Aircraft Conflict Prioritization and Resolution Using the Solution Space Diagram
Leonor Pinto Inverno da Piedade
leonor.i.piedade@tecnico.ulisboa.pt
Instituto Superior Técnico, Lisboa, Portugal
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Abstract
To expand airspace capacity without compromising safety under Free Flight conditions, this paper presents a fully decentralized, implicit and automated two-dimensional approach to conflict resolution based on the Solution Space Diagram (SSD). The SSD is a proficient traffic display that aims to assist in detecting, resolving and preventing conflicts in a multi-conflict environment, by combining the aircraft’s performance limits with the Velocity Obstacles (VOs) created by aircraft operating in its vicinity. VOs represent combinations of velocity and heading based on the current states of aircraft involved, which the ownship should avoid to prevent losses of separation. Because satisfactory results have not yet been achieved in previous research, the goal was to improve the SSD as a conflict resolution method by means of conflict prioritization, thereby suggesting a sequential approach. This approach consisted in resolving different subsets of conflicts each time step, based on their urgency. To test the performance of this method, fast-time simulations were conducted in the BlueSky ATM simulator. A comparative performance analysis was conducted using two different sequential resolution strategies, the former global and unprioritized SSD-method and a proficient pairwise strategy, the Modified Voltage Potential (MVP)-method. Sequential strategies had an overall superior performance over the former SSD-method in terms of safety and efficiency, while compromising airspace stability. Nevertheless, the MVP-method still outperformed any SSD-based strategy in most metrics of safety and efficiency. The reason for this lies in undesired behaviors related to uncoordinated and invalid deconflicting maneuvers, which persisted in all SSD-based strategies.

Keywords: Conflict Resolution (CR), Conflict Prioritization (CPrio), Solution Space Diagram (SSD), Free Flight (FF), Airborne Separation Assurance System (ASAS).

1. Introduction
Air traffic has grown excessively during the last few years, with an average increase of 7.4% a year since 2015 [1]. This outstanding annual expansion will soon saturate airspace as we know it, demanding a radical change in the way air traffic is managed and structured [2, 3, 4]. One of the limiting factors of this trend is the increase in Air Traffic Control (ATC) workload, given the more complex traffic patterns and consequent loss in safety. This means that constraining aircraft to predefined airway-based trajectories will no longer sustain the increasing traffic demands [4].

In the hopes of accommodating a further expansion of air traffic without compromising safety, this project is carried out in the scope of the Free Flight (FF) concept. FF is an Air Traffic Management (ATM) concept based on allowing direct routing in airspace, permitting the cockpit crew to fly their optimal route and deviate from their original flight plan without that decision passing by an Air Traffic Controller (ATCo) [5, 6]. As such, the responsibility and decision making in ensuring a safe separation between aircraft would be moved from an ATCo to the cockpit crews, with the assistance of an Airborne Separation Assurance System (ASAS). Thus, the ATM system would change from a centrally organized system to a distributed system (or decentralized). This concept aims not only to provide an increase in airspace capacity, but also shorter flights, lower flight costs, better airspace sustainability and a more efficient airspace utilization [7, 8].

However, assuring safety, efficiency and predictability in a decentralized system has yet to show satisfying results in ensuring safe separation between aircraft, both in human-in-the-loop experiments and automated methods. While human-in-the-loop experiments have often shown inconclusive results as to the right strategies to use in conflict scenarios, automated or analytic methods lack robustness by only being effective in specific traffic scenarios. This gave rise to the need for
proper automated and implicit coordinated solutions, in which aircraft resolve a conflict simultaneously without the need to negotiate resolution maneuvers explicitly.

For the purpose of developing a successful Conflict Resolution (CR)-algorithm that is both safe and efficient in busy airspace, the Solution Space Diagram (SSD) is used as baseline. The SSD is an air traffic display that aims to assist in detecting, preventing and resolving conflicts, based on the combination of Velocity Obstacles (VOs) and an aircraft’s performance limits. Despite being successfully used for many applications, the SSD has yet to prove its value for automated conflict resolution in multi-aircraft scenarios, in which more than two aircraft are involved [9]. For that reason, the objective of this work was to improve the SSD as a CR-method by means of conflict prioritization, to ensure its effectiveness even in very complex and busy multi-aircraft conflicts.

To provide an overall contextualization of this paper, the upcoming section, Section 2, presents relevant definitions and previous work in the field of Conflict Detection Prevention & Resolution (CDP&R). Then, Section 3 addresses new concepts that form the foundations of this research and presents novel ways of conveying conflict prioritization and sequential resolution using the SSD. The experiment design is explained in Section 4, in which the experiment setup and both independent and dependent variables are described. Section 5 presents relevant results that are then briefly discussed in Section 6. Finally, conclusions about the analysis conducted in this paper and recommendations for future work are presented in Section 7.

2. Background

According to ICAO Doc 444 [10], en-route aircraft operating at low altitudes (below FL290), fully cover by radar and equipped with surveillance systems shall maintain a minimum horizontal distance of 5 nm and a minimum vertical distance of 1000 ft. The volume of airspace created by these standards is often called the Protected Zone (PZ) [11], which should not be compromised. Whenever there is an evasion of a PZ, a Loss of Separation (LoS) occurs, which often results in very severe maneuvering to avoid collision. In its turn, a conflict is detected if a LoS is predicted to occur within the predefined look-ahead time. The on-board system that is responsible for ensuring safe separation between aircraft - often referred to as a CDP&R system - can be broken down into three main components: Conflict Detection (CD), Conflict Prevention (CP) and Conflict Resolution (CR) [7]. CD is responsible for the detection of conflicts, based on the information broadcast via Automatic Dependent Surveillance-Broadcast (ADS-B), which includes the current position, velocity and heading of aircraft operating in the vicinity. Assuming that aircraft will maintain their current states, CD can be based on the linear propagation of their trajectories, thus being classified as state-based [11]. CP is responsible for identifying maneuvers that lead to conflicts. Finally, CR refers to the method that suggests deconflicting maneuvers once a conflict is detected, meaning that it is only active whenever a conflict alert is issued. In light of the present research, a new concept is introduced: Conflict Prioritization (CPrio). This refers to the criteria used to assess the urgency of conflicts in a multi-conflict scenario, with that determining which conflicts should be resolved first.

As further explained throughout this paper, CD, CP, CR and CPrio can all be performed by using the concept of Velocity Obstacles (VOs), which are introduced in Section 2.1.

2.1. Velocity Obstacles

A conflict’s geometry between two aircraft can be easily defined through the concept of the Forbidden Beam Zone (FBZ) of Van Dam et al [12]. The FBZ is derived from the concept of Velocity Obstacles (VOs) introduced by Fiorini and Shiller in 1998 [13], which was firstly used for CD&R in the field of robotics. The geometry provided by the FBZ concept allows to analyze and characterize a conflict in the relative velocity plane.

![Figure 1: Construction of a Forbidden Beam Zone.](Image 351x287 to 478x395)

In Figure 1, let $A_{own}$ be the controlled aircraft, $A_{intr}$ the intruder aircraft and $\vec{V}_{rel}$ the motion of $A_{own}$ relative to $A_{intr}$. If the relative path of $A_{own}$ intersects the PZ surrounding $A_{intr}$, then a Loss of Separation (LoS) is expected in the future. Hence, a conflict is detected if $\vec{V}_{rel}$ lies within the area defined between the two lines drawn tangent to the PZ and towards the position of $A_{own}$. This area defines the FBZ between two aircraft and it contains all relative velocities that will lead to a LoS, also referred to as the forbidden relative velocities.

In addition, the Closest Point of Approach (CPA) defines the point at which the two aircraft will not approach any closer, i.e., when the distance between
the two aircraft is the smallest. The absolute distance between the two aircraft at CPA is called the distance at Closest Point of Approach \( d_{CPA} \). Thus, it can also be said that two aircraft are in conflict whenever the value of \( d_{CPA} \) is less than the Radius of the Protected Zone (RPZ).

Other important concepts related to the definition of a conflict in two dimensions are:

- **Time to Loss of Separation (t\( _{LoS} \))**: Time remaining until the controlled aircraft enters the intruder’s PZ;
- **Distance to Loss of Separation (d\( _{LoS} \))**: Remaining distance until the controlled aircraft enters the intruder’s PZ;
- **Time to Closest Point of Approach (t\( _{CPA} \))**: Time remaining until the ownship reaches the CPA.

Alternatively to analyzing conflicts in the relative velocity plane, it is more intuitive to visualize them in the absolute plane, specially when it comes to conflict resolution. Figure 2 depicts a Collision Cone (CC), which can be seen as an extension of a FBZ also containing the intruder’s PZ. Just like a FBZ, a CC contains all forbidden relative velocities in a conflict. By adding the intruder’s velocity to the CC, one obtains a Velocity Obstacle (VO), which in turn represents the area of forbidden absolute velocities (see Figure 3). Because of their advantages, VOs mostly substitute CCs throughout this work.

2.2. The Modified Voltage Potential Method

The Modified Voltage Potential (MVP) method, firstly introduced by Eby in [14] and later modified by Hoekstra et al. in [5], is a successful pairwise conflict resolution method proven in many complex traffic scenarios both in two and three-dimensions.

For each conflict detected, the MVP-method calculates the intrusion vector, \( \vec{i}(t) \), which is the vector issued from the CPA towards the closest edge of the PZ \((i = R_{PZ} - d_{CPA})\), and determines the avoidance maneuver \( \vec{V}_{MVP}(t) \) with

\[
\vec{V}_{MVP}(t) = \frac{\vec{i}(t)}{t_{CPA}}
\]

where \( t_{CPA} \) is the time to closest point of approach, which, in this case, yields the time to resolve the conflict. If more than one conflict is detected, then the final deconflicting velocity vector results from the summation of all avoidance vectors of current conflicts \((j)\):

\[
\vec{V}_{MVP}(t) = \sum_{j} \frac{\vec{i}_j(t)}{t_{CPA}} = \sum_{j} \vec{V}_j(t)
\]

If the maneuver is considered to be cooperative between aircraft, then the magnitude of the deconflicting velocity vector is cut by half.

Finally, the deconflicting vector is added to the aircraft’s current velocity vector yielding a new state. Therefore, this algorithm is able to resolve multiple conflicts simultaneously, both in two and three dimensions.

One of the drawbacks of the MVP-method is not always providing the global optimal solution when solving conflict scenarios involving three or more aircraft, as it resolves conflicts pairwise without performing CP.

2.3. The SSD CR-Method

The Solution Space Diagram (SSD) is an advanced CDP&R display, firstly introduced by Van Dam et. al. in [8] as an envelope interface design of an airborne conflict tool, and later adapted by S.Balasooriya in [9] as an automatic CR-tool. It aims to display a 2-D conflict scenario as seen by a single aircraft, providing conflict and conflict-free areas as combinations of speeds and headings within the aircraft’s performance limits. If an aircraft’s velocity vector points to a conflict area (depicted in red), then the aircraft is in conflict, otherwise being free of conflict. When a conflict is detected, resolution maneuvers can be presented in the SSD that suggest the relocation of the current velocity vector towards conflict-free areas according to the shortest way out strategy, as suggested in [9]. In Figure 4, the red-colored zones represent the velocity obstacles of current and possible conflicts on a 360-degrees heading view, while the inner and outer circles centered on the aircraft represent its minimum and maximum cruise velocity, respectively.

The information provided by these displays allow to visually identify areas of the absolute velocity map that lead to conflict-free trajectories.

In terms of terminology, the set of Reachable Velocities (RV) is defined by the area between the outer circle - representing the maximum cruise velocity - and the inner circle, representing the stall speed. The areas in red are called the Forbidden Reachable Velocities (FRV) which result from the
intersection between RV and the union of all velocity obstacles created by aircraft within ADS-B range (typically between 170 and 200 nm). Finally, the Available Reachable Velocities (ARV) represents the available solution space (or conflict-free trajectories) which is the area defined by RV except FRV.

Because it resolves all conflicts simultaneously, this CR-method is global. Furthermore, this method encompasses CP due to not only considering current conflicts but also possible conflicts in all directions.

2.4. SSD vs MVP
Concerning the system characteristics, the MVP and SSD-methods have the same features: both these methods are implicit, decentralized and coordinated. However, the SSD-method performs CR in global-fashion, meaning that considers all conflicts simultaneously, whereas the MVP-method analysis conflicts pairwise. In addition, the SSD-method avoids secondary conflicts by comprising CP, contrarily to the MVP-method. Therefore, on a preliminary analysis, a superior performance would be expected from the SSD-method, since it always ensures a conflict-free trajectory no matter the number of detected or possible conflicts. However, global resolution as presented by the SSD-method occasionally results in uncoordinated behavior [9], meaning that two or more aircraft would maneuver towards each other instead of away from each other. One additional undesired behavior is the appearance of no solution when too many conflicts are detected (both via CD and CP) [9]. Due to the complexity of the encountered traffic scenario, the solution space area can sometimes be reduced to zero, making the algorithm unable to provide a valid deconflicting maneuver. For those reasons, a previous research has shown that the MVP-method is still superior to the SSD-method [9], regardless of the evident advantages of using the SSD for CR-purposes. Thus, this paper suggests to further develop the SSD-method’s CPrio-component towards sequential conflict resolution, as discussed in the next section.

3. Implementation
This section addresses the main ideas proposed with the objective of improving the SSD as an automated CR-method.

3.1. Modified SSD
When conflict is detected within a given look-ahead time, \( \tau \), it is said that a LoS is expected to occur at time \( t_{LoS} = t_0 + \tau \). However, that does not give enough insight into the urgency of a conflict, which would be of great value in busy conflict scenarios. Instead, it is possible to take the bisector of a VO and take it as a measure of time to collision \( t_c \), just as suggested by Mercado et al. [15]. Indeed, a velocity vector pointing to any point along a VO’s bisector would lead to a direct collision with that intruder, since \( d_{CPA} \) would be zero. Thus, if the current velocity vector points to the center of the intruder’s PZ, then the collision is immediate \( t_c = t_0 \), whereas if the current velocity points to the VO’s apex, an infinite time to collision is obtained \( t_c \to \infty \), meaning that aircraft are taking parallel tracks.

This idea can also be applied to time to loss of separation, as opposed to time to collision. As such, it is possible to define consecutively smaller “protected zones” along the VO, in which each curve would represent a different time to loss of separation (see Figure 5). Thence, a more restrictive area of the VO can be selected for resolution, considering a specific look-ahead time. This yields a round-off velocity obstacle as depicted in Figure 6.

When in combination with the SSD, the form of the modified-VO can yield information about the urgency of conflicts or restrict conflict resolution to fewer conflicts considering a specific look-ahead time. This also allows to obtain an expansion of solution area, which ultimately can prevent unsuccessful solutions due to scenario complexity. For instance, the SSD images in Figures 7 and 8 present the same conflict scenario. However, the solution areas considered are very distinct: Figure 7 depicts all conflicts within ADS-B range regardless of their time to LoS, whereas Figure 8 considers only conflict areas within five minutes to LoS.

These results show one of the many examples where using a modified SSD makes a considerable difference in the solution space and how it can sug-
gest a sequential resolution. In fact, using the SSD of Figure 7 would yield a deconflicting maneuver to avoid both conflicts simultaneously, while in the SSD of Figure 8, only one conflict would be resolved and the other would eventually be resolved once it became urgent (according to the look-ahead time defined).

3.2. Prioritization Strategies

Relevant criteria that can be used to prioritize conflicts are certainly not straightforward, as it is very problem dependent. For example, if all conflicts are predicted to occur at the same time, then the time to LoS criterion would be of no use. Alternatively, a relevant prioritization criterion would be to resolve conflicts at lower distance to LoS. As such, a thorough analysis about relevant prioritization criteria was conducted in this research, which culminated in the seven Prioritization Strategies (PSs) presented in Table 1. Note that PS1 corresponds to the strategy used by the former SSD-method. Small time and distance thresholds are added in some strategies, such as PS2 and PS6, to make sure that the selection of conflicts is as relevant as possible, thereby avoiding the same conflicts to be triggered in subsequent time steps.

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Level of Prioritization</th>
<th>CP</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS1</td>
<td>Resolve considering all FRV areas</td>
<td>None</td>
<td>Yes</td>
</tr>
<tr>
<td>PS2</td>
<td>Resolve considering FRV areas within $t_{LA} + 1$ minute</td>
<td>Low</td>
<td>Yes</td>
</tr>
<tr>
<td>PS3</td>
<td>Resolve only current conflicts within $t_{LA}$</td>
<td>Medium-low</td>
<td>No</td>
</tr>
<tr>
<td>PS4</td>
<td>Resolve considering FRV areas within $\min(t_{LA}) + 1$ minute</td>
<td>Medium</td>
<td>Yes</td>
</tr>
<tr>
<td>PS5</td>
<td>Resolve only current conflicts within $\min(t_{LA}) + 1$ minute</td>
<td>Medium-high</td>
<td>No</td>
</tr>
<tr>
<td>PS6</td>
<td>Resolve only current conflicts at $\min(d_{LoS}) + 10$ nm</td>
<td>High</td>
<td>No</td>
</tr>
<tr>
<td>PS7</td>
<td>Resolve only current conflicts at $\min(d_{LoS})$</td>
<td>High</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 1: Overview of Prioritization Strategies.

Most criteria do not comprise the same level of prioritization. In fact, considering conflicts at minimum time to LoS tends to be more selective than considering conflicts at a specific look-ahead time. Additionally, if a specific strategy only considers current conflicts, then the selection of conflicts is generally more restrictive, since CP is not performed. In those PSs, the concept of modified-VO is never used, and VOs are used in full.

3.3. Sequential Resolution Strategies

By recognizing more urgent conflicts and suggesting its immediate resolution over less urgent ones, the proposed method suggests a sequential approach to CR. Because the relevance of each PS is problem dependent, Sequential Resolution Strategies (SRSs) consist of a combination of prioritization strategies, which cooperate among them to find the safest way out of conflicts. For that purpose, each SRS contains a set of PSs ordered in increasing levels of prioritization - called a sequential chain - and selects the PS that is most adequate for resolution given the severity of the encountered conflict scenario and the maneuvering space available. For example, if the first PS on the sequential chain is not able to provide a valid deconflicting maneuver, then the SRS tries to solve using the strategy that is second in the chain. This process is continued until a solution is returned. Therefore, by recognizing more urgent conflicts and suggesting its immediate resolution over less urgent ones, the algorithm is expected to ensure that aircraft would resolve, regardless of the encountered conflict’s severity.

In total, two main sequential resolution strategies are proposed, which are summarized in Table 3.3.

<table>
<thead>
<tr>
<th>Method</th>
<th>Sequential chain</th>
<th>Prioritization levels</th>
<th>CP</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRS1</td>
<td>PS2,PS4,PS6</td>
<td>Low to high</td>
<td>Yes</td>
</tr>
<tr>
<td>SRS2</td>
<td>PS4,PS5,PS7</td>
<td>Medium to High</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 2: Overview of the proposed sequential resolution strategies.

4. Experiment Design

For the validation of the proposed method, fast-time simulations of multiple conflict scenarios were conducted. These simulations were carried out using the BlueSky Air Traffic Management (ATM) simulator, an open-source and open-data simulator developed by students and staff of Delft University of Technology, aimed for research in the field of ATM [16]. The conducted experiment had the objective of conducting a performance evaluation of sequential resolution strategies using large-scale scenarios. For that purpose, the large-scale scenarios involved high densities of traffic that were unbiasedly generated - as further explained in Section 4.1 - which allowed to conducted a comparative performance analysis between the proposed SRSs, the unprioritized SSD-method and a CR-Off configuration which represents the case where CR is not active.
For the analysis presented herein, a total of 373,968 flights were generated over 588 three-hour simulations which consisted of 42 different traffic configurations repeated 14 times. Because aircraft were only spawned for the first 2.5 hours of simulation, the experiment duration was set to 1.5 hours starting from the first hour of simulation. This ensures that traffic density was kept constant throughout the experiment duration, therefore discarding an hour of traffic built-up and an extra half-hour in which traffic density started decreasing. In the end, among all simulated flights, approximately 224,603 flights were considered for analysis.

In this experiment, four different independent variables were tested, as presented in Section 4.2. The results are analyzed using metrics of safety, stability, efficiency and relevancy of prioritization criteria, as shown in Section 4.3.

4.1. Traffic Scenarios
The scenarios used in the simulations are mainly defined in terms of traffic density (number of aircraft per unit area) and number of instantaneous aircraft. The experimental setup used is depicted in Figure 9. The setup presented herein is adapted from the work of E.Sunil et.al. in [2, 3].

![Figure 9: Experiment setup of traffic scenarios.](image)

Throughout the three hours of simulation time, aircraft were spawned into the same flight level (FL360) at a rate defined by the desired traffic density. The spawn location (origin) of each aircraft is located on an edge of a squared area, called the spawn square, where aircraft follow a 2-D direct route defined by an origin and a destination. Because both the origin and destination of each route are located on the edges of the spawn square, the ideal (direct) route of each aircraft are confined into the spawn area. Origins and destinations are placed interleaved with equal spacing between them. In total, there are 114 different origins and 114 different destinations.

Routes are generated randomly such that the direct distance between each pair of origin and destination is within the interval [300, 350] nm and initial True Air Speeds (TAS) are uniformly distributed between 400 kts and 500 kts. Additionally, it is ensured that each origin-destination pair is not located on the same spawn square edge. To provide a constant density of aircraft within the spawn area, the rate at which aircraft leave the simulation area is the same as aircraft are spawned.

As far as the ideal experiment goes, aircraft would only operate within the area defined by the spawn square, thereby ensuring a constant density of aircraft within that area. However, aircraft are expected to deviate from their intended path while resolving conflicts, thus often leaving the spawn area. For that reason, a second squared area is considered: the experiment area. This ensures that aircraft encountering conflicts close to their origin or destination are not deleted incorrectly from the simulation, thus being free to operate within the experiment area. Ultimately, an aircraft is deleted from the simulation once it reaches its destination or leaves the experiment area.

4.2. Independent Variables
This section addresses the independent variables used in the experiment, which are described in the upcoming paragraphs.

**Traffic Density** Keeping in mind that it is desired to test the proposed method in very high traffic demand and complexity, high traffic densities are mostly used. In total, three different traffic configurations were defined, as presented in Table 3.

<table>
<thead>
<tr>
<th>Traffic configuration</th>
<th>Low</th>
<th>Moderate</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic density [ac/nm²]</td>
<td>9</td>
<td>18</td>
<td>27</td>
</tr>
<tr>
<td>Number of instantaneous ac</td>
<td>93</td>
<td>185</td>
<td>277</td>
</tr>
<tr>
<td>Total number of ac spawn</td>
<td>382</td>
<td>764</td>
<td>1145</td>
</tr>
<tr>
<td>Average number of ac logged</td>
<td>125</td>
<td>368</td>
<td>645</td>
</tr>
</tbody>
</table>

Table 3: Parameters of each traffic configuration (Low, Moderate and High).

**Strategies** As previously mentioned, five different strategies are considered for analysis, which are summarized in Table 4.

<table>
<thead>
<tr>
<th>Strategy Code</th>
<th>CR-type</th>
<th>CP</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR1</td>
<td>Sequential</td>
<td>Yes</td>
</tr>
<tr>
<td>SR2</td>
<td>Sequential</td>
<td>Yes</td>
</tr>
<tr>
<td>SSD</td>
<td>Global</td>
<td>Yes</td>
</tr>
<tr>
<td>MVP</td>
<td>Pairwise</td>
<td>No</td>
</tr>
<tr>
<td>CR-Off</td>
<td>None</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 4: Strategies tested.

**Look-ahead Time** The look-ahead time defines the time threshold from which the conflicts are detected: the higher the value of look-ahead time, the sooner the detection of conflicts. It is desired to test whether a higher value of look-ahead time would
provide an improve in safety, or instead lead to unnecessary maneuvering, as aircraft may intend to change paths before needing to resolve a conflict. As such, two levels are considered for this parameter: five minutes and seven minutes.

**Speed constraints** Speed constraints narrow the maneuvering area of the SSD by increasing the stall speed of the aircraft. Contrarily to the maximum engine speed ($v_{\text{max}}$), the stall speed ($v_{\text{min}}$) is highly dependent on the flight level an aircraft is operating in, which has a big influence on its maneuvering space. For that purpose, two different speed configurations are considered, as shown in Table 5.

<table>
<thead>
<tr>
<th>Speed constraint value</th>
<th>$v_{\text{min}}$ [kts]</th>
<th>$v_{\text{max}}$ [kts]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 % (None)</td>
<td>300</td>
<td>500</td>
</tr>
<tr>
<td>50%</td>
<td>400</td>
<td>500</td>
</tr>
</tbody>
</table>

Table 5: Speed constraints.

It should be noted that these strategies also include a standard constraint in terms of heading, which does not allow the aircraft to maneuver further than ± 90 degrees.

### 4.3. Dependent Variables

The dependent variables used to assess the performance of each strategy can be categorized into one of the following groups: safety metrics, stability metrics, efficiency metrics or relevancy of prioritization criteria metrics. The indicators used for this purpose are summarized in Table 6, which are based on the work developed in [2, 4, 9].

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{cfl}$</td>
<td>Number of detected conflicts per flight</td>
<td>Safety</td>
</tr>
<tr>
<td>$n_{LoS}$</td>
<td>Number of Losses of Separation per flight</td>
<td>Safety</td>
</tr>
<tr>
<td>$\text{DEP}$</td>
<td>Domino Effect Parameter</td>
<td>Stability</td>
</tr>
<tr>
<td>$D$</td>
<td>Distance traveled per flight</td>
<td>Efficiency</td>
</tr>
<tr>
<td>$T$</td>
<td>Flight duration</td>
<td>Efficiency</td>
</tr>
<tr>
<td>% SS</td>
<td>Percentage of sequential solutions</td>
<td>Relevancy</td>
</tr>
<tr>
<td>% US</td>
<td>Percentage of unsuccessful solutions</td>
<td>Relevancy</td>
</tr>
</tbody>
</table>

Table 6: Dependent variables.

The airspace stability caused by a CR-method can be assessed by the Domino Effect Parameter (DEP). This indicator is a measure of the triggered secondary conflicts, as it compares the number of conflicts logged for each strategy ($n_{cfl}^{ON}$) with the number of conflicts detected with the CR-Off configuration ($n_{cfl}^{OFF}$), in which aircraft do not deviate from their ideal path. As such, DEP can be expressed as in Equation 3.

$$\text{DEP} = \frac{n_{cfl}^{ON}}{n_{cfl}^{OFF}} - 1$$  

To provide a better understanding of the relevancy of the designed PSs and SRSs, two metrics are analyzed. The first is the percentage of sequential solutions (% SS), which assesses whether sequential solutions are being selected, or if instead only the first strategy of the sequential chain is used. Finally, the percentage of iterations in which SSD-based strategies where not able to provide a valid deconflicting maneuver due to lack of solution space is represented with % US. These parameters are expressed in percentage as a function of the total number of method iterations.

### 5. Results

In this section, relevant results of the main experiment are unveiled. These are presented as a function of each strategy in the form of box-and-whisker plots, whose whiskers are set to 1.5 times the interquartile range and outliers are omitted. Because there is a high number of independent variables involved, a standard configuration was established for comparison purposes: high density of traffic, 50% speed constraints and five minutes look-ahead time, which are used unless one of these independent variables are being tested individually. Additionally, the results obtained with the CR-OFF configuration may sometimes not be included, as they did not add value to the analysis.

Results can be broken down into the four categories of metrics presented in Table 6, which will be presented throughout the remaining of this section.

#### 5.1. Safety Analysis

The safety of a CR-method can be analyzed through many metrics, starting with the number of conflicts per flight and the number of LoS per flight in Figures 10 and 11, respectively.

Figure 10: Number of conflicts per flight for each strategy and traffic density.

Inevitably, increasing values of traffic density led to higher numbers of conflicts and LoS. Moreover, no matter the traffic density considered, the number of conflicts per strategy shows a similar significant trend: highest with the MVP-method and lowest with the SSD-method. Unexpectedly, performing conflict resolution with any strategy led to a higher number of conflicts in comparison to...
the CR-off configuration, for any traffic demand. This result goes against intuition, since it would be expected that CR-strategies would redirect aircraft towards safer airspace, instead of triggering further conflicts. However, this phenomenon can be related to the absence of PASAS. The PASAS is a CP-method that prevent aircraft from turning into conflicts when starting trajectory recovery, which takes place whenever aircraft complete a deconflicting maneuver.

As for the number of LoS, although not showing a consistent trend throughout different traffic densities, the MVP-method systematically showed the lowest number of LoS for low and medium density. The SSD strategy, on the other hand, showed the poorest result in all traffic demands. Nonetheless, all sequential strategies showed a decrease in number of LoS in comparison to the original SSD-method in high traffic demand.

Another interesting result for this analysis is the effect of look-ahead time. Figures 12 and 13 respectively summarize the extra number of conflicts and extra number of LoS triggered when the look-ahead time was changed from five to seven minutes.

Figure 12: Percentage of extra number of conflicts due to an increase of two minutes of look-ahead time.

Figure 13: Extra number of LoS due to an increase of two minutes of look-ahead time.

13, the increase in look-ahead time was only relevant for CR-purposes when in high traffic densities, in which this number was decreased. In contrast, for low and medium traffic densities, the increase in look-ahead time only triggered an incorrect and unnecessary detection of conflicts as it did not act to considerably decrease the number of LoS. Therefore, it is clear that most strategies benefited from the increase in look-ahead time for the high traffic demand.

5.2. Stability Analysis
The stability analysis conducted in herein considers one metric only: the Domino Effect Parameter (DEP). Ideally, providing CR should lead to an increase in airspace stability (negative values of DEP) in the hopes of redirecting flights towards safer airspace. However, as results in Figure 14 show, that statement is far from being true.

Figure 14: Domino effect parameter per strategy for each traffic density.

As expected, the MVP-method performed worse in terms of stability due to not performing CP. Nonetheless, the differences in DEP between strategies with CP and without are only considerably large for high density of traffic, since for medium and low traffic the differences did not reach 3% between median values.

5.3. Efficiency Analysis
The efficiency analysis focuses on flight data, which included the total distance traveled and flight duration. Results have shown that traffic density was the main cause for flight inefficiency, as analyzed in
As expected, by only considering current (detected) conflicts, the MVP-method was able to fly most efficiently in terms of distance traveled and flight duration - when compared to the remaining strategies - at the cost of higher number of conflicts (referring back to Figure 10). This result is another metric that rules in favor of the no-CP and pairwise configurations, showing the need for triggering secondary conflicts to equally push flights away from their ideal path, thereby minimizing the path deviation per flight. Alternatively, strategies with CP concentrate path deviation to a shorter number of flights, making path deviations per flight larger. An aggravated effect of having longer path deviations is that the rate at which aircraft are spawn into the simulation area will not correspond to the deletion’s rate, resulting in an undesired increase in traffic density that ultimately led to even higher path deviations.

5.4. Relevancy of Prioritization Criteria Analysis

For the relevancy of prioritization criteria analysis, the effect of traffic density and the effect of speed constraints on sequential and unsuccessful solutions are examined, as shown in Figures 17 and 18. An increase in traffic density led to smaller ARV areas for all prioritization strategies, resulting in an increase in the number of sequential solutions for both sequential resolution strategies. Because alternative solutions were mostly valid, the number of unsuccessful solutions were very few, leading to median values of zero percent. Additionally, this result did not change with tighter speed constraints, even though more sequential solutions were selected. Nonetheless, it should be noted that strategies further down the sequential chain were not seldom selected, which indicates that solutions were rarely sequential.

6. Discussion

All in all, the strategy that showed overall best results was the pairwise MVP-method. This approach provided better flight efficiency and prevented more losses of separation. However, the MVP-method performed worst in terms of stability, as it triggered the highest number of secondary conflicts due to lacking CP. Second in line are SRSs, with emphasis on strategy SRS2 which showed high-standard results in terms of safety for medium to high traffic demands, and efficiency-wise across all densities. While performing conflict prioritization, these strategies were able to suggest deconflicting maneuvers closer to the current velocity vector, thereby avoiding unfeasible severe maneuvers. Also, this feature decreased the number of unsuccessful solutions, which permitted aircraft to maneuver in much complex scenarios. Finally, the unprioritized SSD was considered the worst strategy.

The poorest performances of SSD-based strategies were due to two main undesired behaviors: the occurrence of uncoordinated behavior and the selection of invalid deconflicting maneuvers. Uncoordinated behavior occurs when two aircraft in a conflict both maneuver in the same direction, i.e,
both end up maneuvering towards one another instead of away from each other. As a result, the two aircraft remain in conflict, thereby increasing its urgency, sometimes even resulting in a LoS. Another unfortunate effect of uncoordinated behavior is the occurrence of bouncing solutions. Because solutions are provided according to the traffic configuration encountered at each five-second interval, the traffic pattern encountered at a given time step may change completely in the next iteration, meaning that maneuvers may considerably change between two consecutive iterations. This led aircraft to bounce between two distinctive resolution maneuvers for as long as the same conflict lasts. Lastly, the selection of invalid deconflicting maneuvers occurred in two distinct situations. The first type takes place whenever the solution point is at a VO’s vertex while an intrusion is occurring, while the second type consists of solutions on the edge of a VO’s round-off area. The former prevents a conflict from being resolved, thus disabling aircraft to reach their destinations. Even though the latter type is not necessarily invalid, it can sometimes be undesired. In fact, these solutions often delay a conflict - instead of resolving it - until it becomes more urgent, sometimes even resulting in a loss of separation.

7. Conclusions
In this paper, a fully decentralized, implicit and automated two-dimensional Conflict Resolution (CR) method was suggested, based on the Solution Space Diagram (SSD). The goal was to improve the former SSD CR-method in [9] by means of conflict prioritization, thereby suggesting a sequential approach to CR. As the urgency of each conflict is very dependent on the traffic scenario encountered, different prioritization criteria were investigated, resulting in seven different Prioritization Strategies (PSs). From PSs, two different Sequential Resolutions Strategies (SRSs) were constructed, whose performance was compared with the former SSD-method and the pairwise Modified Voltage Potential (MVP)-method. The main conclusions drawn from this research are:

- All proposed SRSs outperformed the (global and unprioritized) SSD-method in most metrics of safety and efficiency in medium to high traffic demands. This included a considerable decrease in number of losses of separation. However, the same did not hold for the number of conflicts, which were generally higher.

- SRSs comprising higher levels of prioritization exhibited lower numbers of losses of separation under high traffic demand, hence being more desirable safety-wise.

- All strategies performing Conflict Prevention (CP) showed to benefit from an increase in look-ahead time from five to seven minutes in high traffic demand, having shown to decrease the number of losses of separation.

- The MVP exhibited less path deviations due to not performing CP, which resulted in less distances and durations per flight. As such, this strategy performed better in terms of efficiency, despite triggering a higher number of conflicts in the process.

- Due to providing CPrio and thereby suggesting sequential resolution, SRSs were able to avoid situations in which the SSD was not able to provide any deconflicting maneuver. As a result, these strategies showed better performances in terms of safety in tighter speed constraints and high traffic demands, in comparison to the SSD-method.

- Even though SRSs showed outstanding improvements in performance in comparison to the SSD-method - thereby fulfilling the main objective outlined - the MVP-method performed better than any other strategy in most metrics of safety and efficiency, while compromising airspace stability. These results were caused by undesired behaviors related to the dynamic of VO’s and invalid deconflicting maneuvers, which persisted in all SSD-based strategies.

For future work, a different approach to CR using the SSD is proposed to prevent uncoordinated maneuvers. This would only be possible if the ownership would have information about the deconflicting maneuvers selected by all its intruding aircraft. The main barrier would be to have this prediction done implicitly. A recommendation is to combine all SSD images from aircraft in the vicinity of the ownership and apply a search algorithm. This search algorithm would take into consideration both the possible solutions for the ownship and for all its intruders’ and select the one that would maximize a common goal. For instance, goals could be set to maximize safety (maximize distances at closest point of approach and/or minimize the number of secondary conflicts) or efficiency (minimize path deviations).

It is not enough to allude to the potential of the SSD as an automated CR-method. Despite still presenting some undesired behaviors, the prospects for this method are very promising, as moderate changes to its approach resulted in major improvements in its performance. For that reason, the SSD is considered a big asset towards achieving Free Flight.
References


