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Resilient conflict detection and resolution for high-uncertainty constrained urban airspace operations

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ABSTRACT

The concept of urban air mobility is rapidly advancing, with much research being dedicated towards the development of the air traffic management services required for such operations. An important component of unmanned air traffic management (U-space/UTM) is conflict detection and resolution (CD&R), tasked with ensuring the operational safety of such systems. Strategic flight plan optimisation and tactical CD&R methods have generally been studied independently, leading to suboptimal performance when deployed simultaneously in simulated high-density very-low-level constrained urban airspace environments. Furthermore, the limited flexibility of pre-departure 4D trajectory planning methods towards dynamic and uncertain environmental and operational conditions (i.e., wind and delay) produces a degradation in safety that is difficult to mitigate using tactical manoeuvring. In this work, we design a traffic-flow capacity strategic optimisation method that aims to achieve robustness against flight plan deviations and to better complement tactical CD&R manoeuvring. The performance of the proposed strategic and tactical deconfliction module is tested within constrained urban airspace traffic scenarios simulated using the BlueSky Open Air Traffic Simulator. The results are compared with other methods, such as 4D trajectory planning and state-based CD&R.

1. Introduction

The substantial global interest in urban air operations has led aviation authorities worldwide to initiate concepts of operations for the management of this new type of air traffic. They promise to provide a safe and sustainable alternative to current ground-based transportation methods, and relieve the increasing congestion of cities (Cohen et al., 2021). For example, the U-space (Barrado et al., 2020; Alarcon et al., 2020; Single European Sky A.T.M. Research 3 Joint Undertaking, 2017) and UTM (Unmanned Aircraft System Traffic Management) (McCarthy et al., 2020; Straubinger et al., 2020) proposals, designed for managing urban air traffic in the European Union and United States respectively, establish the groundwork for developing the services for such operations.

An important component of U-space/UTM systems is the conflict detection and resolution (CD&R) module, tasked with ensuring that urban air operations are performed safely. This module is generally composed of two subcomponents: strategic, and tactical CD&R (CORUS-XUAM consortium, 2023). The role of the first is to proactively prevent unsafe operational situations well in advance of their occurrence, while the latter is used to resolve conflicts reactively within a short look-ahead time (Kuchar and Yang, 2000). These components are an area of active research within the U-space/UTM domain, as their compatibility with other urban airspace systems and their robustness within dynamic and uncertain environments still needs to be improved (Wandelt and Zheng, 2024).

One approach to creating a unified CD&R system is the use of dynamic re-routing in combination with tactical deconfliction (Morfin Veytia et al., 2024; Patrinopoulou et al., 2023). This method aims to resolve conflicts by modifying the flight plan of departed aircraft. However, such methods are highly susceptible to inducing airspace instability and negatively affect the predictability of the actions of agents within the system, and need to be intensely studied to predict and capture undesirable emerging behaviour within high-density multi-agent systems such as U-space/UTM.

Another proposal for the architecture of the CD&R module is the sole use of pre-departure strategic deconfliction in combination with tactical conflict resolution (Badea et al., 2025; Sacharny et al., 2022). The first is typically approached as a global optimisation problem (Tang and Xu, 2023), where all flight plans of requested missions are jointly deconflicted before departure. When relying on this manner of pre-departure deconfliction, compliance with the allocated trajectory is

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critical to maintain the safety level of operations, resulting in strict constraints in the execution of the flight plan (Levin and Rey, 2023).

A drawback of this highly constrained approach is that it can impair the effectiveness of the tactical CD&R module, especially if the requirements and functioning parameters of the latter are not accounted for (Badea et al., 2025). The presence of environmental and operational uncertainties can also lead to degradation in the effectiveness of following the flight plan, as the frequent use of tactical manoeuvring can lead to performance degradation (i.e., conflict hotspots and traffic bottlenecks). Thus, the key question is whether to mainly rely on strategic deconfliction with the tactical module handling the remaining, unforeseen situations, or a combination in which the deconfliction responsibility is shared.

The aim of the work at hand is to investigate and develop a low-complexity and robust approach to pre-departure strategic flight planning and tactical CD&R for use in very-low-level (VLL) constrained urban airspace operations. In our previous work (Badea et al., 2024, 2025), we identified several issues that still need to be addressed to improve the synergy and resilience of U-space/UTM operations in the presence of uncertainties (i.e., wind and departure delay). One of the most important factors we identified is the over-optimisation of flight plans (i.e., reducing safety margins for increased efficiency leading to decreased robustness), which greatly affects operational safety in the presence of uncertainties (Joulia and Dubot, 2022). We thus propose a CD&R framework that combines traffic flow capacity management and a tactical resolution method tailored for use in urban airspace based on organic street networks to address this issue.

2. Pre-departure strategic conflict detection and resolution

The following section presents a pre-departure strategic flight planning concept aimed at improving the synergy when combined with tactical CD&R methods for constrained urban airspace and robustness against uncertainties such as wind and delay. The main functioning principle is to replace time or distance-based strategic separation with flow capacity management. Thus, the strategic deconfliction process focuses on mitigating traffic density hotspots, allowing the tactical deconfliction module to function more effectively and solve conflicts locally.

2.1. Design considerations

Our previous research on pre-departure strategic planning for VLL constrained urban airspace (Badea et al., 2025) shows that while 4D trajectory planning can be effective in preventing conflicts in nominal conditions, it is highly susceptible to environmental and operational uncertainties, which hinder the ability of aircraft to comply with their flight-plan and thus the effectiveness of the deconfliction method. As a consequence, conflict hotspots can arise, which in turn lead to further tactical manoeuvring, exacerbating flight-plan non-compliance.

One of the sources of instability and degraded performance against uncertainties is over-optimisation of flight plans in the pre-departure phase (Joulia and Dubot, 2022), which results in a low tolerance for deviations. In nominal conditions, conflicts are prevented, as aircraft are able to comply with the allocated flight plan, with tactical intervention rarely required. However, with increasing level of uncertainty (i.e., wind and delay), the majority of conflicts are resolved through the use of tactical manoeuvring, thus reducing the effectiveness of the strategic planning module (Badea et al., 2025). Because higher local aircraft densities and multi-aircraft conflict hotspots result from these tactical interactions, the performance of tactical CD&R algorithms is also reduced.

Traditional methods like stochastic and robust optimisation could be used to address uncertainty in this optimisation problem. However, stochastic optimisation requires knowledge of the probability distribution of unknown variables, which may not be available (Huang et al., 2023). On the other hand, robust optimisation, while guaranteeing feasibility against worst-case scenarios, can lead to overly conservative solutions that sacrifice system efficiency and capacity (Joulia and Dubot, 2022).

To mitigate these issues, we propose the use of flow-based capacity management as a replacement method for strategically planning the routes of aircraft in VLL constrained urban airspace in combination with a conservative tactical deconfliction algorithm. By limiting the number of aircraft that can traverse an intersection within a specific time window, traffic can be better distributed throughout the network, leading to lower local traffic densities. The focus of the strategic planning module is thus shifted, from resolving individual predicted conflict situations, to reducing their complexity (i.e., reducing the occurrence of multi-aircraft conflicts). Then, the tactical deconfliction module can function more effectively and resolve the remaining conflicts.

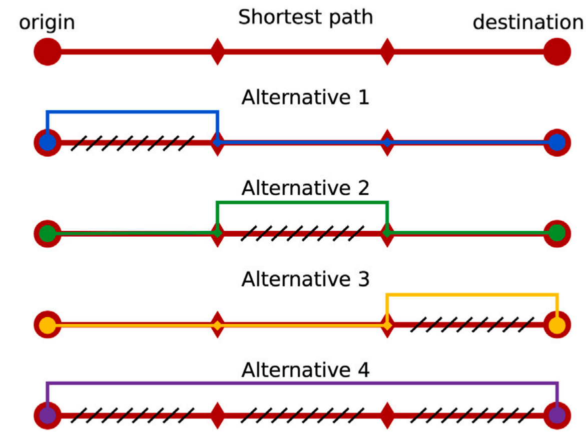

Fig. 1. Alternative route generation functioning principle: routes are generated such that either a part or the whole shortest route is avoided.

2.2. Trajectory planning in constrained urban airspace

The problem of trajectory planning in urban airspace with flow constraints has been previously investigated in Levin and Rey (2023). This study formulates trajectory planning as an Integer Linear Programming (ILP) problem, and uses that to optimise a relatively high number of flights within the standard Sioux Falls network (24 nodes, 76 links) while enforcing a maximum link flow capacity. The issue with such an approach is that the number of variables of the problem increases greatly with increasing number of nodes and links, especially if drones are expected to fly above inner-city streets. The modelling of these areas requires a larger number of network features, increasing the required solving time beyond reasonable limits.

To tackle this, we propose to limit the trajectory choice to a set of pre-generated paths to reduce the number of variables in the problem. This method has been successfully applied in previous work (Bereziat et al., 2022; Badea et al., 2025). Thus, the set of possible paths for a single flight request is created using the method illustrated in Fig. 1. First, the shortest path between the origin and destination is computed. Then, alternatives are generated by making sections of the shortest route undesirable for travel (i.e., increasing the weight of using the network links). Alternatives 1,2 and 3 are generated by dividing the shortest route into three equal sections and routing around each at a time. The last alternative is routed such that the shortest route is avoided completely. A route generation example within the street network of Wien, Austria is presented in Fig. 2.

It should be noted that the methodology used to generate alternative routes is not the main focus of this work, and is only applied to obtain a diverse set of routing possibilities while still maintaining the total

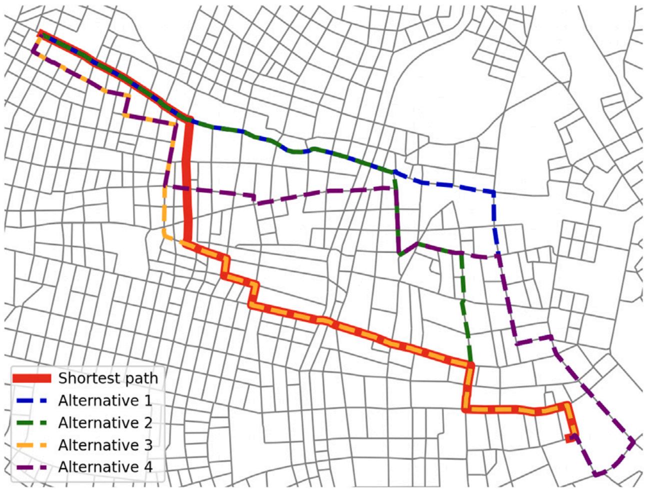

Fig. 2. Route generation example within a street network graph, with the origin in the right bottom corner.

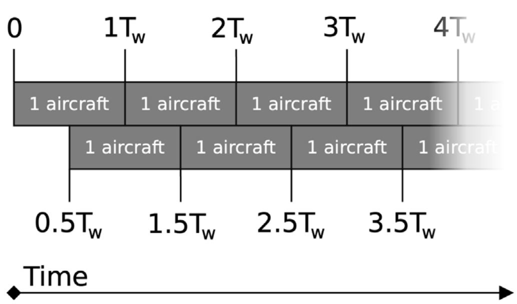

Fig. 3. Structure of overlapping time windows at each intersection within the urban airspace network for flow capacity equals to 1.

travel distance within reasonable margins. Compared to the route generation method used by Bereziat et al. (2022) (i.e., selecting a random intermediate node), the strategy used in this work does not result in self-intersecting or infeasible trajectories. Future iterations of this method should be improved through the use of historical traffic data to generate alternative routes that avoid conflict and traffic hotspots.

2.3. Network flow capacity management

The functioning principle of the strategic CD&R method introduced in this work is the planning of aircraft trajectories such that the number of aircraft that can traverse an intersection (i.e., network node) within a given time window (T_w) is limited. An overlapping time window structure is used, as shown in Fig. 3, to avoid high traffic densities at the boundaries of the time windows. For example, if an aircraft is predicted to be at a node at time $1.8T_w$ and only one aircraft is allowed within one time window, then no other aircraft cross the node between $1T_w$ and $2.5T_w$.

To enforce a flow limit, the time of arrival at each intersection (network node) is estimated for all pre-generated paths. Thus, a parameter can be created that quantifies within which time windows are aircraft predicted to traverse a node in function of the selected path. The optimisation consists in allocating paths such that the flow capacity at all nodes is respected, and the total estimated travel time is minimised. In this work, we investigate three time window values: 5, 10, and 20 s (equivalent to 0.5x, 1x, and 2x of the tactical CD&R look-ahead time).

2.4. Problem formulation

The flow-based flight planning method can be formulated as an ILP optimisation problem. The following section presents the assumptions, parameters, decision variables, constraints, and objective function.

2.4.1. Assumptions

- Aircraft do not change flight altitude during cruise.
- The target cruise airspeed is constant throughout the flight. The actual airspeed adapts in function of flight conditions.
- Take-off and landing manoeuvres do not count towards the flow capacity.
- Aircraft perform turning manoeuvres with a turn radius of 5 metres if the turn angle is greater than 25°.
- Intended departure time cannot be changed.

2.4.2. Parameters

- F: set of all flight plans
- P_f: set of paths that can be allocated to flight f, $\forall f \in F$
- N: set of all nodes in the street network graph
- Y: set of all available flight levels
- T: set of all time windows
- b_p: estimated cruise flight time if path p is allocated to flight f, $\forall f \in F, \forall p \in P_f$
- $x_{p,n,\theta} \in \{0,1\}$: 1 if flight f using path p enters node n within time step θ, else 0, $\forall f \in F$, $\forall p \in P_f$, $\forall n \in N$, $\forall \theta \in T$
- C_n: maximum flow for node n (number of aircraft per time window), $\forall n \in N$
- $\delta_{f,y}$: estimated time for flight f to ascend to and descend from flight level y, $\forall f \in F, \forall y \in Y$

2.4.3. Decision variables

The optimisation problem is governed by the following decision variable, which represents the allocated flight level and route for each mission:

- $z_{p,y} \in \{0,1\}$: 1 if path p and flight level y are allocated to flight f, else 0, $\forall f \in F$, $\forall p \in P_f, \forall y \in Y$

2.4.4. Constraints

The first set of constraints ensure that all aircraft are allocated only one path and one flight level.

$$\sum_{p\in P_f}\sum_{y\in Y} z_{p,y} = 1, \quad \forall f \in F \tag{1}$$

The next set of constraints enforces the flow capacity limit C_n for each node and time window.

$$\sum_{f\in F}\sum_{p\in P_f} x_{p,n,\theta} z_{p,y} \le C_n, \quad \forall n \in N, \forall \theta \in T, \forall y \in Y \tag{2}$$

2.4.5. Objective function

The objective of the optimisation is to minimise the sum of all mission durations, represented as the summation between the estimated vertical and horizontal travel times for each flight, presented in Eq. (3).

$$\text{Minimise}: \sum_{y\in Y}\sum_{f\in F}\sum_{p\in P_f} z_{p,y}(\delta_{f,y} + b_p) \tag{3}$$

2.4.6. Flow constraint relaxation

During the testing phase, we encountered situations in which, because of the traffic pattern, airspace configuration, and flow capacity limits, some missions could not be accommodated such that flow constraints are satisfied. As the goal of the proposed flow capacity management model is to reduce local traffic density as to increase the efficiency of tactical CD&R methods, we consider the relaxation of the flow constraint (Eq. (2)). As a consequence, the enforcement of flow capacity limits is not guaranteed, but is part of the objective function minimisation process. However, it is expected that such flow constraint violation would operationally be handled through the use of tactical manoeuvring. Thus, a second decision variable, that is proportional to the flow capacity violation, is introduced for every node, flight level, and time window:

- $v_{n,\theta,y}$: constraint violation at node n within time window θ at flight level y, $\forall n \in N$, $\forall \theta \in T$, $\forall y \in Y$

Then, the constraint presented in Eq. (2) can be reformulated to allow violations, as shown in Eq. (4).

$$\sum_{f\in F}\sum_{p\in P_f} x_{p,n,\theta} z_{p,y} - C_n \leq v_{n,\theta,y}, \quad \forall n \in N, \forall \theta \in T, \forall y \in Y \tag{4}$$

The violation variable needs to be positive to ensure that capacity is not gained through the use of negative values.

$$v_{n,\theta,y} \geq 0, \quad \forall n \in N, \forall \theta \in T, \forall y \in Y \tag{5}$$

Lastly, the objective function presented in Eq. (3) is reformulated to include the penalisation of the total violation of the flow constraints, as shown in Eq. (6).

$$\text{Minimise} : \sum_{y\in Y}\left(\sum_{f\in F}\sum_{p\in P_f} z_{p,y}(\delta_{f,y} + b_p) + \sum_{n\in N}\sum_{\theta\in T} v_{n,\theta,y}\right) \tag{6}$$

2.4.7. Planning time horizon heuristic

To reduce the size of the problem as well as create a solution-oriented approach, the model can be used in combination with a moving planning time horizon, thus allowing the progressive optimisation of flight plans as they are requested. In this work, we use a planning time horizon of 30 min. After an initial batch of flight plans is optimised, the decision variable $z_{p,y}$ is fixed for the aircraft that are predicted to still be airborne during the next 30 min interval. This is achieved by adding the set of constraints described by Eq. (7), where the parameter $z^{prev}_{p,y}$ represents the values taken by the decision variable z for the previous batch of flight plans F^{prev}.

$$z_{p,y} = z^{prev}_{p,y} \quad \forall p \in P_f, \forall y \in Y, \forall f \in \{F \cap F^{prev}\} \tag{7}$$

2.5. Baseline method

To evaluate the performance of the proposed planning algorithm, we compare it to a baseline method. For this we select a 4D trajectory (4DT) strategic deconfliction method that was previously presented in Badea et al. (2025). This type of flight plan management has been previously investigated in both civil and urban airspace operations (Mondoloni and Rozen, 2020; Pelegrín et al., 2023; Badea et al., 2025), with promising results in delivering improved operational safety.

In the baseline 4D planning method we use in our comparison, strategic conflict detection and resolution is performed by ensuring that a minimum separation threshold between aircraft is respected at intersections. Thus, aircraft are allocated a route, cruise altitude, and departure time, and are issued a required time of arrival (RTA) for each waypoint within their route. Drone operators are then required to comply with the flight plan through the use of speed adjustments. Tactical conflict detection and resolution is then performed if the need arises during the cruise phase.

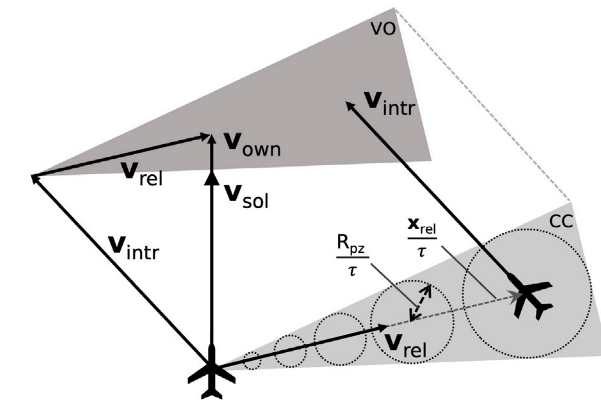

Fig. 4. State-based conflict detection and resolution using velocity obstacles.

3. Tactical conflict detection and resolution

To investigate the performance of the proposed strategic flight planning strategy within a U-space/UTM system, we implemented and developed three tactical CD&R algorithms previously used within VLL constrained urban airspace research. The first algorithm, used as a baseline method for comparison with previous work, is based on velocity obstacle (VO) theory (Fiorini and Shiller, 1998). The second method is developed specifically for use within airspace defined as a (street) network, and uses knowledge of the airspace topology to predict worst-case situations and resolve conflicts using halt manoeuvres. Lastly, the third algorithm is a combination between the first two: conflicts are detected using velocity obstacles, and resolved using halt manoeuvres.

3.1. State-based CD&R using velocity obstacles

Conflict detection and resolution using velocity obstacle theory has been researched and used in previous work pertaining to both classical aviation and U-space/UTM operations (Velasco et al., 2015; Ribeiro et al., 2021), and is used as a baseline method within the investigation at hand. The relative position ($\mathbf{x}_{\text{rel}}$) and the protection zone radius (R_{pz}) between aircraft in a conflict pair are linearly extrapolated in time (τ) to obtain the collision cone (CC) according to Eq. (8). The obtained set contains all relative velocities ($\mathbf{v}_{\text{rel}}$) that would result in the occurrence of an intrusion event within the look-ahead time (i.e., the minimum separation threshold between two aircraft would be breached).

$$\text{CC} = \left\{ \mathbf{v}_{\text{rel}} : \|\mathbf{v}_{\text{rel}} - \frac{\mathbf{x}_{\text{rel}}}{\tau}\| \leq \frac{R_{pz}}{\tau}, \forall \tau \in (0, \infty) \right\} \tag{8}$$

The velocity obstacle can then be obtained by translating the collision cone using the intruder velocity ($\mathbf{v}_{\text{intr}}$), as shown in Fig. 4. Thus, the resolution velocity ($\mathbf{v}_{\text{sol}}$) is obtained by reducing the ownship velocity ($\mathbf{v}_{\text{own}}$) until it lies outside the VO area. The implementation of the velocity obstacle state-based CD&R algorithm is presented in Alg. 1. Firstly, loss of separation events are handled as they pose a high safety risk, then conflicts are approached on a pair-wise basis. After priority has been established for all conflict pairs, aircraft with priority are allowed to continue as normal.

3.2. Worst-case CD&R using halt manoeuvres

The worst-case CD&R method uses a conservative approach to deconfliction that takes advantage of knowledge of the street network characteristics to improve the conflict detection accuracy (more extensively explained in Badea et al. (2024)). It is shown to perform better in nominal conditions compared to the state-based VO method through the use of halt manoeuvres performed closer to the predicted conflict location. Thus, many false-positive conflicts are resolved before any

Algorithm 1 State-based CR using velocity obstacles.

```
conflict_pairs = all (ownship, intruder) | state-based conflict
for all ownship, intruder in conflict_pairs do
    priority_ownship = True          ▷ Assume priority until proven otherwise
    if loss of separation then
        if intruder is in front or closer to path intersection then
            priority_ownship = False         ▷ Ownship does not have priority
            return Halt                      ▷ Allow the other aircraft to pass
        end if
    else if intruder is in front then
        priority_ownship = False             ▷ Ownship does not have priority
        return Match intruder speed
    else if intruder closer to intersection then
        priority_ownship = False             ▷ Ownship does not have priority
        return Lower speed VO command        ▷ Slow down to resolve conflict
    end if
end for
for all aircraft do
    if priority_ownship is False for this aircraft then
        return Nominal cruise speed command  ▷ Aircraft with priority fly their nominal speed.
    end if
end for
```

action is required, which improves airspace stability and lowers the flight-plan non-compliance rate. However, its performance degrades significantly in situations where wind is present due to the resulting increased local densities and decreased position prediction accuracy.

Conflicts are detected by considering all the possible paths that a potential intruder can follow within the constrained airspace network, portrayed in Fig. 5(a). In this example, three potential conflict nodes are identified by the ownship (AC_1). For each node, the priority ranking is determined in function of the distance to the node: the closest aircraft has priority.

The conflict resolution strategy makes use of halting manoeuvres ahead of intersections to allow aircraft with priority to pass. For the situation presented in Fig. 5(a), the most imminent potential point of conflict is node N_2, for which the ownship (AC_1) has priority. Thus, the resolution manoeuvre presented in Fig. 5(b) is implemented, where the intruder AC_2 halts at point p_{stop} such that the minimum separation distance between the aircraft is respected. After the priority aircraft has cleared the intersection, the other aircraft resumes normal navigation. The algorithmic implementation of the worst-case algorithm used in this work is presented in Alg. 2.

3.3. State-based CD&R using halt manoeuvres

The third and last tactical CD&R algorithm used in this work attempts to combine the advantages of the state-based VO and worst-case methods. The first excels in high-uncertainty environments due to its simplicity and adaptability (Hoekstra and Ellerbroek, 2021), while the latter performs better within constrained urban airspace by using the (street) network topology to only react when deemed necessary (Badea et al., 2024). Thus, the aim of the development of this method is to investigate whether the use of halting manoeuvres can improve the false-positive manoeuvring rate of the state-based CD&R method while retaining its robustness against uncertainties such as wind.

For this method, the detection process remains the same as described in Fig. 4. However, instead of selecting a resolution velocity using VO methods, a halt command is issued ahead of the estimated point of intersection between the two aircraft, as shown in Fig. 6. The algorithm is implemented similarly to Alg. 1, with the only difference consisting in the issuing of a "Halt command" instead of a "Lower speed VO command".

Algorithm 2 CR algorithm used in combination with Worst-case CD from the ownship point of view.

```
conflict_pairs = all (ownship, intruder) | state-based conflict
for all ownship, intruder in conflict_pairs do
    if intruder is behind and on same route then
        return None        ▷ Ownship has priority, no manoeuvre is applied.
    else if intruder is in front and on same route then
        return Match intruder speed      ▷ Intruder has priority, match its speed.
    else
        solutions = []  ▷ List to store all potential solutions for this conflict.
        for all nodes in intersection_nodes do  ▷ All potential conflict nodes are checked.
            Estimate time to reach node for both aircraft
            Calculate the position of the stopping point for this node
            if ownship will reach node faster then
                store None in solutions   ▷ For this conflict node, the intruder must halt.
            else if close to stopping point then
                    ▷ Ownship will not reach node faster and must start halt manoeuvre soon.
                store Halt in solutions
            else
                    ▷ Ownship is not yet close to stopping point, no manoeuvre is applied for now.
                store None in solutions
            end if
        end for
        if Halt in solutions then      ▷ Determine ownship course of action.
            return Halt      ▷ Ownship must halt as it is close to one of the conflict intersections.
        else
            return None                ▷ Ownship does not apply a manoeuvre.
        end if
    end if
end for
```

4. Experiment

The following section presents the experiment design used to investigate the proposed conflict detection and resolution methods. The setup is identical to that used in our previous work (Badea et al., 2025) to enable the comparison of results of a 4D trajectory strategic deconfliction method with the novel network-flow method in this work.

4.1. Hypotheses

The 4D trajectory planning method is expected to achieve a higher level of safety and efficiency in nominal conditions (i.e., no wind or delay) compared to the flow-based strategic planning method, especially when RTA commands are enforced. Such methods allow a higher proportion of aircraft to use shorter routes, thus lowering the flight time. Furthermore, the use of RTA commands ensures that aircraft comply with the optimised flight plans, reducing the occurrence of conflicting situations. Thus, hypothesis **H1** is formulated as follows:

H1 The use of the 4D trajectory planning method will result in a higher safety level in nominal conditions compared to the flow-based strategic planning method.

On the other hand, the flight plans produced by the flow-based strategic planning method are expected to be more resilient when uncertainties are present. Due to the more even distribution of aircraft within the airspace network, the severity of resulting bottlenecks and conflict hotspots should be lower than when using the 4DT pre-departure deconfliction strategy. However, this is also expected to increase the average mission travel time. Therefore, the following hypotheses are formulated:

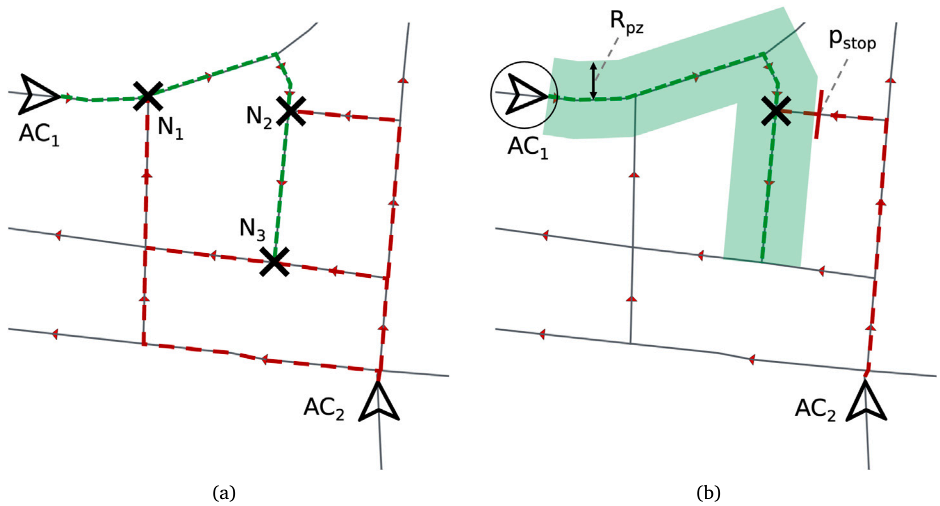

Fig. 5. Functioning principle of the worst-case CD&R method within a uni-directional street network (directionality represented by the small red arrows). The ownship (AC_1) accounts for all possible paths of the intruder (AC_2), and determines all conflict nodes (N_1, N_2, and N_3). The intruder resolves the conflict by stopping at p_{stop} ahead of the most immediate conflict node, ensuring the minimum separation distance R_{pz}.

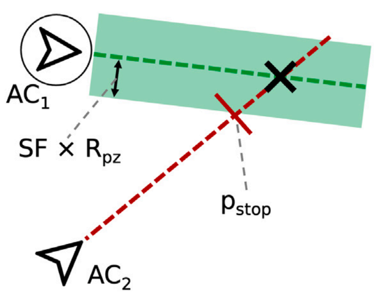

Fig. 6. Resolution using halt manoeuvres for state-based conflict detection methods: the intruder (AC_2) must halt at point p_{stop} ahead of the predicted intersection.

H2 The safety level of operations will experience a lower degradation rate when using the flow-based strategic planning method compared to the 4D trajectory deconfliction methods, at the expense of efficiency.

The last hypotheses considered in this experiment concern the selection of tactical CD&R strategy. The worst-case CD&R method is expected to deliver the highest level of safety due to the conservativeness of resolution manoeuvres. For the same reason, the use of halting commands is also predicted to improve the performance of the state-based tactical CD&R method. However, in both cases, this might come at the cost of increased travel time, leading to the following hypotheses:

H3 The worst-case tactical CD&R method will deliver the best safety performance level across all conditions due to its conservative conflict handling algorithm.

H4 The performance of the state-based tactical CD&R method will increase across all conditions when using halt commands due to the reduction in false-positive conflict resolution manoeuvres.

H5 The use of halt commands will increase the average mission travel time compared to VO-based manoeuvres.

4.2. Simulation software

The BlueSky Open Air Traffic Simulator (Hoekstra and Ellerbroek, 2016) is used to simulate traffic scenarios and study the proposed CD&R methods. This software has been utilised previously in U-space/UTM research (USEPE consortium, 2022; Chen et al., 2024), and facilitates the implementation of custom plugins for CD&R methods, the wind model, and the departure delay model. Simulations can also be reliably reproduced using BlueSky scenario files.

4.3. Navigation in constrained very-low-level urban airspace

The simulation environment for this research is based on the street network of the central districts of Wien, Austria (Fig. 7), chosen for its varied topology: some sections are grid-like, others have an organic topology. The network is extracted from OpenStreetMap (OpenStreetMap contributors, 2017) using OSMnx (Boeing, 2017), then processed to give each edge a single direction. Edges are grouped into smooth "strokes" using the COINS algorithm (Tripathy et al., 2020), then a genetic algorithm (detailed in Badea et al. (2021)) assigned stroke directions to minimise total travel distance between any two nodes while ensuring unidirectionality. Lastly, the airspace is divided into 50 ft (15.24 m) flight layers, to a maximum height of 500 ft (152.4 m) above the lowest allowable flight altitude.

4.4. Traffic scenario generation and optimisation

Air traffic demand scenarios are generated within the considered urban airspace environment by planning point-to-point missions between the nodes of the network. Flight requests are generated for a demand level of 120 aircraft per minute (ac/min), based on the high end of estimated future traffic levels (Doole et al., 2020; Veytia et al., 2022).

To further process the flight requests, an implementation of the proposed flow capacity management method is created using the Python package of the Gurobi optimiser (Gurobi Optimization, 2024) (available online: (Badea, 2024)). The No Relaxation Heuristic method is used to rapidly obtain feasible solutions, and then allowed to further run up to a cut-off time of 30 min to improve the route selection and average travel time. The optimisation is performed on a machine running Ubuntu 22.04.3 LTS on an AMD Ryzen 5950X CPU and 128 GB of RAM using the following parameters:

- CPU Threads : 16
- Time Limit : 1800 s
- Presolve method : 2
- Optimality threshold (MIPGap) : 1%

Fig. 7. The constrained VLL urban airspace network used in this work, based on the street network of the city centre of Wien, Austria.

Table 1
Characteristics of the DJI Matrice 600 drone model included in BlueSky, based on manufacturer specifications (DJI, 2023).

Maximum horizontal speed	18 m/s
Horizontal acceleration	3.5 m/s^2
Maximum bank angle	25 °
Maximum wind resistance	8 m/s
Turn velocity	4.78 m/s
Turn radius	5 m

The processed flight plans are then converted to BlueSky scenarios and simulated.

4.5. Aircraft model and characteristics

In this experiment, we focused on a single aircraft type, the DJI Matrice 600 drone, to reduce the effect of confounding factors on the results and to focus on the fundamental differences between the CD&R methods. The BlueSky simulator includes a simplified model of this drone, with characteristics detailed in Table 1. The turn velocity is used when the drone must perform a change in heading of more than 25 ° to avoid overshoot and remain within the limits of the streets.

4.6. Uncertainty models

4.6.1. Wind model

A simplified wind model is used to induce variations in the cruise velocity of cruising aircraft, described by Eq. (9)–(11). A global wind magnitude (mag_{roof}) is selected and projected onto streets in function of the bearing difference between the street and wind direction ($\Delta_{bearing}$).

$$\text{mag}_{street} = \text{mag}_{roof} \cos(\Delta_{bearing}) \tag{9}$$

$$\text{dir}_{street} = \begin{cases} 1, & \text{if } \Delta_{bearing} < 90 \\ -1, & \text{otherwise} \end{cases} \tag{10}$$

Then, the effect on the ground speed of aircraft (Δ_{gs}) is given by the street wind magnitude (mag_{street}) and the wind direction (dir_{street}), producing either an increase or decrease in velocity. Furthermore, the maximum attainable velocity of aircraft is also lowered by the same amount.

$$\Delta_{gs} = \text{mag}_{street} \times \text{dir}_{street} \tag{11}$$

4.6.2. Departure delay model

The departure delay is modelled as an exponential distribution in accordance to literature (Mueller and Chatterji, 2002). Past experiments (Badea et al., 2025) show that a 30% departure delay probability provides insight into the behaviour of traffic in high uncertainty conditions. Thus, this value is also used for the work at hand. Then, a random delay value, limited to a maximum of 5 min, is sampled from an exponential distribution (λ = average delay magnitude^{-1}) and added to the nominal departure time.

4.7. Independent variables

The experiment conditions are given by the following independent variables:

1. Pre-departure strategic CD&R method (4 conditions)
   - 4D trajectory deconfliction method (4DT) with waypoint required time of arrival enforcement, and flow management method with T_w = 5s, 10s, and 20s
2. Tactical CD&R method (3 conditions)
   - State-based VO, state-based halt, and worst-case halt
3. Rooftop wind magnitude (3 conditions)
   - 0 (no wind), 2, and 4 m/s
4. Rooftop wind direction (4 conditions)
   - 0 °, 90 °, 180 °, 270 °
5. Average delay magnitude (3 conditions)
   - 0 (no delay), 10, and 30 s

The experiment consists of three distinct parts: nominal conditions, wind variations, and delay scenarios. Each experimental condition is replicated five times using different sets of randomly generated traffic requests, resulting in a total of 660 simulated traffic scenarios and over 7 million missions.

4.8. Dependent measures

The following performance metrics are considered during the experiment, used to quantify the operational safety and efficiency performance of the proposed CD&R models.

1. Total number of detected conflict aircraft pairs
   - A conflict is defined as a situation that requires intervention to prevent an intrusion event from happening.
2. Total number of intrusion events
   - Within the present study, the minimum separation limit between two aircraft is set as 32 metres, as used in previous work (Badea et al., 2025).
3. Intrusion distance at closest point of approach
   - Used to quantify intrusion severity

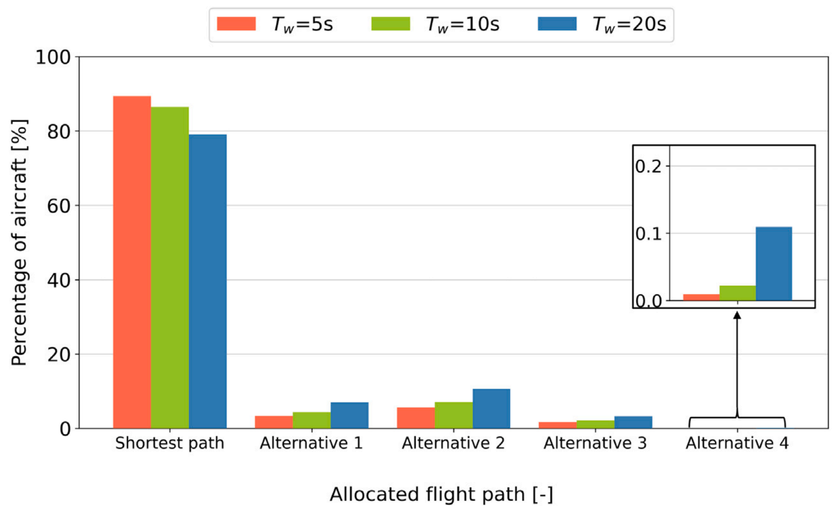

Fig. 8. Histogram of allocated flight paths in function of flow time window value. The alternative routes are labelled in accordance with Fig. 1.

Table 2
Control variables used for all experiment conditions.

Name	Value
Traffic demand level	120 ac/min
Node flow capacity C_n	1 ac/min
CD look-ahead time	10 s
CD&R module update interval	0.5 s
Maximum flight altitude	500 ft (152.4 m)
Minimum flight altitude	50 ft (15.24 m)
Number of flight layers	10
Target cruise velocity (true air speed)	15 m/s
Minimum separation threshold	32 m

4. Average mission duration

- Used to quantify efficiency over the whole span of one experiment condition (one traffic scenario), and reflects the level of disruptiveness of the CD&R methods.

4.9. Control variables

Table 2 summarises the control variables of the experiment. Most of these conditions are identical to previous experiments in Badea et al. (2025) to allow the comparison of results.

To enable comparability with previous work (Badea et al., 2021, 2025), the minimum separation threshold is set to 32 metres. This value is sourced from the signal-in-space positioning performance requirements for from Table 3.7.2.4-1 of the ICAO Aeronautical Telecommunications specifications (International Civil Aviation Organisation, 2018).

5. Results

The following section is divided into two parts: the first presents the results of the flight plan optimisation process; the second part contains the results of the air traffic scenario simulations.

5.1. Flight plan strategic optimisation

The flight plan optimisation process was able to successfully allocate routes to aircraft without flow violations (described in Eq. (2)) in most cases. Furthermore, the objective function value was within approximately 5% of the lowest bound in most cases, including when the process was interrupted due to the time constraint. However, in one instance (T_w = 20s, repetition 3), a single flow violation was not resolved within the allocated time, leading to an optimality gap of 15%.

The optimiser was able to allocate the shortest path between the origin and destination to most aircraft, as shown in Fig. 8. Out of the alternative routes, the most used was alternative 2, which avoids the middle section of routes. This was expected, as this section will on average be closer to the city centre, and thus more congested. The fourth alternative, which completely avoids the shortest route path, was used the least in all cases (less than 0.4% of flights). Thus, a high percentage of traffic (80% or more) used the most efficient routing, with much of the rest being diverted around one portion of the ideal path. Lastly, increasing the time window value (i.e., the average time separation between two aircraft as shown in Fig. 3) resulted in greater use of alternative routes, as this resulted in a lower flow allowance for every node.

The altitude allocation results also show a similar trend. In all cases, the majority of aircraft were assigned to the lowest flight level, and an increase in the time window value led to higher altitude flight levels being increasingly used, as shown in Fig. 9. The altitude distribution of the T_w = 10s case is most similar to the 4D trajectory planning method. However, it should be noted that, in the case of the 4DT method, the optimiser (described in Badea et al. (2025)) was able to allocate all aircraft to their respective shortest routes.

5.2. Simulated performance metrics

Fig. 10 shows the number of unique conflict pairs considered by the tactical CD&R methods. The results between the two state-based methods (VO resolution or halt manoeuvres) are similar, with the use of halt manoeuvres leading to a relatively small increase in the number of conflicts. Furthermore, the worst-case method detected significantly more conflicts, in line with expectations.

However, an important result can be seen when comparing the results in Fig. 10 between strategic planning methods. Regardless of the choice of tactical CD&R method, the use of a flow time window value of 20 s led to the detection of considerably fewer conflicts. This resulted in the occurrence of fewer intrusion events, as shown in Fig. 11. The number of intrusions in nominal conditions also reveal that the use of the worst-case tactical CD&R method in combination with the flow capacity management with T_w = 20 yielded the highest level of safety. While the use of halting manoeuvres improved the performance of the state-based method, enhancing conflict predictions using knowledge of

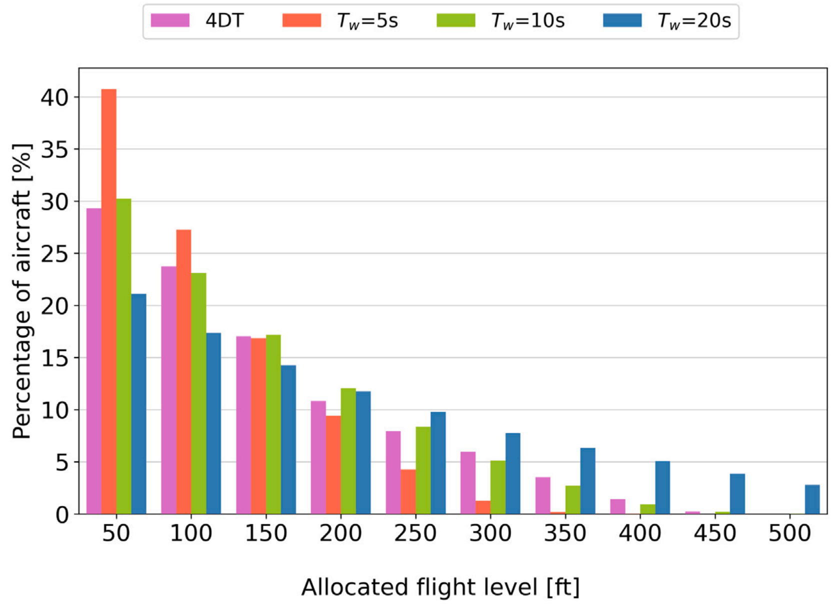

Fig. 9. Histogram of allocated altitude levels in function of strategic planning method.

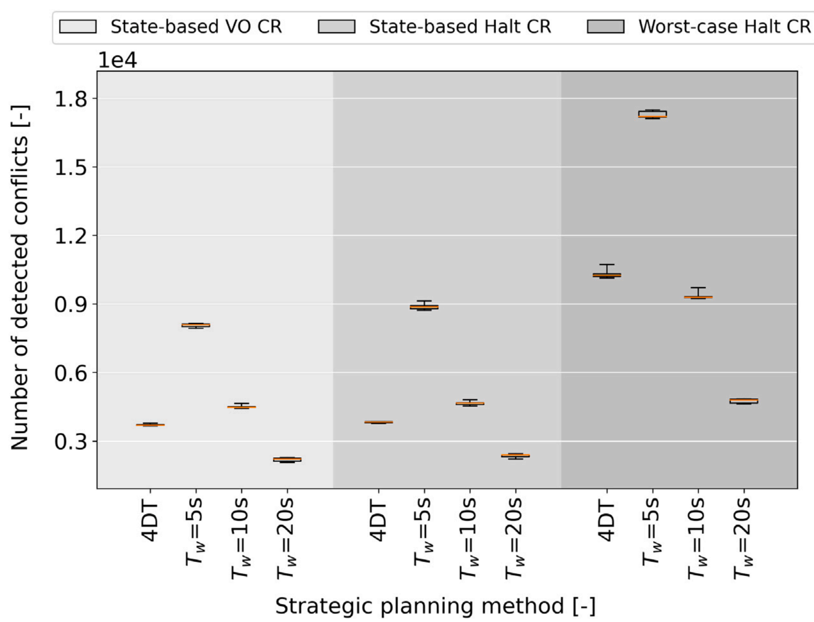

Fig. 10. Average number of unique conflict pairs detected by each tactical CD&R method in nominal conditions (no wind and delay).

the airspace network topology helped greatly reduce the number of intrusions.

The simulations in which wind was present reveal that the use of halting manoeuvres results in a lower degradation in performance when compared to nominal conditions, as shown in Fig. 12. Furthermore, results indicate that the worst-case CD&R method performed best when flight plans were optimised using the T_w = 20s method, with minimal degradation in the safety level. The traffic scenarios in which 4D trajectory planning was used were also robust against wind, as the use of RTA commands for each waypoint enabled aircraft to adapt their velocity and remain compliant with their flight plan.

On the other hand, the scenarios optimised using the 4DT method experienced a high degree of degradation when departure delay uncertainty was present, presented in Fig. 13. Whereas in nominal conditions, the safety level is comparable to the T_w = 20s method, the increase in delay led to the occurrence of more intrusion events when compared to the flow-based capacity management methods, which remained relatively consistent in performance with increasing uncertainty level. This results from the need for aircraft to cruise at higher velocities to comply with the RTA commands for each waypoint, attempting to enter a state of flight plan compliance.

A noteworthy result is that, for the high average departure delay case (30s), the 4DT method performed similarly to the flow-based method with T_w = 5s when combined with the worst-case tactical CD&R algorithm. This shows the susceptibility of 4D trajectory optimisation methods to over-optimise flight plans, leading to reduced resilience against uncertainties, also reported in other work (Joulia and Dubot, 2022).

The higher robustness of the flow capacity management methods can also be observed in Fig. 14, which presents a histogram of the distance at the closest point of approach during intrusion events. In all situations, the use of the flow-based capacity management method

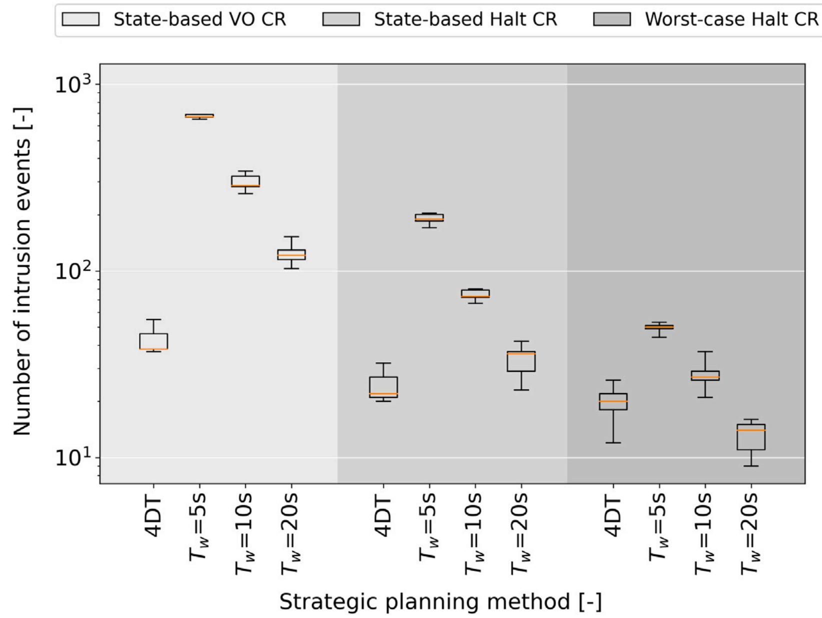

Fig. 11. Average number of intrusion events in function of strategic and tactical CD&R method in nominal conditions (no wind and delay).

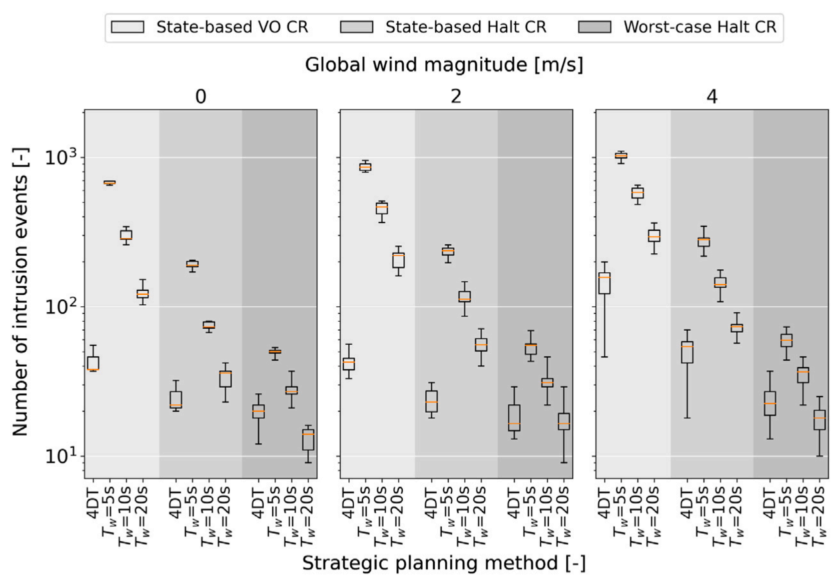

Fig. 12. Average number of intrusion events in function of strategic and tactical CD&R method in function of global wind magnitude.

resulted in a higher proportion of low-severity intrusions (i.e., smaller intrusion distance). This can be a result of the higher use of shortest routing when using the 4DT method (i.e, over-optimisation), leading to higher local traffic densities and thus higher conflict complexity (multi-aircraft conflicts). The use of alternative routes contributed towards the mitigations of such situations. Furthermore, while the results also indicate that the use of the worst-case CD&R method also leads to an increase in the intrusion severity level, it should be noted that the total number of such events was considerably lower when this tactical algorithm was used, leading to higher safety overall.

Lastly, the results portrayed in Fig. 15 show that the increase in safety level achieved by the flow-based capacity management method is achieved by modestly sacrificing operational efficiency. With increasing flow time window value, the average mission time increased by approximately 20 s (approximately 5%) compared to the 4DT case, which allocated the shortest route for all missions. The tactical CD&R method used did not have a significant influence on the average mission travel time, thus resulting in a higher level of safety with no impact on operational efficiency.

6. Gurobi optimisation performance

Table 3 presents the performance metrics of the flight plan optimisation tool. The optimisation was performed using the No Relaxation Heuristic method of Gurobi (Gurobi Optimization, 2024). The gap parameter represents the percentage difference between the final value of the objective function and the lowest bound at the end of the optimisation process. In one case (T_w = 20s, repetition 3, 1800s-3900s), one violation remained when the time limit of 1800s was reached, resulting in a large gap value. The optimisation time predictably increased with larger time window values resulting in a stricter set of flow constraints.

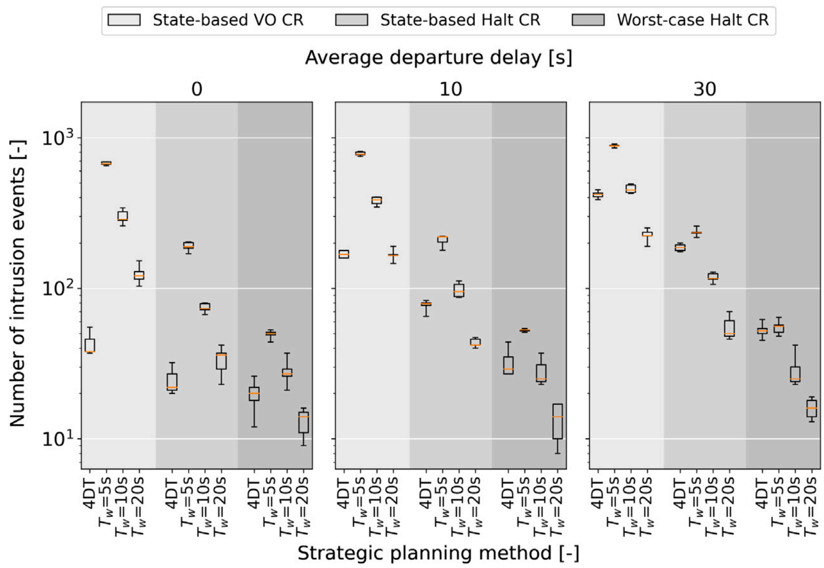

Fig. 13. Average number of intrusion events in function of strategic and tactical CD&R method in function of average departure delay.

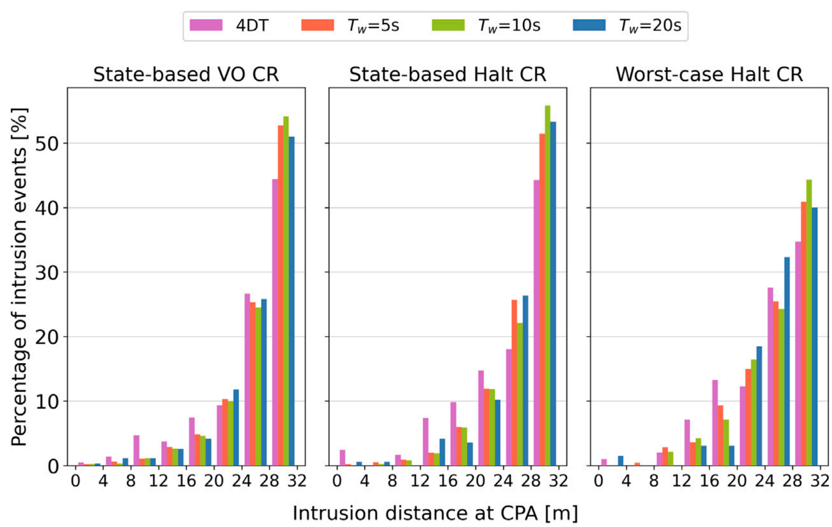

Fig. 14. Histogram of the distance at the closest point of approach (CPA) during intrusion events in function of tactical and strategic CD&R method in nominal conditions (no wind or delay).

Table 3
Flight plan optimisation performance for every air traffic scenario.

		Planning time window [s]								
		0–2100			1800–3900			3600–5700		
T_w	Rep.	Time to no violations [s]	Total time [s]	Gap[%]	Time to no violations [s]	Total time [s]	Gap [%]	Time to no violations [s]	Total time [s]	Gap [%]
5s	1	23	679	0.97	31	140	0.92	38	100	0.68
	2	25	619	0.99	33	169	0.92	51	113	0.78
	3	20	875	0.99	30	152	1.00	40	99	0.76
	4	20	524	0.99	36	97	0.97	38	86	0.71
	5	25	696	1.00	31	102	0.99	61	113	0.74
10s	1	46	1800	1.86	48	1800	1.14	64	331	0.95
	2	49	1800	2.24	54	1800	1.16	60	390	1.00
	3	44	1800	1.93	45	1800	1.06	54	288	0.97
	4	31	1800	1.90	48	1800	1.13	57	301	0.94
	5	31	1800	1.94	51	1800	1.11	63	237	0.99
20s	1	567	1800	4.81	919	1800	2.31	1566	1800	1.71
	2	850	1800	4.91	1560	1800	2.60	1249	1800	1.71
	3	896	1800	5.06	-	1800	15.78	-	1800	1.37
	4	350	1800	4.46	968	1800	2.27	941	1800	1.43
	5	442	1800	4.85	1539	1800	2.73	1395	1800	1.70

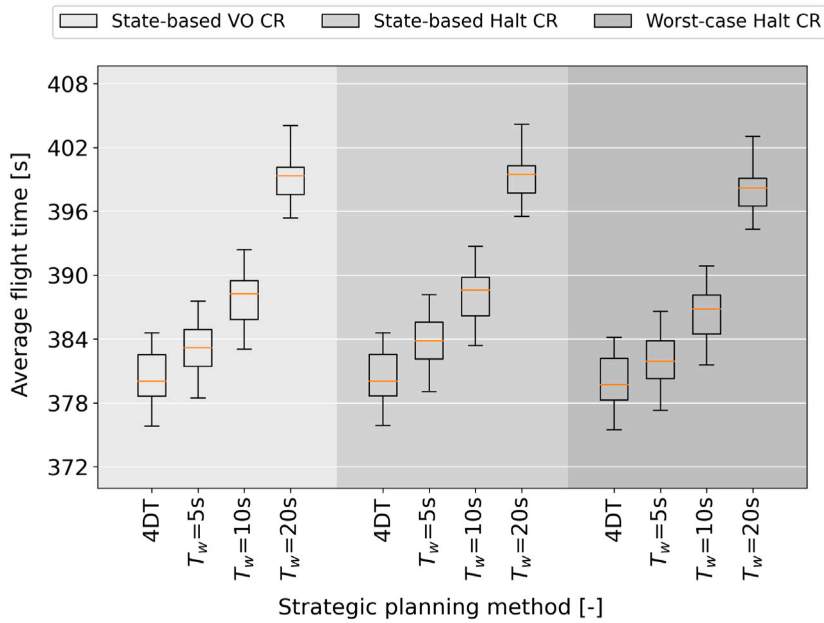

Fig. 15. Average flight time per simulation scenario in function of tactical and strategic CD&R method.

7. Discussion

The results presented in this work highlight the benefits of designing tactical and strategic conflict detection and resolution methods that can effectively cooperate towards higher airspace safety when facing high traffic densities or uncertainty levels. While the 4D trajectory planning method performed better in combination with the state-based velocity obstacle tactical CD&R method, the reduction in the number of conflicting situations while using flow capacity management allowed the worst-case CD&R method to function more effectively in ensuring separation, as a result of distributing aircraft more evenly within the airspace. The use of RTA commands to ensure flight plan compliance was unable to compensate for the deviations induced by the presence of wind and departure delay. Thus, hypothesis **H1**, which states that the use of the 4DT method would result in a higher safety level compared to the flow-based method, is rejected.

The other hypotheses concerning the performance of the strategic CD&R methods (**H2**) can be accepted. The network flow capacity management method produced flight plans that are more robust against time deviations. By enforcing flow constraints instead of using the time-based separation strategy of the 4D trajectory planning method, traffic was better distributed throughout the airspace network, achieving lower traffic densities regardless of the uncertainty level.

The robustness of the flow-based flight planning method was further enhanced by using overlapping time windows, which reduced the effect of the inaccuracies in the time of arrival estimations for each waypoint within a trajectory. This induced a more conservative approach, and the increased use of alternative routes for more strict flow constraint levels. However, this produced a modest increase in the average travel time due to the more prevalent use of non-optimal routing.

Hypotheses **H3** and **H4** regarding the tactical conflict detection and resolution methods can also be accepted. The results strongly suggest that the use of halting manoeuvres improves the safety level of constrained urban airspace, as reactions to false-positive conflicts can be delayed until the need to stop arises, rather than applying a resolution velocity upon first detection. This effect is further strengthened when airspace structure information is used to further reduce unnecessary manoeuvring and lower operational disruptions resulting from tactical intervention. Furthermore, the reduction in the number of tactical interventions also allowed aircraft to fly at cruise speeds for a larger proportion of their mission, therefore compensating for the operational inefficiency of halt manoeuvres, as the average mission travel time was not significantly affected by the choice of tactical CD&R method. Furthermore, the amount of time a drone spends at resolution velocities is small compared to the total mission length. Thus, hypothesis **H5** can be rejected.

Overall, the study at hand shows that improved compatibility between tactical and pre-departure strategic CD&R methods for VLL urban airspace operations is beneficial for airspace safety while producing a relatively low effect on the efficiency level. Flight plan over-constraining through the use of strict 4D trajectory planning is thus not necessary, as it can lead to over-optimisation and decreased flexibility in the face of uncertainties such as wind and departure delay. The delegation of the responsibility for local deconfliction towards the tactical deconfliction module can be beneficial, and can thus result in a reduction in the required complexity of the CD&R module of a U-space/UTM system, while increasing both the levels of efficiency and safety.

8. Conclusion

8.1. Main findings

The study at hand sought to develop and test combinations of pre-departure strategic, and tactical conflict detection and resolution methods that are resilient in dynamic and uncertain operational environments. We developed and tested a traffic-flow capacity management planner with the aim of delegating a higher proportion of the deconfliction responsibility to the tactical CD&R module, while improving the distribution of traffic within the airspace network. Several combinations of strategic and tactical methods were tested using high-density urban air traffic scenarios, and compared with 4D trajectory optimisation pre-departure methods.

Simulation results indicate that the use of flow-based strategic planning achieves a higher safety level at the strictest flow capacity allowance when compared to the baseline 4D trajectory method, regardless of the choice of tactical CD&R strategy. Furthermore, the use of the Worst-case CD&R method is the most resilient against the effects of wind and departure delay, as this tactical method benefits from the reduction in local traffic density and conflict complexity. However, the use of flow-based strategic planning results in a (modest) decrease in operational efficiency due to the more prevalent use of alternative routes.

Overall, we demonstrate the importance of designing conflict detection and resolution methods for interoperability and system-wide compatibility with other services. Furthermore, our findings indicate that delegating a higher proportion of the deconfliction task to the tactical resolution module benefits the safety of operations. By eliminating the need for strict flight plan temporal compliance, the complexity of air traffic management for U-space/UTM systems can be reduced.

8.2. Recommendations for future research

The methods presented within this study are subject to several limitations that require future research and development ahead of a potential deployment. First, the alternative routes generated by the method described in Fig. 1 are highly dependent on the geometry of the shortest path between the origin and destination, and the topology of the surrounding network. This process can be further enhanced by considering historical traffic density and conflict information, similar to the method presented in Morfin Veytia et al. (2024), to provide more effective routing that better avoids known traffic bottlenecks.

Another limitation of our work stems from the simulated traffic scenarios and conditions. While the traffic density is consistent with future urban air traffic demand predictions, the distribution of origin and destination vertiport is homogeneous throughout the airspace network. In reality, certain areas within cities are subject to higher demand for departures and arrivals, creating traffic patterns that might influence the performance of the CD&R methods presented in this work. Lastly, the simulation of uncertainties is limited, as both the implementation of wind and delay makes use of simplified models that might capture a relatively narrow range of possible uncertainties in urban airspace environments. Thus, future research should focus on higher-fidelity simulations including heterogeneous traffic, as well as live experiments and demonstrations, to further validate the performance of the proposed capacity management and deconfliction modules in realistic conditions that include more sources of uncertainty (e.g., sensor errors, communication latency).

CRediT authorship contribution statement

Călin Andrei Badea: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Joost Ellerbroek:** Writing – review & editing, Supervision, Software, Funding acquisition, Conceptualization. **Andrija Vidosavljević:** Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Jacco Hoekstra:** Writing – review & editing, Supervision, Software, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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