional with the total amount of new tourists
    - The proportionality factor was assumed to be between 0 and 1 (assumed 0.8), i.e. the new tourists are assumed to be less rich than the present (since they first come to Greenland, if it is less travel to travel there).
    - This factor was then split into the 3 regions (East, West, South)
2. The growth was balanced to fit totals
3. A doubly constrained gravity model was run to distribute the total flow between destinations
4. A so-called pivot correction was used to fit the model to base-year matrices in the base year network

The domestic tourism model (and all other demand models) where implemented by ArcGIS Model Builder and Traffic Analyst.

3.2 Visitor model

The visitor model works as follows;

- Calculate improvements of supply data;
    - Weighted average on airport level
- Calculation of growth factors
    - Domestic trips using a gravity like formulation (combined formula)[1];

      $$T_j = \gamma \cdot Bef_j \cdot LoS_j^{-\alpha} \cdot \exp\left(-\beta \cdot LoS_j\right)$$
    - Foreign trips using a pure elasticity model
- Balancing growth (secure fit to totals)

[1] γ, α , β are parameters. *Bef* is the population in the source zone, *LoS* is the weighted average of level of service in the zone.

- Double constrained gravity model[2]

$$T_{ij} = K_{(G)i} \cdot K_{(A)j} \cdot O_i \cdot D_j \cdot f\left(LoS_{ij}\right)$$

$$s.t.\ (subject\ to)$$

$$O_i = \sum_j T_{ij}\ ,$$

$$D_j = \sum_i T_{ij}\ ,$$

$$K_{(O)i} = \frac{1}{\sum_j \left(K_{(A)j} \cdot A_j \cdot f\left(LoS_{ij}\right)\right)},$$

$$K_{(D)j} = \frac{1}{\sum_i \left(K_{(G)i} \cdot G_i \cdot f\left(LoS_{ij}\right)\right)}.$$

- Pivot correction – this is basically a relative correction, that modify the modelled matrices to fit with the estimated base-year matrices.

3.3 Business and cargo

The business model runs more ore less similar to the tourism model. The main difference is, that the international traffic is modelled by an elasticity model, and that domestic growth uses a formula, that includes work places (*Arb*);

$$T_i = \left(\gamma_b \cdot Bef + \gamma_a Arb\right)_i \cdot LoS_i^{-\alpha} \cdot \exp\left(-\beta \cdot LoS_i\right)$$

4. ROUTE CHOICE MODEL

The passenger route choice model finds the following equilibrium;

- *An equilibrium is obtained where no passengers perceived utility can be improved by he/her unitarily changing route at the desired time of departure*

Where the utility function is dependent of

- *Trip purpose*
- *The passengers preferences*
- *The time use*

The utility is strongly flow dependent, since most airports in Greenland can only be served by small air plains (the main type is DASH7 with maximal 50 seats), while the main international airports (Kangerlussuaq) is served by a 245 seat Airbus, the other international airport (Nasarsuaq) by a 180 persons Boing, and the third (Kulusuk) can only be served from Iceland (Keflavik) by another propeller-driven airplane (Fokker 50 – which is quite similar to DASH7). The strict capacity restrictions combined with the low frequency led to

[2] The balancing factors K's secure that the row, *i*, sums of the T_{ij} matrix fits with the expected sums (O_i), and the same for the columns, *j*. The set of equations are solved by the Furness procedure.

the decision to implement a Stochastic User Equilibrium timetable-based assignment model.

This model was then modified to reflect a number of special issues in Greenland;

- Passenger capacity is a strongly limiting factor (passengers are simply rejected, not only delayed as e.g. in the classical BPR[3]-formula)
- Air mail has higher priority than passengers
- (Weight) restricts the number of passengers at long flights
- Limited fleet of airplanes
- Airplane (schedules) have to be part of the model
- Weekly schedule!
- Trips may even have to wait to the next week

The model has the following explanatory variables that are optimised in a utility function for each class of passengers (and by simulating statistical distributions of each passenger as well);

- Early departure penalty (sort of "hidden waiting time)
- Late departure penalty (traditional "hidden waiting time)
- Travel / air time
- Transfer time.
    - Strongly non-linear, as long transfer times can be used constructively, e.g. on musk ox trips, or visiting the inland ice at Kangerlussuaq using long transfer times for e.g. tourism
- Transfer penalty (disutility by non-direct travels)
- Overnight penalty (disutility and cost when need for overnight transfers/stays)
- Cost (share of ticket time)

5. NETWORK DESIGN MODEL

The network design model design/forecast the

- Air network (service network)
- Schedule
- Use of airplanes (types and numbers)

This is done conditional on the expected passenger flows, which are the results of a route choice model on the output of the network design (i.e. a bi-level optimisation problem[4]).

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[3] US Bureau of Public Roads.

[4] Where the sub-problems are non-linear, discrete and with a non-closed form formulation, and is solved internally by iterative procedures.

The air model, may then take the following decisions;

- Passengers choice of routes, and possible upgrading of airplane type
- Downgrading of airplane type
- Airplane allocation model
- Removing or adding direct legs
- Time-schedule design

The main solution approach was decided as follows (refer also to Figure 6);

- Step 1; A gross network is generated
  - Hourly departures between all relevant destinations
  - Possible airplanes
    - Depends primarily of the lengths of the runway
    - Secondarily from this by how long it is possible to fly with the most far reaching airplane that can operate
- Step 2; Calculations are made based on weekly schedules (some destinations may have down to 1 connection each week)
  - Each leg (flight between airports) can be flown by a list of possible airplane types with different sizes and operations costs
  - Based on modelled passenger potentials, all legs are downgraded to the optimal type of airplane
- Step 3; Capacity free route choice
- Step 4; Links with very few passengers are deleted
- Step 5; Downgrading of airplanes to fit demand
- Step 6; Iterative network improvement
  - Closing of legs with least utility (given a set of minimal criteria for operations and whether the leg has not been investigated before)
  - A new assignment is made. After 5 iterations, airplanes may be upgraded during assignment. The network is redesigned then due to possible increased speed
  - Airplane disposition / scheduling (estimation of turn-arround costs and balancing of legs and airplanes on airports).
  - New stochastic capacity dependent route choice (legs can be closed, upgraded and using bigger and faster plains), which influence route choices.
  - The overall utility function is calculated. If this is improved, the changes takes place, otherwise, they are regretted and marked as tabu
  - Stop criterion
- Step 7; Detailed optimization of the airplane scheduling
- Step 8; Final route choice model

The model may be said to represent at “three player game” consisting of – and finding an equilibrium between;

- Home rule decisions
  - Airport structure (location, length of runways)
  - Subsidies and/or packages of routes
- Air company decisions
  - Legs (and general structure of network)
  - Schedule
  - Airplane allocation
  - Non-Greenland flights
  - Fare
- Passenger decisions
  - Number of trips, destination, mode choice (domestic to some limited extend), route choice, time of travel (partly part of route choice), fare level, company.

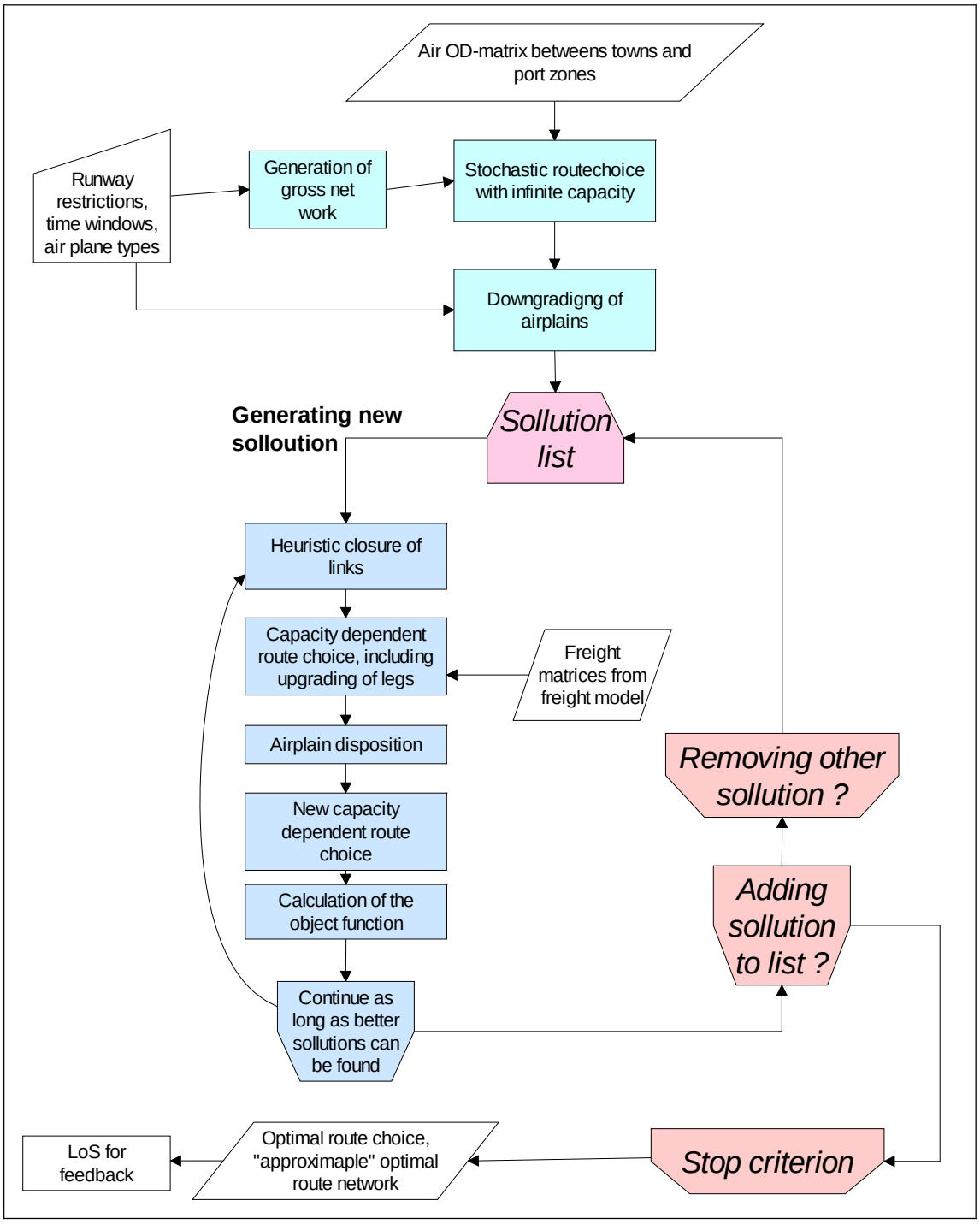

Figure 6 *Main flow in the air optimisation model*

6. SOME RESULTS

The model has just been finalised as the paper is written. Therefore it is still in the process of calibration and validation. In the following, some temporary results are presented though.

Figure 7 shows the resulting air network structure by running the model. The model was able to reproduce the existing network quite well. Recall that the base situation have all possible leg connections between all 27 airports, i.e. 729 possible connection, 8 air plain types, and departures of 60 minutes interval. With the restrictions on airport sizes and flying length, this resulted in 36,762 legs in the Gross network, and 439 in the final optimised network.

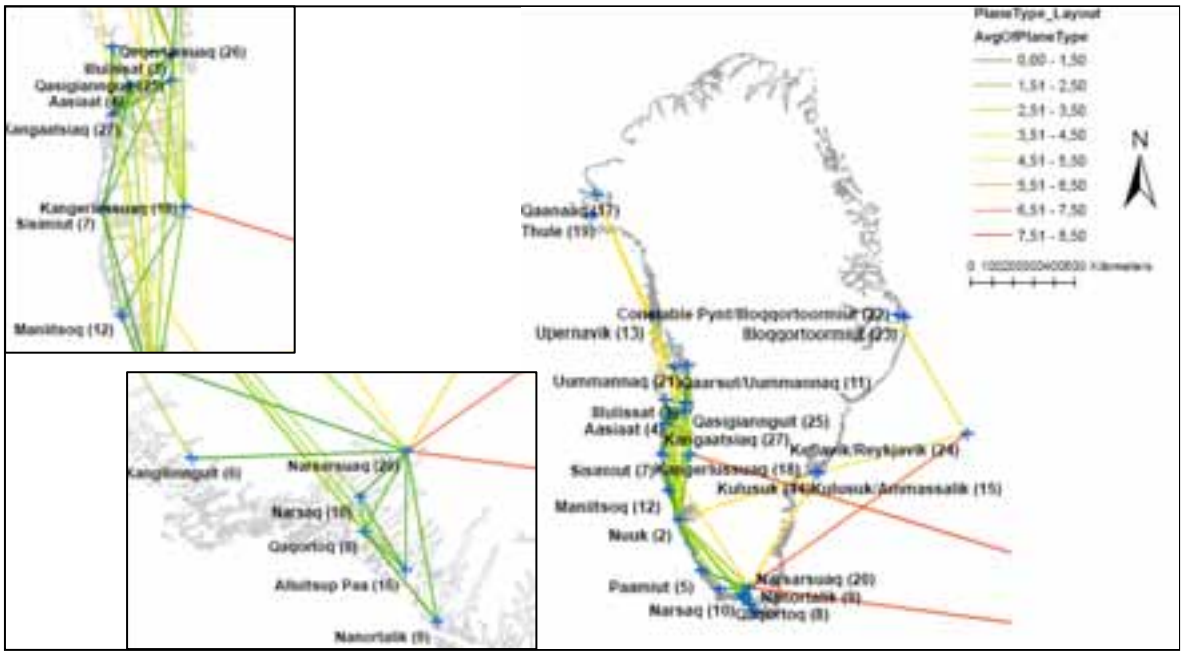

Figure 7 *Results from the air network optimisation, on the base year situation. The 8 plain types have been classified in order, where 1 is the smallest helicopter, 3 is the largest – a Sikorsky – 4 and 5 small airplanes, 6 Dash7, 7 Boing757-200, and 8 Airbus330-200.*

The network differed from the existing in some details. However, these cases had mostly logically explanations, and the suggestions proposed by the model seem sometimes even to be better than the existing network.

The model can hereby be used to evaluate the existing network. However, the main benefit is, that the very large effort figuring out which network to code, which airplanes to use, and which schedule to implement, can be avoided in modelling of scenarios, since the air model simply generate a new optimal network given the new restrictions - e.g. a longer runway in the capital, Nuuk.

Figure 8 shows the results of this scenario. As expected, the main connection to Copenhagen moves to the new airport (which confirms the illogical location of the existing airport in Kangerlussuaq). Another result is that the present two-hub structure for domestic flights in both Kangerlussuaq (serving the connections out of Greenland) and Nuuk (serving con-

nections to the Capital) is now replaced with a one hub-structure (Nuuk). This also allow for more frequent direct flights to Nuuk and longer flights as well.

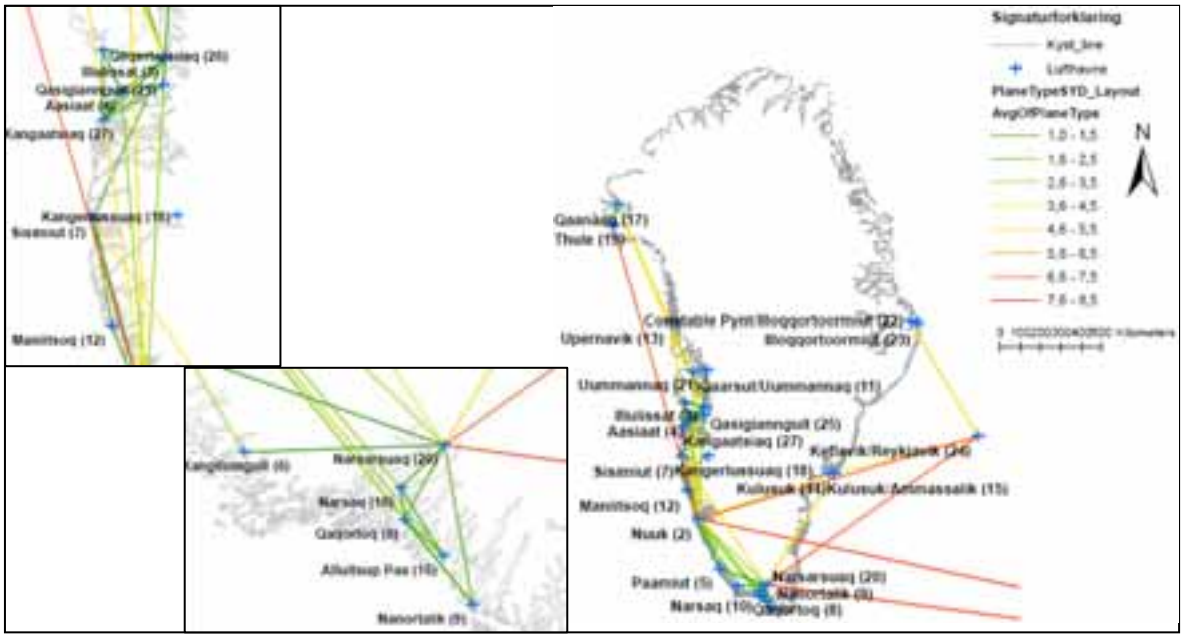

Figure 8 *Run of the model on the scenario with a longer runway in Nuuk.*

Similar figures showing passenger flows and leg-frequency showed similarly logically results.

7. SUMMARY AND CONCLUSION

The Greenland model is quite complex as indicating in Figure 9 that shows the overall modelling process. It has – however – been possible to implement, modify, optimise, calibrate, test and validate this model fairly easily by using ArcGIS Model Builder and Geoprocessing Framework. A similar "tailor-made" model would have been very difficult – if not impossible – to implement by standard traffic modelling software.

Another interesting conclusion is, that it indeed were possible to implement a model system, where there was an interaction between a traffic model (demand and route choice), and a model that designs the service network, optimised the leg-structure and airplane departure time, and optimised the airplane allocation (scheduling). The outer loop between the different model components converged, and the final solution was not only able to be similarly as good as the existing system, but also suggest improvements.

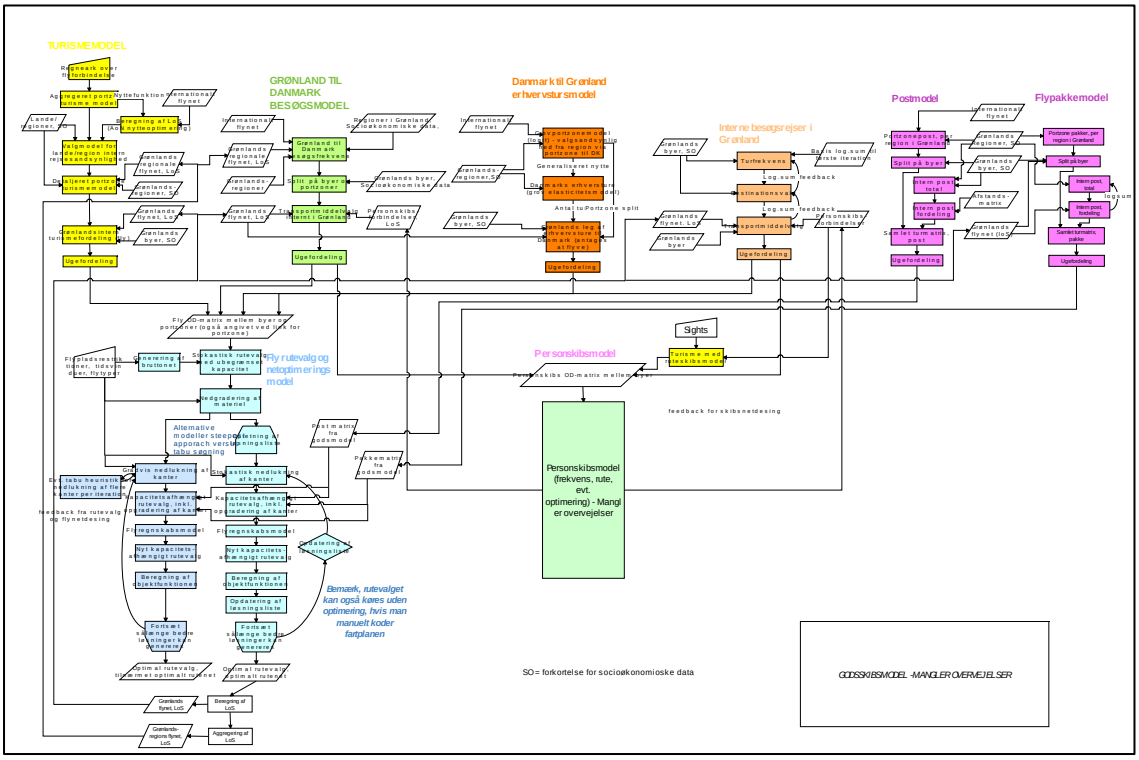

Figure 9 *Flow-chart for the overall modelling process.*