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Georges Mykoniatis[1], Stephane Puechmorel[1], Felix Moracamino[1], Leila Zerrouki[2], Marcel Richard [3]

[1] Ecole Nationale de l'Aviation Civile
e-mail: georges.mykoniatis@enac.fr , stephane.puechmorel@enac.fr , felix.moracamino@enac.fr
web page: http://www.enac.fr
[2] EUROCONTROL
e-mail: leila.zerrouki@eurocontrol.int web page: http://www.eurocontrol.int
[3] NEOMETSYS
e-mail: marcel.richard@neometsys.fr web page: http://www.neometsys.fr

Keywords: Modal shift, Climate change, Greenhouse gas emissions, Short-haul flight, Train, Aviation Travel time, network manager, multi-modality, Demand Capacity Balancing, Air Traffic Management,

Abstract. The current Air traffic System in Europe relies on airspace and airport capacity estimates computed by the Air National Service Providers (ANSPs) using demand forecast and Air traffic Controllers operations schedules.
The Demand Capacity Balancing (DCB) aims at reducing the Air Traffic Management resources held in reserve to cope with demand peaks by providing the system with demand smoothing means.
A recent study on the subject suggests introducing a congestion-based route fee that encourages users to avoid crowded slots for a given departure and arrival airport [1]. An optimal equilibrium point can then be reached through a clever choice of penalties incurred by flying at departure times adversely impacting congestion.
Alternative routes may also be considered in the planning, as for a whole category of customers price tag is more important than travel time.
However, taking into account that for short haul flights alternative means of transportation may be a viable option, DCB can be addressed in a wider scope by considering surface vehicles along aircraft.
A side effect of this holistic approach is the ability to cope with disruptive events. The present work describes a simulation and optimization model tailored to this particular problem.

1. INTRODUCTION

According to the forecast, by 2040 traffic in Europe is expected to grow over 16.2 million flights in the Regulation and Growth scenario (most-likely) (European Aviation in 2040 Challenges of Growth – Eurocontrol [2]). The estimated traffic growth will create a demand that require to efficiently use tall he available capacity. The result will be a pressure on airport capacity and will have an impact on the global network performance and will certainly reduce the means to cope with contingency. With this future level of congestion, it will become difficult to accommodate minor deviations from plan, and delays will begin to accumulate rapidly.

But the delays and the cancellations have already an important impact on network operations, in 2018, the share of reactionary delay was 46% of total delays, contributing 8.2 minutes per flight. Reactionary delays are generated as a result of an aircraft's late arrival from a previous flight which in turn affects the punctuality of its next flight with the same aircraft, as well as potentially delaying connecting passengers. Subsequently there are two types of reactionary delays: firstly, as a result of the same aircraft being delayed on its next flight (rotational delay) and secondly when another aircraft is delayed as a result of another aircraft typically through passengers, crew and load connection (non-rotational delays) (Eurocontrol CODA 2018 [3]).

Since 2013, there has been an 80% increase in delays attributable to weather. But the weather is not the only cause of disruptions, the example of the 2010 eruptions at Eyjafjallajökull in Iceland which, although relatively small for volcanic eruptions, caused enormous disruption to air travel across western and northern Europe is one of them. There is also Industrial action; Armed conflict; Security incidents; Nuclear accident; Staff shortages; Social movement, Staff shortages; Uncontrolled re-entry of satellites (https://www.eurocontrol.int/articles/disruptions-and-crisis-management) .

The demand capacity balancing is addressed actually by the Air National Service Providers by adaptation of the services on part of the airspace set in various predefined configurations based on volumes called sectors and also functional sectors (the functional sectors allow the allocation of the traffic to a groups of controllers according to the type of operation, e.g. Departure, Arrivals). The airports also have published capacities for the Landing and take-off that could vary according to the meteorological or operational constraints. The network manager is issuing regulation according to the published setting of the airspace and airports, taking into account their relevant declared capacity by the Air National Service Providers (ANSPs) [4].

But Air Transportation has to face also the environment challenge. The aviation sector is responsible of 6% of the CO3 emissions (IEA, 2018 [5]), and the air traffic growth significantly more than 4% per year (Airbus Global Market Forecast 2018-2037 [6]). The IPCC special report 2018 **[7]** is calling for drastic reductions of greenhouse gas emissions in order to limit warming to 1.5° above pre-industrial levels.

For a distance less than 1500 km, short haul flights (Eurocontrol defintition: airport-to-airport distance is less than or equal to 1500 km [8]) the alternative of another transportation mode could be consider (Follmer et al. (2008) **[9]).**

A recent study for Finland by Stefan Baumeister 2019 [10] showed that replacing short-haul flights could significantly reduce country’s transportation climate impact. Furthermore, they found that existing land-based transportation modes can keep up with the travel times of aircraft on routes up to 400 km.

But replacing short-haul flights by ground transportation could not be the way to face the demand in term of transportation for the coming years. The existing ground transportation infrastructures are already facing problem of saturation in the cities and between the cities. Our approach here will not address these critical points.

Our approach is to address the demand capacity balancing by modeling an extended network of operation including air and ground connections. The alternative of ground transportation will only be focused on the short haul (less than 1500 km). This study proposes to address Demand Capacity Balancing by taking into account that for short haul flights alternative means of transportation may be a viable option. The DCB is then addressed in a wider scope by considering surface vehicles along aircraft.

The following scenarios are compared:

1) Full Aviation Solution
2) Short-hauls replaced by ground transportation
3) Full air and ground (less than 1500km) network operation
4) Disruption management with various usecases

Our analysis will be based on the real travel time estimation, emissions estimation and cost of operation.

We will keep the definition and values given by Stefan Baumeister 2019 [10] for the real travel time (RTT) from door to door.

The role of the regional airports could be crucial in the coming years in term of offering potential opportunities to face the demand/capacity challenge. It will be addressed in our approach in one of the uses cases to face the disruptions. The usage of a management tool to help in the collaboration decision making could be envisaged in future works and will take benefits of what have been done on the OPTIMODE project [11].

The work will be performed by using the Pi-rat Simulator of ENAC which allows to simulate a large amount of flights and evaluate their time of flight and the emissions. The simulation is using the Base of Aircraft Data (BADA) is an Aircraft Performance Model (APM) developed and maintained by Eurocontrol [12].

The ground transportation part will be modelled and introduced in the Pi-rat simulator.

2. REAL TRAVEL TIME (RTT) MODEL

The real Travel time should take into account the time from the city to the airport, the time in the airport to perform the checking and reach the gate, the time of flight, the connection time between two flights, the time for collecting luggage, crossing the customs and finally the time between the airport and the city.

2.1. ADOPTED HYPOTHESES:

Passenger departing from a given airport

We consider as average time from city center to airport of 45mn but usually in Europe the passengers take a buffer for the connection of about 15mn, that gives 1H.

We consider arriving 30min before check-in closes and usually it closes 45 mn before departure time which should allow passengers enough time to clear security and reach the departure gate in time.

That gives: 60+30+45= **2h15mn** as Real time from Door to Gate

Passenger making a connection in a given airport:

The average connection time that we will consider is **45 mn (**time of connection between the two flights or between a flight and ground transport).

Passenger arriving at a given airport:

We consider that average time to go out of the aircraft, claim baggage, cross customs is of 40mn.

Plus, then the time from the airport to the city which is could be an average of 45mn.

That gives for a passenger in an arrival airport a Real time of **1h15mn** from aircraft to door.

3. DEMAND MODELLING

For addressing the demand issue, we will consider one day of operation in Europe based on the flight plan information collected form the Demand Data Repository of Eurocontrol https://www.eurocontrol.int/ddr.

For all the flights we will consider a given aircraft load factor depending of the city pair: departure and arrival.

The difficulty is to estimate the number of passengers making a rotation in a given airport.

The Demand modeling should take into account the passengers' expectations, in term of traveling time, arrival time, and also type of transportation. Several studies based on passenger's centric transportation have been done, **[16]** and it is difficult to address this issue.

Our approach here is to suppose that we have a distribution of the passenger demand that could be extrapolated on our knowledge of the air transportation figures.

The demand modelling should take into account its increase in the coming years and should consider that the air network and ground network could be close to be saturated. The assumption, that we are taken here is to consider that the initial demand is based on the assumption of the existing today air traffic filled at 87% (about the figures of today for Air France https://fr.statista.com/statistiques/495354/air-france-klm-coefficient-occupation-sieges/).

This initial demand will allow to give figures by city pairs and then an extrapolation is performed with the assumption of an increase of 4% per year (figure also coming from the Aviation domain **[15]**). This approach has the restriction to not take into account possible evolution of the actual capacity of the network, these could be addressed in future work by modeling the evolution of its capacity.

The various scenarios will be run with a different demand schemes: the initial, the 5 years forecast and the 10 years forecast.

4. COST OF OPERATION AND EMISSION MODEL

The model for the cost of operation and emission is based on a value per hour of flight according to the type of aircraft and the weight factor for the fuel consumption.
For ground transportation an amount per hour will be taken as basis for the emission:
For the ground cost of operation, it will be based on an average value.
The $CO2$ emmission will use the data provided by the French SNCF: https://www.oui.sncf/aide/calcul-des-emissions-de-co2-sur-votre-trajet-en-train

5. EVOLUTIONS OF PI-RAT:

Pi-rat is a fast time simulation tools developed in the premises of the French civil aviation school (ENAC) for the needs of air traffic management research. It is a feature rich tool, based on the well known BADA database from Eurocontrol, and implementing a continuous time point mass model. Weather effects are considered using GRIB meteorological data. A very accurate taxi model along with the ability to simulate UAVs makes it an integrated traffic simulation tool.

For the ongoing work on multimodality, a ground transportation module will be developed, using a graph-based approach and dynamic programming to model user's behavior. Optimized cost functions may include value-of-time considerations, as longer but uncongested routes or cheaper means of transportation may be selected instead of the usual time criterion. Finally, randomness has to be added to the system to better model the travel time uncertainties. Implementing on a realistic, large scale basis such a simulation is quite challenging. The surface transportation system cannot be modeled on a per-vehicle basis due to the overwhelming number of mobiles that would be needed. Instead, the original problem is turned into a maximal flow one, which is easier to deal with. In the current implementation, the surface transportation network is a directed graph G(V,E,f) where V is the set of vertices, E the set of edges and $f\colon E \to R+$ is the capacity function that maps an edge to its maximum available flow. To cope with uncertainties, for any $e \in E$, the value $f(e)$ is in fact a random variable with a known distribution and for $e \neq l$, $f(e)$ and $f(l)$ are assumed to be independent.

6. DEMAND CAPACITY BALANCING

This regulation is performed seven days or more before the day of operation, called the Strategic phase, one day to six days before the day of operations, called the pre-tactical phase and finally on the day of operation, called the tactical phase. The actual algorithm used for addressing the Demand Capacity Balancing in Europe is Computer Assisted Slot Allocation (CASA), but it will evolve in the coming years to address the issue of the Collaborative Air traffic Flow Management (cooperation between airspace users and airspace service providers) and also the environmental concerns. In our case, we selected to use an algorithm described below using a given heuristic but where other greedy heuristics could be proposed, some, through the computation of the environmental impact of each candidate route, or through a trade-off between airlines costs and environmental impact.

The Demand/Capacity algorithm:

Let F be the set of programmed flights for the considered day of operation, then for each programmed flight f_i $i \in F$, is built from the preferred 4D route, r=1, a set of alternate routes r =2 to R_i. These 4D routes are either delayed or lengthened or both to provide a diversity of offers able to overcome, through delay or increased flying costs, congestion situations in air traffic control sectors. An airline additional cost aac_{ir} can be assigned to these routes with $c_{i1} = 0$.

The whole considered airspace is subdivided into S air traffic sectors while time is discretized with period of 3 minutes: $t_k = t_0 + k\,\delta T$, $0 \leq k \leq K$, where t_0 is the opening operations time and K is the number of considered successive periods in a day. At time t_k, $k \in \{1,\ldots,K\}$, sector $s \in \{1,\ldots,S\}$ is supposed to have a known traffic capacity (measured in number of aircraft) written sc_{sk}.

An incident matrix M can be computed between the (i, r) flights, $i \in F$, $r \in \{1,\ldots,R_i\}$and the (s,k) sectors, $s \in \{1,\ldots,S\}$, $k \in \{1,\ldots,K\}$, it is given by:

$M(i,r,s,k)=1$ if route (i,r) is in sector s at time period k and $M(i,r,s,k)=0$ otherwise.

Then the Demand Capacity Balancing problem can be formulated as a discrete optimization problem such as:

$$\min \sum_{i \in F} \sum_{r=1}^{R_i} aac_{ir} \cdot x_{ir}$$

under the constraints

$$\sum_{r=1}^{R_i} x_{ir} = 1 \quad \forall i \in F$$

$$\sum_{i \in F} \sum_{r=1}^{R_i} M(i,r,k,t) \cdot x_{ir} \leq sc_{sk} \quad \forall s \in \{1,\cdots,S\},\ \forall k \in \{0,\cdots,K\}$$

$$x_{ir} \in \{0,1\} \ \ \forall i \in F, \forall r \in \{1,\cdots,R_i\}$$

Here the first restriction set, about the binary variable x_{ir} , indicates that only one route will be selected for flight i. The second restriction set indicates that at anytime in any sector, traffic cannot be higher than planned capacity.

The prior generation of all candidate 4D routes for each flight may appear to be a huge task, but it has some important advantages:

- Involve airlines to candidate route set definition, this is someway a collaborative situation.
- Avoid at the solution stage to have to rebuilt 4D trajectories while involved with searching for a global solution.

A greedy heuristic solution can be easily constructed according to the following steps:

1) Rank for each flight the candidate routes by increasing additional airline costs.

2) Start at iteration zero for each flight i with $x_{i1}=1$, $x_{ir}= 0$, $r \in \{2,\ldots,R_i\}$, i.e. the preferred route of flight i.

3) Define the set of active routes as $A=\{(i,r): x_{i1}=1\}$.

4) Check if the capacity constraints are satisfied with the current active route set. For that, compute current traffic demand D_{sk} for each sector at all instant:

$$D_{sk} = \sum_{i \in F} \sum_{r=1}^{R_i} M(i,r,s,k) \cdot x_{ir}$$

If $D_{sk} \leq sc_{sk} \ \ \forall s \in \{1,\cdots,S\}, \forall k \in \{0,\cdots,K\}$, the active set is the solution set: End

Otherwise proceed to next step.

5) Rank each active route (i,r) in A by decreasing order with respect to its global capacity impact factor Φ_{ir} given by:

$$\Phi_{ir} = \sum_{s=1}^{S} \sum_{k=0, D_{sk} > cs_{sk}}^{K} M(i,r,s,k) \cdot (D_{sk} - cs_{sk})^{\alpha} \quad \forall\ (i,r) \in A$$

where α is a positive parameter.

6) Choose *i** such that (*i**,*r**) is the first of the above ordered list and do:

If $r^* < R_i$: route (*i**,*r**) is replaced by route (*i**,*r**+1) in the active set *A*.

If $r^* = R_{i^*}$, flight *i** cannot be downgraded, then take the second flight (*i***, *r***) in the ordered list, reassign indexes *i** and *r** to route (*i***,*r***) and restart step 6).

Once the change in the route of flight *i** has been performed go back to step 4.

Observations:

- In the improbable case in which no route shift can be performed at step 6, this algorithm fails and the procedure can be restarted with extended candidate route sets, especially for the leading flights of the ordered list of step 5.
- The algorithm can be speed up by shifting more than one route at each iteration (step 6).
- The proposed heuristic presents a unique setting parameter, α, which can be taken as a constant or may be changed (increased) during the search process to cope with small excesses of traffic demand.
- The algorithm is compatible with dynamic traffic control sectors.
- The algorithm must be modified slightly to cope with landing and take-off capacities at airports considered as two-way sectors.
- To take into account somehow ground transportation, a fictitious ground sector can be attached to airports to take into account, the ability of ground transportation to tackle departing and arriving passengers in an hourly basis.
- Other greedy heuristics can be proposed, some, through the computation of the environmental impact of each candidate route, can propose a trade-off between airlines costs and environmental impact.

7. THE SCENARIOS

The network cities to take into account could be just a model as in the study performed by Jung, M. &al , Classen, A.B., Rudolph, F., Pick, M., Noyer , U., [11] or a given airspace such as the whole European area, the French airspace, a region…

7.1. FULL AVIATION SOLUTION

In this scenario, the inputs will be one day of traffic and the analysis will be performed based on city pairs (departure-arrival airport).

7.2. SHORT-HAULS REPLACED BY GROUND TRANSPORTATION

For all the short haul, the flight connection is replaced there by a model for the ground transportation. The value taken for the emission will be based on the Thalys figures considered as an average comparatively to other train emission :(TGV : 2,4 g $CO2$ /km, Thalys : 8,6 g $CO2$ /km ,Eurostar : 11,45 g $CO2$ /km, Gala : 8,4 g $CO2$ /km, Alleo : 9 g $CO2$ /km: https://www.oui.sncf/aide/calcul-des-emissions-de-co2-sur-votre-trajet-en-train
Alternative scenario could be considered in the future with different values for the emission.

7.3. DISRUPTION MANAGEMENT WITH VARIOUS USECASES

7.3.1. INTRODUCTION

In our approach only two use cases will be addressed, considering that they are the mains causes of delay in our current operations. Other use cases will be defined in the future such as airspace closure or others.

7.3.2. USECASE WEATHER

For this use case we consider that a part of the airspace will create significant delays for the air transportation. This will be done by a random selection of a group of city pairs in a given area of operation. The delay introduce will vary according to the size of the area of perturbation. In term of emission impact is will be connected to the duration of the flight only not to the evaluation of Gaz emission need to keep the navigability in difficult weather operation.

7.3.3. USECASE AIRPORT CLOSURE

For this use case one of the major hubs is close and the traffic should be diverted to neighboring airports.

11 CONCLUSIONS

However, taking into account that for short haul flights alternative means of transportation may be a viable option, DCB can be addressed in a wider scope by considering surface vehicles along aircraft.
A side effect of this holistic approach is the ability to cope with disruptive events. The present work describes a simulation and optimization model tailored to this particular problem. It has been addressed by a set of scenarios, use cases and by consideration on the real travel time, emission and cost of operation. The future work will allow to run the scenarios on various type of airspaces and to provide useful conclusions for the new way to approach the demand capacity issues in the coming years.

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