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Jacek SKORUPSKI
Warsaw University of Technology, Faculty of Transport
Koszykowa 75, 00-662 Warszawa, Poland
Corresponding author. E-mail: jsk@it.pw.edu.pl

DYNAMIC METHODS OF AIR TRAFFIC FLOW MANAGEMENT

Summary. Air traffic management is a complex hierarchical system. Hierarchy levels can be defined according to decision making time horizon or to analyze area volume. For medium time horizon and wide analysis area, the air traffic flow management services were established. Their main task is to properly co-ordinate air traffic in European airspace, so as to minimize delays arising in congested sectors. Those services have to assure high safety level at the same time. Thus it is a very complex task, with many goals, many decision variables and many constraints.

In the paper review of the methods developed for aiding air traffic flow management services is presented. More detailed description of a dynamic method is given. This method is based on stochastic capacity and scenario analysis. Some problems in utilization of presented methods are also pointed out, so are the next research possibilities.

DYNAMICZNE METODY ZARZĄDZANIA PRZEPŁYWEM STRUMIENIA RUCHU LOTNICZEGO

Streszczenie. System zarządzania ruchem lotniczym jest złożonym systemem hierarchicznym. Poziomy hierarchii można wydzielić w zależności od długości horyzontu czasowego podejmowanych decyzji oraz od wielkości obszaru analizy. Dla średniego horyzontu czasowego i dużego obszaru analizy powołano służby zarządzania przepływem strumieniu ruchu lotniczego. Zadaniem ich jest właściwa koordynacja ruchu lotniczego w obszarze europejskim tak, aby zminimalizować czasy opóźnień związanych z przebywaniem w przestrzeniach o dużym natężeniu ruchu, przy jednoczesnym zachowaniu wysokiego poziomu bezpieczeństwa ruchu. Jest to bardzo złożone zadanie wielokryterialne o wielu zmiennych decyzyjnych i wielu ograniczeniach.

W artykule przedstawiono przegląd metod opracowanych na potrzeby wspomagania służb zarządzania przepływem strumieni ruchu lotniczego. Bardziej szczegółowo omówiono metodę dynamiczną, opartą o pojęcie pojemności stochastycznej oraz o analizę scenariuszy. Wskazano problemy przy stosowaniu omówionych metod oraz kierunki dalszych badań.

1. INTRODUCTION

Air traffic management is a complex hierarchical system. Hierarchy levels can be defined according to decision making time horizon or to analysis area volume. For medium time horizon and wide analysis area, the air traffic flow management (ATFM) services were established. Their main task is to properly co-ordinate air traffic in European airspace, so as to minimize delays arising in congested sectors. Those services have to assure high safety level in the same time. Thus it is very complex task, with many goals, many decision variables and many constraints.

The continuous growth of the air transportation industry has put an enormous strain on the aviation system. Congestion phenomena are persistent and arise almost on a daily basis as a consequence of bad weather conditions which cause sudden capacity reductions. The resulting delays have a significant economic impact. As a result, ATFM has become increasingly crucial [1].

2. AIR TRAFFIC FLOW MANAGEMENT SERVICES

Airline flights generally follow structured traffic streams that are limited in the number of flights they can safely accommodate. When the airspace capacity drops below the demand (e.g., due to weather) or when traffic exceeds the available capacity, air traffic controllers must reduce the traffic on the impacted stream to acceptable levels. Air traffic flow management (ATFM), therefore, involves careful planning and re-planning, requiring controllers to react and anticipate developments in a dynamic system in order to keep traffic flowing without compromising safety [9].

Bad weather is one of the major causes of congestion in the airspace. Convective weather, winds, precipitation, and reduced visibility may make certain airspace regions not available for aviation or require greater separation between flights. In both cases airspace capacity is reduced. Under adverse weather conditions, ATFM often becomes necessary in order to reduce airborne holding and avoid overloading Air Traffic Control (ATC) facilities [4].

Typical ATFM actions include ground delay and ground stops, in which certain flights are delayed from their scheduled departure times, rerouting to avoid weather-affected regions, and delaying flights already en route. Among these actions, ground holding is the most common because ground delay imposes less cost, controller workload, and risk than airborne delay. Most ground delays are implemented in response to airport capacity reductions caused by adverse weather, but they are also sometimes used to mitigate capacity reductions in the airspace.

Rerouting flights is another common ATFM technique. Rerouting reduces the need for ground delays when severe weather impacts multiple airspace sectors. The reroutes are usually selected from a standard set developed for common adverse weather scenarios in the airspace.

3. SELECTED METHODS FOR ATFM SUPPORT

There is a substantial literature on optimization models to support ATFM decision making. In almost all such models, the objective is to minimize system-wide delay cost, which has two components - ground and airborne delays. Most of the optimization models in the literature are formulated as linear and/or integer programming models. Previous research that considers airspace as well as airport capacity constraints has focused mostly on deterministic cases addressed weather-related uncertainty in routing individual flights. However, their methodology is more relevant to controlling individual aircraft while en route, whereas ATFM requires tools at the planning stage for mitigating demand-capacity imbalances. Uncertainty in resource capacities in ATFM has been addressed mainly in context of the single airport ground holding problem.

3.1. Ground holding methods

ATFM attempts to prevent local demand-capacity imbalances by adjusting the flows of aircraft on a regional basis. Until now, the ATFM have been mainly focusing on airports' congestion. On this subject, the most popular approach, by far, has been the allocation of ground delays to departing flights, i.e., postponing their departure time. A lot of models and algorithms have been developed to detect optimal strategies to assign ground delays to flights.

However, it has become increasingly evident that very significant delays and system throughput degradations have arisen from en-route airspace problems and limitations. One of the implications of the simultaneous presence of airport and en-route airspace constraints is that devising good strategies is a much more complicated task. Any mathematical model developed for this purpose has to consider a true network of capacitated elements, en-route sectors and airports. Moreover, a larger set of options to resolve congestion is available: ground holding, airborne holding, miles-in-tails and rerouting, i.e., the possibility of reroute a flight on a different flight path if the current route passes through a region that unexpectedly becomes congested.

3.2. Re-routing methods

As opposed to the airport congestion case, the research literature dealing with en-route congestion is quite sparse. There exist some models however, for instance:

– a multi-commodity minimum-cost flow on a time-space network to assign airborne and ground delay to aggregate flow of flights, commodities of the network flow model,
– disaggregate deterministic 0-1 integer programming models for deciding ground and airborne holding of individual flights in presence of both airport and airspace capacity constraints,
– deterministic 0-1 integer programming model to decide on the departure time and sector occupancy time of each aircraft.

Modeling rerouting decisions has posed one of the greatest challenges in this field of research. The main goal is to develop the model which helps to decide the time of departure, the route, the time required to cross each sector and the time of arrivals taking into account the capacity of all sectors and airports. The main feature of the model has to be the formulation of rerouting decisions in a very compact way.

3.3. Dynamic methods - stochastic capacity and scenario analysis

Rerouting decisions as well as the ground delay decisions, are based on weather forecasts that are subject to considerable error. Convective weather forecasting skill at the 2-5 h timescale on which strategic ATFM decisions must be based remains rather low. While ATFM decision makers recognize weather uncertainty, they lack tools that support probabilistic decision making. Incorrect forecasts may force airborne flight re-planning, but this is done tactically rather than as part of a unified, probabilistic, dynamic decision-making framework. One reason for this is that probabilistic weather forecasts are not widely available. Research on developing probabilistic weather forecasting tools and integrating them into ATM decision support is, however, currently underway [4].

Thus, it is necessary to develop models that can use probabilistic information to efficiently manage air traffic flows. In this paper a method to support ground holding and flight rerouting decisions when adverse weather reduces the capacity of an airport and its surrounding terminal area, and when information about future weather and its capacity impact is uncertain and evolving is presented in brief. More on this method can be found in [5, 6, 7]. This method may be useful to support ground holding decisions in situations in which capacity of the destination airport is reduced as the result of bad weather. It also helps in the cases when dynamic rerouting decisions are related to evolving information about future weather. It could help a traffic flow manager determine whether to hold a flight, release it and risk airborne holding if terminal area or airport weather does not improve, or release it with the possibility that that a reroute may be required once it reaches a destination airport. Moreover, the choices among these options are informed by the prospects for more reliable weather forecast information becoming available as time progresses.

In relationship with the fact, that the calculations of future capacity of region of airport are burdened with uncertainty we can define a random variable D_t, defining capacity of airport at certain moment t in the future. Moreover, there should be rather used the term: expected value of future capacity. The random variable D_t is dependent on the occurrence of phenomena causing the change of capacity.

Unfortunately, some of these phenomena also have probabilistic character and we can only talk about the occurrence of premises suggesting the change of capacity. It is possible for these premises to try determine the probability of occurrence of the phenomenon to which the given premise testifies.

It is assumed that the problem is considered for one day, it means the following moments are considered:

$$j: j=t_1,t_2,...,t_K \tag{1}$$

where: t_1 - the moment of beginning of traffic in a given airport, t_K - the moment of end of traffic.

The number and length of time intervals depends on the speed of changes of the phenomenon causing the change of capacity. In hitherto existing investigations of this type the most often met is the division of day on 1 hour sections.

Now, the value of random variable D_t, , i.e. the expected value of the capacity of airport at moment t will be calculated. The calculations will be done for:

- the constant known value of lowering of capacity,
- the change in capacity, whose value is defined by certain distribution of probability,
- the change lasting for one time interval
- as well as for a change lasting for several time intervals.

Constant value of change of capacity, time of duration of change - 1 interval

It is assumed, that in moment k there becomes recognised the premise on the basis of which the prognosis is formulated, that in moment x the change of capacity of the sector will happen. Let's put that the change of capacity will depend on its lowering by a constant value δ_C. Moreover, this change will last for one time interval x only. The probability, that the change prognosed at the moment k, will really happen at the moment x is equal to P_k^x.

The probabilities of capacity at the moment x are then equal to

$$P(D_x = C_T - \delta_C) = P_k^x \tag{2}$$

$$P(D_x = C_T) = 1-P_k^x \tag{3}$$

The expected value of capacity of the region of airport at the moment x, defined at the moment k is therefore

$$E(D_x) = (C_T - \delta_C) \cdot P_k^x + C_T \cdot (1 - P_k^x) = C_T - P_k^x \cdot \delta_C \tag{4}$$

Variable value of change of capacity, time of duration of change - 1 interval

It is assumed, that in moment k there becomes recognised the premise, authorising to presumption, that at the moment x lowering of capacity will happen. The extent of this lowering is a random variable, which takes values $\delta_C=\delta_0, \delta_1,..., \delta_{DM}$. On the set of value δ_C it is possible to determine the distribution of probability of their occurrence.

$$R_{\delta_C} = \sum_{i=0}^{DM} R_{\delta_i} = 1 \tag{5}$$

Therefore the expected value of of the lowering of capacity will be

$$E(\delta_C) = \sum_{i=0}^{DM} \left(R_{\delta_i} \cdot \delta_i \right) \tag{6}$$

The formula for the expected value of capacity at the moment x, prognosed at the moment k can therefore be modified to the form:

$$E(D_x) = C_T - P_k^x \cdot E(\delta_C) = C_T - P_k^x \cdot \sum_{i=0}^{DM} \left(R_{\delta_i} \cdot \delta_i \right) \tag{7}$$

Constant value of change of capacity, time of duration of change - several intervals

In the case of taking the length of time interval equal 1 hour it is possible, that the change in capacity will last for one time interval. However, both in this case, and in the case of shorter time intervals it is extremely probable that the change in capacity will keep on for at least several time intervals.

Let's accept therefore that at the moment k the occurrence of the premise has been affirmed, on basis of which it is possible to formulate the prognosis, that in time intervals $x_0,x_1,...,x_L$ there will occur lowering of the capacity by a constant value δ_C.

Then

$$\forall x_j \in (x_0, x_1, \dots, x_L) \qquad E(D_{xj}) = C_T - P_k^{x_j} \cdot \delta_C \tag{8}$$

If the probabilities of occurrence of assumed constant reduction in capacity are equal in each time intervals, then obviously $P_k^{x_0} = P_k^{x_1} = \dots = P_k^{x_L} = P_k^{x}$. One can assume, however, that these probabilities are different, in dependence on the number of time intervals. For example the smallest in time intervals x_0 and x_L, whereas the largest in the centre of the time interval $[x_0,x_L]$.

Variable value of change of capacity (the same distribution), time of duration of change - several time intervals

Here it is assumed, that for each time interval $[x_0,x_L]$ there is prognosed the possibility of occurrence of lowering of capacity of different intensity. It is a random variable, taking values $\delta_C=\delta_0$, $\delta_1,...,\delta_{DM}$ (Fig.1). It is also assumed that for every time interval x_j for the set of values δ_C the identical distribution of probability can be determined.

$$\forall x_j \in [x_0, x_L] \qquad R_{\delta_C} = \sum_{i=0}^{DM} R_{\delta_i} = 1 \tag{9}$$

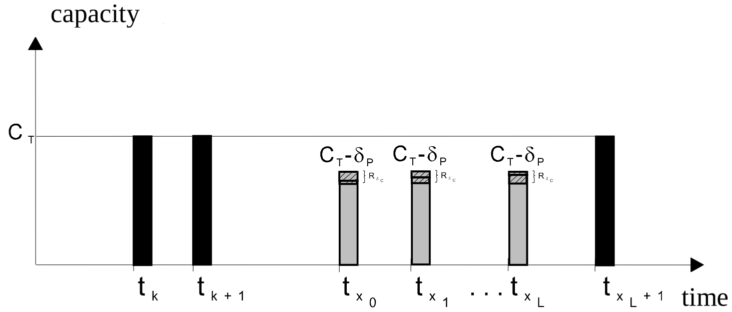

Fig. 1. Variable value of change of capacity (the same distribution), time of duration of change – several intervals

Rys. 1. Losowa zmiana pojemności (taki sam rozkład), czas trwania zmiany – kilka przedziałów

Therefore the expected value of lowering of capacity will be the same for each section of the considered time interval $[x_0,x_L]$ and it will be

$$E(\delta_C) = \sum_{i=0}^{DM} \left(R_{\delta_i} \cdot \delta_i \right) \tag{10}$$

The formula for expected value of capacity at the moments x_j,, prognosed at the moment k can be therefore modified to the form:

$$\forall x_j \in (x_0, x_1, \dots, x_L) \qquad E(D_{x_j}) = C_T - P_k^{x_j} \cdot E(\delta_C) = C_T - P_k^{x_j} \cdot \sum_{i=0}^{DM} \left(R_{\delta_i} \cdot \delta_i \right) \tag{11}$$

Variable value of change of capacity (any distribution), the time of duration of the change - several time intervals

Let's now consider the case, when in each section of time interval of lowered capacity $[x_0,x_L]$ the intensity of reduction of capacity is given with a different distribution of probability. Then one should define the whole family of distributions of probability with the following form:

$$R_{\delta_C}^{x_j} = \sum_{i=0}^{DM} R_{\delta_i}^{x_j} = 1 \quad , \quad where \ x_j \in \left(x_o, x_1, \dots, x_L \right) \tag{12}$$

For each of considered sections x_j of lowered capacity the expected value of magnitude of reduction will be in this case

$$E(\delta_C^{x_j}) = \sum_{i=0}^{DM} \left(R_{\delta_i}^{x_j} \cdot \delta_i \right) \tag{13}$$

Finally the expected value of capacity at the moments $x_j \in (x_o, x_1, \dots, x_L)$, prognosed at the moment of occurrence of the premise *k* will be given by the following formula:

$$E(D_{x_j}) = C_T - P_k^{x_j} \cdot E\left(\delta_C^{x_j}\right) = C_T - P_k^{x_j} \cdot \sum_{i=0}^{DM} \left(R_{\delta_i}^{x_j} \cdot \delta_i\right) \quad , \quad x_j = x_0, x_1, \dots, x_L \tag{14}$$

Scenario analysis

The detailed rules of co-operation of ATC services with the ATFM services have not been so far defined exactly. So it is also not defined when the information about a foreseen change in capacity should be passed on to the ATFM organ. In this case it is useful to propose certain mathematical model. In this model there will be used observation, that the assessment of premise inducing us to undertaking prognose can evolve in the time. The following scenarios are possible:

1. The premise to change of capacity is entirely incorrect – the capacity will not change.
2. The premise is underestimated – the capacity will change to the foreseen extent, but earlier.
3. The premise is underestimated – the capacity will decrease, but to larger extent.
4. The premise is overestimated – the capacity will decrease, but later than prognosed.
5. The premise is overestimated – the capacity will decrease, but less than assumed.
6. The assessment of validity of premise is correct – the capacity will be in accordance with the prognosis.

Of course, there are possible intermediate cases (especially for points 2 and 3 as well as 4 and 5), but we will not consider these for the reason of simplifying.

Let's put that the expected value of capacity $E(D_{xj})$ is given in each time interval in which we prognose its lowering.

For each of moments *j* we can determine the number of aircrafts N_j landing on the airport in the time interval *j*.

Let's define moreover N_{sj} as the number of aeroplanes, which start at the moment *s* and land on studied airport at the moment *j*. Let's notice, that

$$N_j = \sum_{s=t_0}^{t_j} N_{sj} \tag{15}$$

assuming, that all moments preceding t_1 are marked as t_0.

Let’s mark by M_{kj} the number of aeroplanes which can be stopped on the ground at the moment *k*, i.e. the aeroplanes, which have not taken off by the moment *k*, and whose planned arrival is to take place at the moment *j*. We can see, that

$$M_{kj} = \sum_{s=t_o}^{t_k} N_{sj} \tag{16}$$

If $N_j - E(D_{x_j})$ is positive we have to deal with the case when one should limit the traffic because the capacity has been surpassed. In the opposite case it is possible to wait for a more detailed premise to induce us to prognose.

Let's accept like previously, that premise has been observed at the moment *k* and on the basis thereof we prognose, that at the moment *x* lowering of capacity to value $E(D_x)$ will happen. Knowing, that the probability that observed premise will cause occurrence of phenomenon reducing the capacity is equal P_k^x we can formulate the following task of multi-criterion programming:

$$\begin{aligned} & \max M_{jx} \\ & \min \varepsilon_j^x \\ & bounded: \\ & N_x - E(D_x) > 0, \\ & N_x, M_{jx} \geq 0 \ and \ \text{int} \\ & j = k, k+1, \dots, x \end{aligned} \tag{17}$$

where: ε_j^x is the measure of error made during prognosing at the moment *j* about the change of capacity at the moment *x*.

This error is the largest in the case, when probability that the capacity at the moment x is D_x, equals $\frac{1}{2}$, whereas the smallest when this probability is equal 0 or 1. It is possible therefore to define it as follows:

$$\varepsilon_j^x = 1 - \left|1 - 2 \cdot P_j^x\right| \tag{18}$$

which means that

$$\varepsilon_j^x = \begin{cases} 2 \cdot P_j^x \; for P_j^x \leq \frac{1}{2} \\ 2\left(1 - P_j^x\right) for P_j^x > \frac{1}{2} \end{cases} \tag{19}$$

This task can be, of course, reduced to a one-criterion problem, by transfer of the criterion of maximisation of the number of aeroplanes which can be delayed on the ground to the boundary conditions. It can be done as follows:

$$\begin{aligned} &\min \varepsilon_j^x \\ &bounded: \\ &M_{jx} \geq N_x - E(D_x) \\ &N_x - E(D_x) > 0, \\ &N_x, M_{jx} \geq 0 \; and \; \mathrm{int}, \\ &j = k, k+1, ..., x \end{aligned} \tag{20}$$

Obviously this second formulating can lead to solutions which give a lot fewer possibilities of intervention for the ATFM services. In the boundary situation this intervention would be stopping on the ground all aeroplanes landing on the studied airport at the moment x, for which this is possible. Such solutions cannot be accepted by the ATFM services.

The task is strongly dependent on time. Probability P_j^x may undergo changes in time because factors taken into account in prognosis change, confirming or denying the put forward thesis. Time in this problem is considered in the form of temporary moments $j=k,k+1,...,x$, so it is in discrete form.

This suggests the possibility of defining the task with the use of the methods of Dynamic Programming. The formulation of this task is following.

At the stage j (at time moment j) decide whether to inform the ATFM services about appearing of the lowering of capacity. This means that possible decisions are:

$$x_j = \begin{cases} 1 \quad if \;\; ATFM \; has \; been \; notified \\ \quad 0 \; if \;\; contrariwise \end{cases} \tag{21}$$

The state of the system is equal to:

$$s_j^x = M_{jx} - \left(N_x - E(D_x)\right) \tag{22}$$

which corresponds to the number of aeroplanes, by which the number of aeroplanes possible to be delayed on the ground is larger than the shortage of capacity of the target airport.

$f_j(s_j^x, x_j)$ - the minimum error of prognose at the moment j about capacity at the moment x, with the assumption, that the state of system is equal s_j^x , and that at the time moment j the decision x_j about informing or non informing the ATFM services about change of capacity was taken.

$f_j\left(s_j^x\right)$ - the minimum error of prognose at the moment j about capacity at the moment x, with the assumption, that the state of system is equal s_j^x.

With so defined a problem of Dynamic Programming we can determine recurrent dependence:

$$f_j\left(s_j^x, x_j\right) = \begin{cases} \varepsilon_j^x \;\; if \;\; x_j = 1 \; or \; s_j^x \leq 0 \\ \min(\varepsilon_{j+1}^x, \varepsilon_{j+2}^x, \ldots, \varepsilon_{x-1}^x) \; if \;\; x_j = 0 \quad and \;\; s_j^x > 0 \end{cases} \tag{23}$$

If we accept, that the value of variable of state for which we take the decision $x_n=1$ is not equal zero, but to certain minimum value set by the ATFM service, one should suitably modify the above mentioned recurrent dependence.

4. CONCLUSIONS

Applying optimization methods in ATFM is the key to increase airspace efficiency. Many delays and risks are inevitable if within next few years decision making in ATFM is not optimized. The ideas presented in this paper address stochastic capacities, which is necessary to implement decision-making tools in practice. In the future years, along with research on optimizing ATFM, efforts must be put to implement those tools in real world decision making.

In most cases, the dynamic rerouting model releases flights with lower ground delays compared to the static route choice model. When the unit cost of airborne delay is so high as to foreclose trades between airborne and ground delay, or, when the airport is the only bottleneck, there is little or no benefit from rerouting. In cases where the airport is the main, but not the only, bottleneck, the dynamic model may assign higher ground delay than the static model so that rerouting decisions can be deferred until more information on en route weather becomes available.

Further research is required to address problems in which the scenario probabilities themselves are uncertain. Such problem can however be solved by constructing a scenario tree with a distribution of probabilities of occurrence of scenario branches. However, if the weather forecasts provide completely new information, the problem may not be solvable by purely dynamic programming techniques. Such problem will require approximations and heuristic methods to achieve solutions.

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