STRATEGIC CONFLICT PROBABILITIES IN THE EUROPEAN AIR TRAFFIC MANAGEMENT NETWORK

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Abstract

The complexity of European Air Traffic is accompanied by a continuous risk of conflicts between aircraft. In particular, inaccurate forecasts of aircraft positions prevent a fail-proof prediction of conflicts, especially for large look-ahead times. Uncertainty of departure times is one of the most important factors in trajectory prediction. Therefore, we compute strategic conflict probabilities between planned trajectories with stochastic departure times. First, potentially conflicted flight pairs are geometrically identified and further interpreted to gain critical periods of time in which conflicts would materialize with a given probability. Conflict probabilities of planned trajectories of a complete daily traffic sample are calculated. Results dissect the dependency of conflict probabilities on departure time deviations and on conflict geometry. Finally, an upper bound of strategic conflict reduction by strategic time shifts is computed.

1. INTRODUCTION

A conflict between two aircraft in flight occurs when these aircraft converge in space and time so that the effective separation minima may become violated. Conflicts are resolved by air traffic controllers who provide instructions to prevent separation violations. To improve safety, the Single European Sky ATM Research program seeks to reduce conflicts strategically [1]. It is intended to realize conflict reduction in the scope of strategic and pre-tactical Air Traffic Flow Management measures by incorporating respective traffic forecasts.

Inexact forecasts of aircraft positions prevent a precise prediction of conflicts, especially for large look-ahead times. In Europe, more than half of all flights deviate more than five minutes from their estimated departure time [2]. However, commercial jet aircraft at typical cruise speed cover a distance of more than forty nautical miles within this time period, representing eight times the lateral en-route separation of five nautical miles. Known methods to quantify conflict probabilities are mostly intended for short forecast horizons [3,4]. Studies on pre-flight deconfliction under uncertainty are limited to time-deviations of less than five minutes [5,6,7]. Understanding probabilities of conflicts in the strategic planning phase allows assessing the potential for strategic trajectory deconfliction and flight plan pre-processing to increase flight safety.

We present a method to compute strategic conflict probabilities between planned trajectories. Trajectory predictability before take-off is affected by the departure, so that the uncertainty before take-off is larger than afterwards [8]. Therefore, statistical departure time deviations are chosen to represent all stochastic deviations from the planned trajectories without considering spatial deviations. Probabilities for deviations from estimated departure times are inferred from respective statistics about planned and actual departure times [2].

Conflicts are spread in space [9], therefore conflicted flight pairs are analyzed geometrically. A spatiotemporal interpretation of potential conflicts yields exactly which trajectory points are in conflict with each other's. From these points and their respective time differences, a conflicted time window of conflicted departure time combinations is computed. The conflicted time frames are combined with their departure time probabilities to gather strategic conflict probabilities. Peak conflict probability prevails when two flights are scheduled to arrive in the same area at the same time. Conflicts may also arise between flights which are delayed, so conflict probabilities between delayed flights are also quantified. Moreover, each flight can have several conflicts.

Strategic conflict probabilities of planned trajectories of a complete day are calculated. Results show the conflicted trajectory nodes (referred as trajectory points in this study), conflicted time windows and conflict probabilities. The resulting conflict probabilities can be used to assess the potential for reducing conflict probabilities by strategically shifting a flight in time.

2. EUROPEAN AIR TRAFFIC MANAGEMENT NETWORK

To be able to generate a comprehensive flight plan data set, airlines have to file their flight plans to the Integrated Flight Plan Processing System (IFPS) operated by Eurocontrol. The system initially receives processes and distributes flight plan data for all Eurocontrol member states according to the Initial Flight Plan Processing Zone (IFPZ). A flight plan data set generally contains aircraft ID, arrival and departure aerodromes, intermediate navigation points along the planned route and respective timestamps. Flights have to adhere to pre-defined routes and are restricted to different flight levels, depending on their heading.

The European airspace is divided into ATC sectors, in which air traffic controllers make sure that minimum separation is maintained at all times. If two aircraft converge in space and time so that a loss of separation is threatened, a conflict occurs. To resolve these conflicts, controllers give instructions to the pilots. Depending on the number of converging aircraft within an ATC sector at a specific time and the prevailing traffic situation, these instructions may dominate actual controller workload which again impacts sector capacity. Air Traffic Control generally applies a safety margin controller workload which could be adapted when conflict forecast is improved.

In contrast to losses of separation, the definition of conflicts lacks precise conditions for look-ahead time or severity within different planning stages. It is therefore important to not only define conflicts as ad-hoc events, but also to shape definitions of conflicts of different prediction quality. Therefore, this study addresses conflict probabilities at the strategic ATFM planning level with longer look-ahead times. A strategic conflict occurs when there is a violation of the lateral and vertical separation minima between two planned point-profiles in at least one discrete node in space and time [11]. Because many airlines file their flight plans up to six months in advance, there is a strategic flight plan information resource which is utilized within this study

3. STRATEGIC CONFLICT PROBABILITIES

To compute the strategic conflict probability between two flights with uncertain departure times, all conflicted departure time combinations have to be considered. To identify exactly, which departure time combinations are in conflict, neither the time difference between a single conflicted trajectory point pair, nor the time difference of entering a conflicted area is sufficient. To be precise, the time differences of all conflicted point pairs are necessary. Departure time deviations represent overall trajectory time deviations since planned flight trajectories are assumed to be deterministic in this study. Strategic conflict probabilities constitute joint probabilities of departure time combinations which lead to a conflict between two planned trajectories.
At first, we compute uncertainty of departure time deviations. Second, we identify all trajectory pairs which are possibly in conflict. This demands at least a minute-based trajectory time granulation. Third, we perform a trajectory point interpolation with second based precision and exactly identify which point pairs are in conflict. Consequently, the conflicted time window is identified as the set of all time-differences of the conflicted point pairs. The strategic conflict probabilities are given by the joint probabilities of all departure time combinations, which are identified to be within the conflicted time windows.

3.1. Trajectory Uncertainties in Time

In this study, uncertainty in time prediction of trajectories is represented by departure time uncertainty. The probabilities for different departure times are given by the planned departure times and the probabilities for deviations from the planned departure time. A probability mass function for departure time deviations is extracted from Eurocontrol statistics [2]. The statistics for deviations[1] are given in several intervals (which are not bound negatively or positively). We use the mean value of each interval for the probability of each minute to create the following probability mass function (FIGURE 1). The distribution has imperfect information about the boundaries and is cut at -30 and +120 minutes.

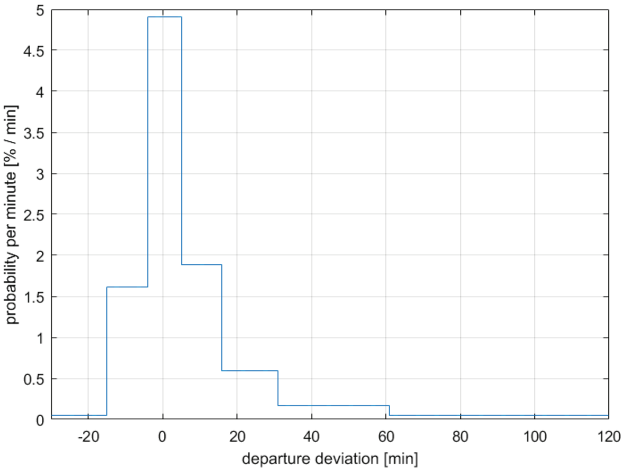

FIGURE 1. Probability mass function of deviations from planned departure times

The probabilities for departure deviations are interpolated for each second interval. The probability mass function for departure time differences is calculated by the autocorrelation of the departure time deviations (FIGURE 2). The autocorrelation computes the sum of all probabilities of departure time combinations which result in each departure time difference. Kinks of the probability mass function result from the discrete base data of FIGURE 1.

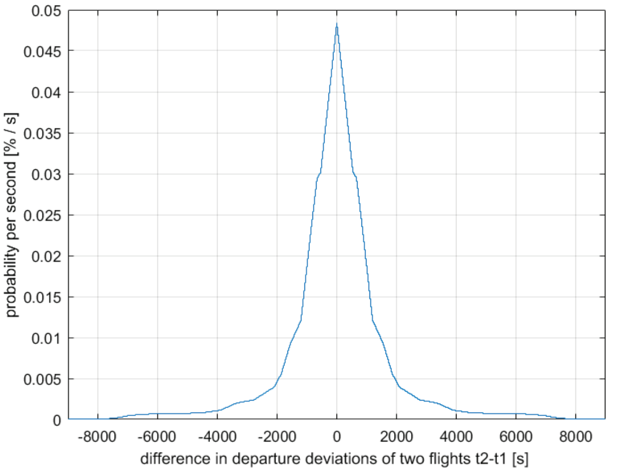

FIGURE 2. Probability mass function of differences in departure deviations between two flights. The probabilities are given for intervals of one second length

A time difference between two points on individual trajectories can be equalized by a departure time difference. For example, when one trajectory point is planned to be reached 7010s before the point of another flight is reached, a departure delay of the same 7010s for the first flight would yield that both points are reached at the same time. In fact, any combination of departure deviations that result in the equalization of the 7010s means that both points are reached at the same time.
The probability that two aircraft arrive at two points at the same time is determined by the effective departure time probabilities. The effective departure times for both flights

[1] CODA sample of 69.1% of commercial flights in the European Airspace (ECAC region) 2014

are the departure time combinations that equalize the planned time difference. The probabilities for the effective departure time combinations are given by the probability that the departure times deviate exactly for the amount of the planned time difference. (Probabilities of differences in departure time deviations are shown in FIGURE 2.) From the distribution of the differences of time deviations follows that only for time deviations of less than 150 minutes at conflicted point pairs there are nonzero conflict probabilities.

3.2. Detection of Strategic Conflict Geometries

Potential conflicts between trajectories and the involved point pairs need to be identified. The spatial condition for a conflicted point pair is a maximum distance of 1000ft vertically and 5nm laterally. When the distance of two points on different trajectories is below these values, but there is a separation in time, there is still a conflict potential, because of the stochastic character of departure times. All potential conflicts with a maximum time difference of 120 minutes are taken into account.
To achieve acceptable calculation times, a grid approach is used [11]. Only trajectory points in neighboring grid cells are checked for conflicts with each other. Planned trajectories are interpolated linearly from DDR2 data[2] with second based accuracy so that there are the initial points and at least one point at the start of every minute. The points are added to the respective grid elements and all grid elements are searched for potential conflicts.
Potentially conflicted trajectory segments are interpolated in second intervals to accurately identify the conflicted parts. The conflict geometry in space and time can be described by the combination of all conflicted point pairs.

FIGURE 3 introduces an exemplary conflict between two flights. Only the conflicts of the last conflicted point of flight 2 are shown, so that the visualization of the conflicted point pairs is introduced. The exemplary conflict is used throughout this chapter to illustrate the concept.

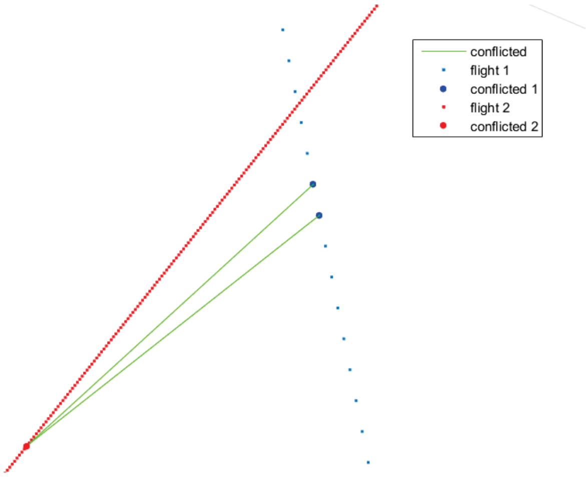

FIGURE 3. Extract of exemplary conflicted points of two trajectories with second-interval interpolation in three dimensions. Flight 1 moves slower in the image projection than flight 2. Conflicts for the last conflicted point of flight 2 are shown

[2] EUROCONTROL DDR2 flight plan trajectories

FIGURE 4 shows all conflicted point pairs of the two exemplary flights. These point pairs span the conflicted space and form the conflict geometry (green). In this example, the peripheral points have fewer conflicts than the central points. The central points have more conflicts because the trajectories are crossing each other. For each point pair, the planned arrival time difference is known from flight times and planned departure times.

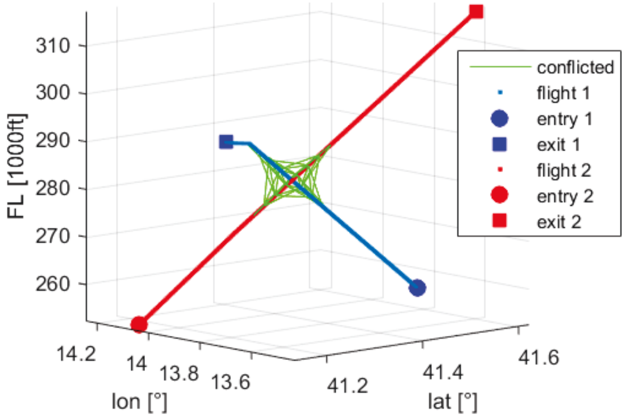

FIGURE 4. Points of two exemplary trajectory-segments with marked entry (circle) and exit (square). Every 10th conflict is marked by a green link

3.3. Identification of Conflicted Time Windows

The time window of all conflicted departure time combinations can be extracted from the conflict geometry. A conflicted time window constitutes the set of all time differences between the conflicted points. For the exemplary conflict, the time differences between two trajectories are shown in FIGURE 5 where the conflicted point pairs are pigmented according to their local time difference.

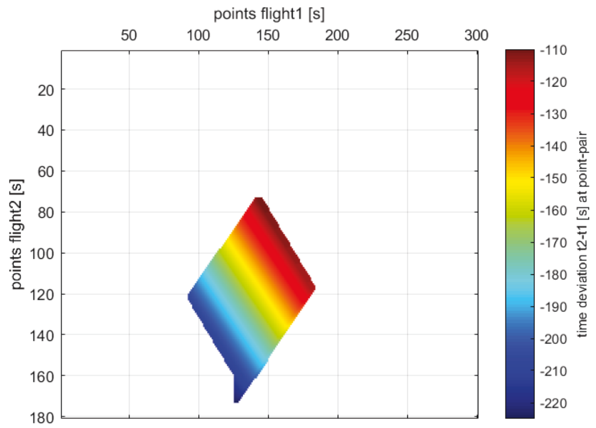

FIGURE 5. Time differences between the two exemplary trajectories at the conflicted point pairs (pigmented). White areas represent point-pairs which are not conflicted

A Monte-Carlo simulation with conflict detection between flights for all possible departure time combinations results in the same conflicted time windows. The presented method is thereby validated against the Monte-Carlo approach, which takes more time to compute.

The number of conflicted point pairs for each departure time difference of the exemplary flights is shown in FIGURE 6. They represent the number of point pairs for each departure time difference of FIGURE 5.

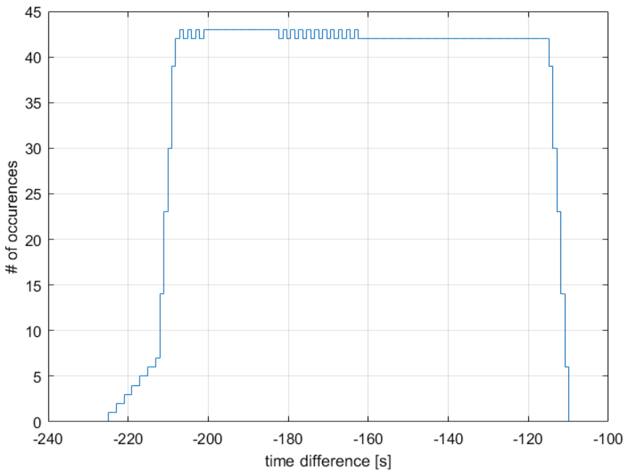

FIGURE 6. Critical time window: Number of conflicted point pairs with each departure time difference for two exemplary flights

Critical flight time differences occur in the interval from -225s to -110s. Therefore, the duration of the critical time window is 116s. With the departure time difference of -115 minutes between the flights, the conflicted time window is given as the interval from -7125s to -7010s. The conflicted time window maps all conflict geometries to the time domain to enable the calculation of conflict probabilities under time uncertainties.

3.4. Calculate Strategic Conflict Probabilities

Strategic conflict probabilities are the sum of the joint probabilities of conflicted departure time combinations. Concerning departure time uncertainties, we use the probability mass function for departure time deviations. Conflict probability is the sum of probabilities of conflicted departure time differences. The probabilities of each conflicted time difference of the exemplary conflict are shown in FIGURE 7.

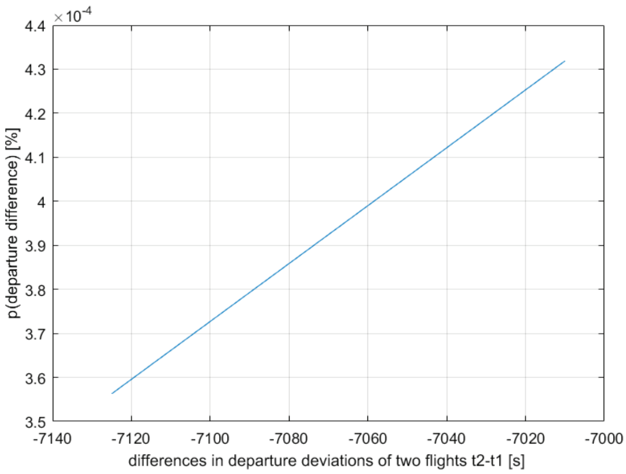

FIGURE 7. Exemplary Probabilities for conflicted departure time deviation combinations of the two exemplary flights

The calculated strategic conflict probability of the exemplary conflict with the conflicted time window from -7125s to -7010s is 0,05%.

To compute strategic conflict probabilities of a full day of European traffic, the presented method of conflicted time windows is applied. Changes of conflict probabilities due to strategic shifts of departure times are also calculated.

4. RESULTS

Strategic conflict probabilities between 28.296 European flights in the IFPZ on 7th June 2012 are evaluated. Trajectories are interpolated so that they have at least one point per minute. Only trajectory points with flight level 100 or more are considered. These are the initial network level trajectory points which are checked to identify conflicted flight pairs. Conflicts between point pairs which have a time difference of maximum two hours are detected. A potential strategic conflict exists, if a flight pair has at least one conflicted point pair (in the following, a strategically conflicted flight pair is referred to as a *conflict*). Conflict detection found 16.936.143 conflicted point pairs which belong to 1.098.828 flight pairs. Without a time difference between the conflicted point pairs, there are 93.441 conflicted point pairs.

The numbers of conflicts for each number of conflicted point pairs are shown in FIGURE 8. Mean number of conflicted point pairs per conflict is 15,4. The maximum number of conflicted point pairs for any conflict is 627 (FIGURE 9).

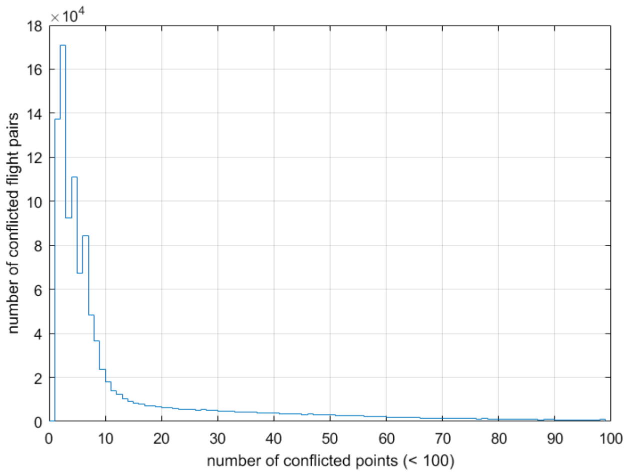

FIGURE 8. Number of conflicted flight pairs over the number of conflicted point pairs smaller than 100

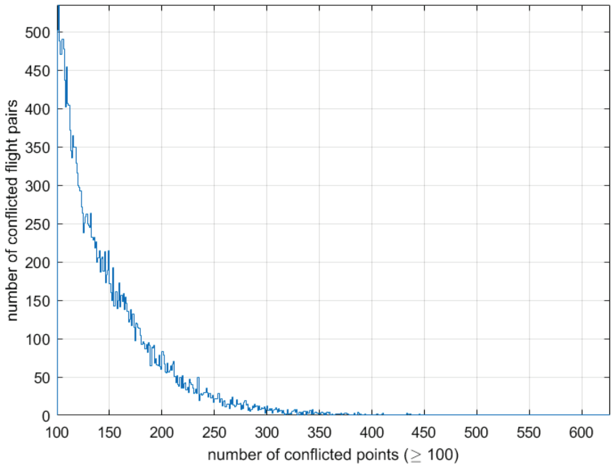

FIGURE 9. Number of conflicted flight pairs over the number of conflicted point pairs greater than or equal to 100

The numbers of conflicts for each length of the conflicted time window (from second based interpolation) for time windows shorter than 500s are shown in FIGURE 10. Mean conflicted time window length is 138,5 seconds.

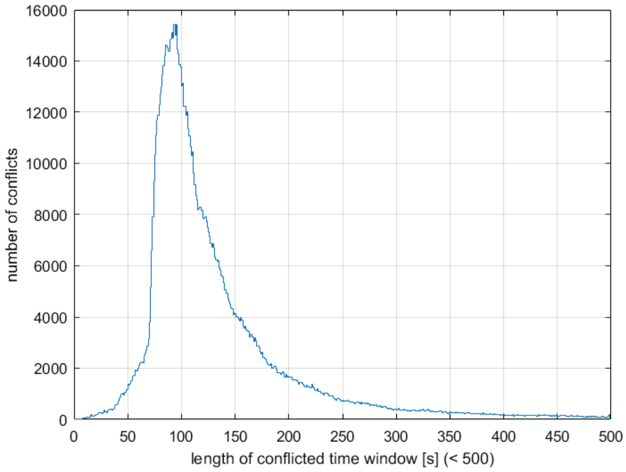

FIGURE 10. Number of conflicts by length of conflicted time windows in one second intervals. Only conflicted time windows shorter than 500s

The numbers of conflicts for each length of the conflicted time window for time windows with at least 500s are shown in FIGURE 11. Maximum duration of the conflicted time windows is 10.138 seconds.

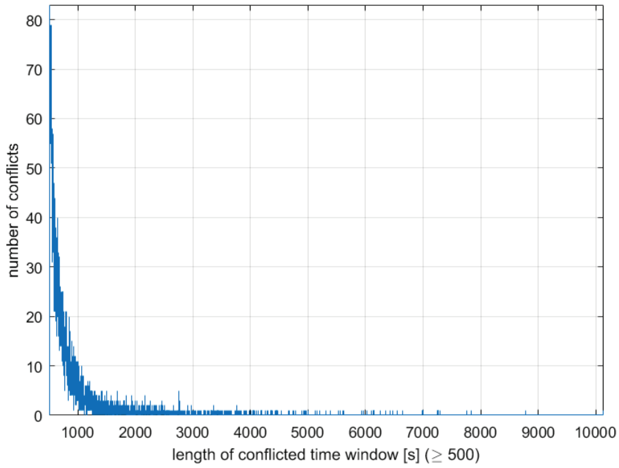

FIGURE 11. Number of conflicts by length of conflicted time windows in one second intervals. Only conflicted time windows with at least 500s

The numbers of conflicts for each strategic conflict probability smaller than 10% are shown in FIGURE 12. Mean probability per conflict is 1%.

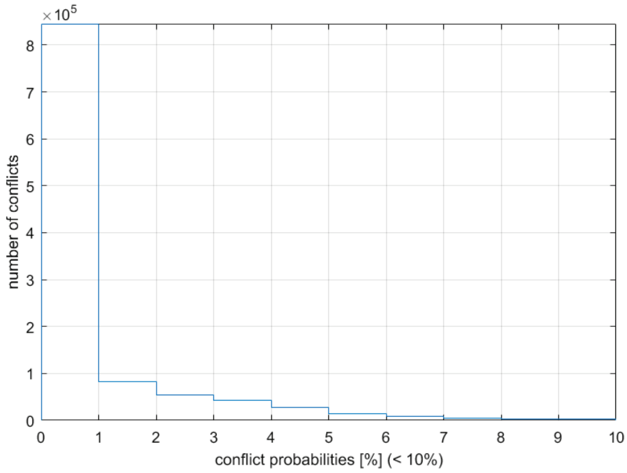

FIGURE 12. Number of conflicts by conflict probabilities in 1% intervals. Only conflict probabilities lower than 10% are shown

The numbers of conflicts for each conflict probability with at least 10% are shown in FIGURE 13. Maximum conflict probability is 96%.

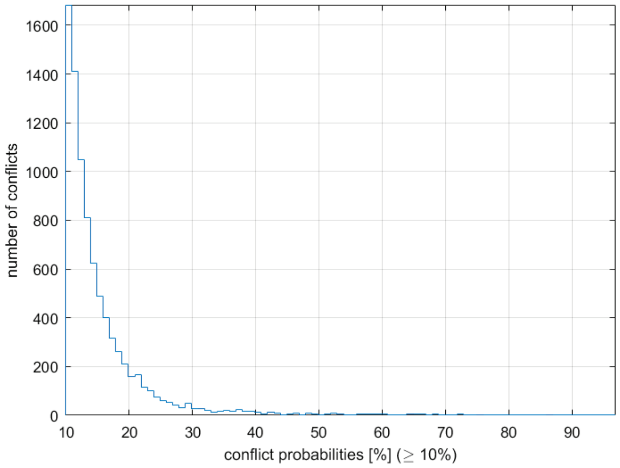

FIGURE 13. Number of conflicts by Conflict Probabilities in 1% intervals. Only conflict probabilities with at least 10% are shown

Numbers of conflicts per flight with ascending number of potential conflicts per flight are distributed as follows (FIGURE 14). Half of flights have 85% of all conflicted points. Around 8,3% of flights have no conflicted points.

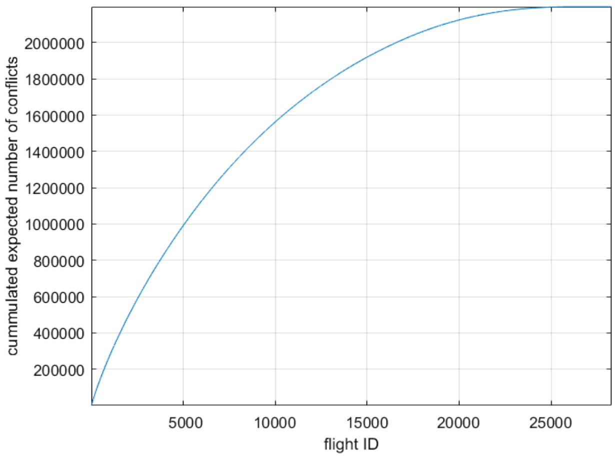

FIGURE 14. Cumulated number of potential conflicts per flight

For each flight, the sum of expected conflict probabilities of all its conflicts can be calculated. The sums of conflict probabilities of flights are cumulated as follows (see FIGURE 15): Half of flights have 85% of total conflict probability.

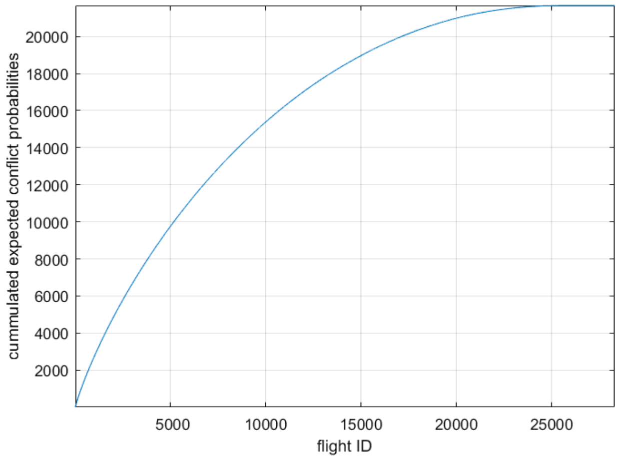

FIGURE 15. Cumulated sum of conflict probabilities for all flight IDs

Conflict probabilities with different conflicted time windows (centered on zero deviation) can be computed. By shifting the time window in time, the conflict probability for every minute of planned timeshift is reduced. This is shown for several time window lengths (FIGURE 16).

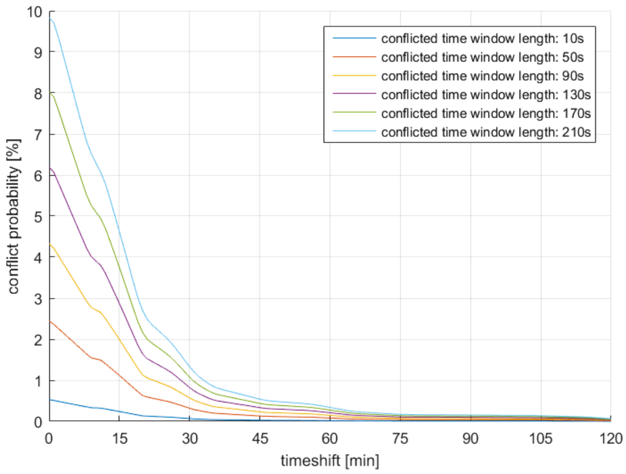

FIGURE 16. Conflict probabilities by timeshift of one flight with different lengths of time windows

The reduction of conflict probabilities by shifting flights in time is shown in FIGURE 17. A shift by 15 minutes yields 49%, a shift by 30 minutes yields 85% and a shift by 60 minutes yields 96% conflict probability reduction.

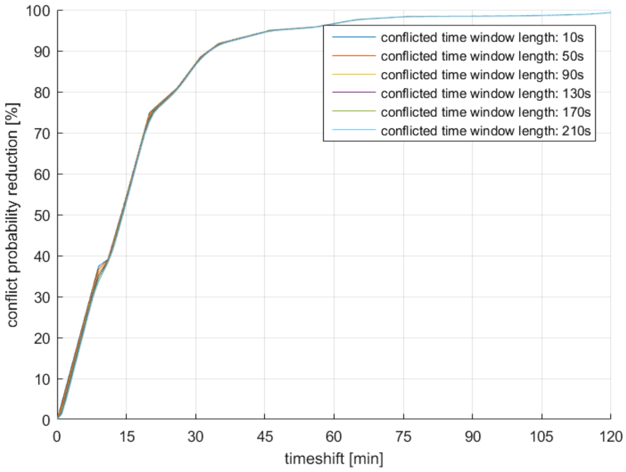

FIGURE 17. Reduction of conflict probabilities by timeshift with different lengths of time windows

5. CONCLUSION

We presented a method to calculate strategic conflict probabilities for planned trajectories under departure time uncertainty. Conflicted trajectory point pairs have been identified with a spatiotemporal analysis resulting in a conflicted time window for each conflict. Conflict probability is defined as a time-related probability that both flights arrive in the conflicted time window. It is shown that conflict geometry and the derived conflicted time window are fundamental factors for conflict probability.

We calculated strategic conflict probabilities between 28.296 European flights in the IFPZ on 7th June 2012. With a time difference of up to 120 minutes between the conflicted points, the number of conflicted flight pairs is 1.098.828. The mean number of potential conflicts per flight is 38. Only 8% of flights are conflict-free. The maximum number of conflicted point pairs (initial network level trajectory points) for one conflict is 627. The mean number of conflicted point pairs per conflict is 15. Mean conflicted time window duration is 138 seconds. Maximum conflicted time window is 10.138 seconds. Maximum probability for a single conflict is 96%. Mean conflict probabilities are only 1%. Half of flights have 85% of total conflict probability. A strategic reduction of conflict probabilities by shifting flight plans yields a maximum reduction of 49% for 15 minutes, 85% for 30 minutes and 96% for 60 minutes.

6. OUTLOOK

The method to calculate conflict probabilities can incorporate more detailed departure deviation statistics, e.g. on an airport-, time- or weather basis. An adaptation of the basic idea to arrival deviations, wind influence or individual statistics for airports is also viable. The method could be extended to lateral and vertical trajectory uncertainties. Improved punctuality or improved trajectory forecasts could reduce the underlying uncertainty of conflict probabilities.

The presented method could be used to calculate strategic conflict probabilities for (re-)planned trajectories and subsequently help in the decision making. To reduce strategic conflict probabilities on a network level, second level conflicts need to be taken into account. Minimal conflict probabilities on the network level could be found by global optimization methods like Integer Programming.

For calculating conflict probabilities in pre-tactical Air Traffic Flow Management with shorter forecast times, pre-tactical departure time uncertainties should be used. In this timeframe, time uncertainties are reduced by updates about e.g. airborne flights or allocated delays. The potential for conflict probability reduction in pre-tactical Air Traffic Flow Management should be assessed accordingly.

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