Journal of Open Aviation Science (2025), Vol.**3**
doi:10.59490/joas.2025.7921

JOAS

ARTICLE

Very-low-level U-space Conflict Detection and Resolution: Focused Developments, Analysis, and Future Prospects

Calin Andrei Badea [1], Andres Morfin Veytia [1], Andrija Vidosavljević [2], Joost Ellerbroek [1] and Jacco Hoekstra [1]

[1]Faculty of Aerospace Engineering, TU Delft, Delft, The Netherlands
[2]OPTIM, Ecole Nationale de l'Aviation Civile (ENAC), Toulouse, France

(Received: 9 Nov 2024; Revised: 25 Feb 2025 and 29 Apr 2025; Accepted: 6 May 2025; Published: 20 May 2025)
(Editor: Peng Wei; Reviewers: Shulu Chen, Christopher Conrad, and Yutong Chen)

Abstract
A safe and efficient integration of U-space operations necessitates robust conflict detection and resolution (CD&R) mechanisms, particularly for very-low-level (VLL) operations in constrained urban airspace. Research has focused on the development of navigation and traffic management concepts suitable for such operations that aim to mitigate the challenges posed by this novel environment. However, the current research landscape is fragmented, with CD&R methods still needing to be integrated within a more unified framework. In this paper, we present an overview of our approach towards air traffic management for VLL U-space operations and analyse their limitations compared to other work. Then, based on the conclusions of other existing work, we identify key areas for improvement and propose recommendations for future research and development for VLL airspace structure design, conflict detection and resolution, and U-space operations simulations. We conclude that a unified approach should be used towards integrating and investigating the interdependencies of U-space services within a standardised verification and validation framework.

Keywords: U-space; CD&R; tactical; strategic; dynamic; uncertainties;

Abbreviations: CD&R: Conflict Detection & Resolution, 4DT: 4D Trajectory planning, VLL: Very Low Level

1. Introduction

Urban air mobility holds the potential to deliver a sustainable alternative to traditional ground-based transportation and to alleviate mounting urban traffic congestion [1]. The U-space initiative [2, 3], designed to manage urban air traffic within the European Union, establishes the groundwork for developing the necessary services to support such operations. While a robust foundation has been established, further research and development are still needed to translate this conceptual framework into a fully implementable system.

A vital component of the U-space system is conflict detection and resolution (CD&R), responsible for guaranteeing the safe execution of urban air operations [4]. Research efforts have been focused on establishing how this service will be provided, with a particular emphasis on ensuring its effectiveness, reliability, and scalability to meet the demands of the anticipated increase in urban air traffic [5]. This includes investigating both centralised and decentralised CD&R architectures, as well as methods to ensure the resilience of operations against uncertainties (e.g., wind, delay).

Very-low-level (VLL) airspace operations, such as package deliveries, represent a critical segment of the U-space market demand [6]. Such operations will take place at flight altitudes below 500 ft (ca. 152 m) [4]. This poses challenges for establishing the structure and guidance procedure of such airspace [5] due to factors such as the presence of buildings and other urban obstacles, or privacy. Although not directly part of the CD&R subsystem, the design of the airspace structure influences the effectiveness of deconfliction processes, and ensuring their compatibility is important.

The challenge with these components lies in their integration into a larger, unified U-space framework [5]. Each element must be compatible with the others to address both pre-flight and in-flight uncertainties, while also accommodating factors like weather or airspace restrictions. In our past work [7, 8, 9, 10], we developed such approaches and investigated the relationships between them. However, similarly to other work in this domain, this research is based on simulations that are limited in capturing a complete picture of the performance of the CD&R modules within a greater U-space air traffic management system. Thus, the development of solutions for the aforementioned challenges needs to continue as the deployment of U-space operations approaches.

This article aims to provide an overview and analyse how VLL U-space air traffic guidance and deconfliction have been addressed in research. We present the methods developed in our previous work for this problem, critically evaluate their limitations, and compare them with other existing literature. Based on this analysis, we offer recommendations for future research and development by integrating both our findings and the insights from existing studies. Our goal is to contribute to reducing fragmentation in the research of this domain to promote a more unified and practical implementation of VLL U-space operations.

2. VLL U-space CD&R: Overview of Our Approach

The following section presents our previous work on developing, modelling, and simulating conflict detection and resolution methods for VLL urban airspace cruise operations. It seeks to establish the context and rationale behind our research methodology, facilitating the subsequent analysis and comparison with other existing work. The first part explains the approach we developed for creating a basic structure for VLL airspace, followed by the methodology we used for generating and simulating air traffic scenarios are described. Then, the traffic management and deconfliction modules that we have developed and investigated are explained.

2.1 VLL urban airspace structure

Designing the airspace for VLL urban air operations is a key research area, with ongoing debates on how it should be structured. One debate is about the degree of constraints that the urban infrastucture imposes on the airspace. The two ends of this spectrum are: (1) open airspace above most buildings, similar to traditional aviation, and (2) constrained airspace, limited to the space above streets. While there are fewer operational constraints in open airspace, the use of constrained airspace could improve efficiency in cities where tall buildings are prevalent (e.g., New York).

In our research, we chose to focus on constrained airspace operations as it is more challenging to approach, and to determine whether improvements in efficiency can be attained without compromising safety. As part of the Metropolis 2 project [11], we developed an approach to VLL airspace structure design that has demonstrated favourable results and can be applied to a wide range of urban street network topologies. Previous work has shown [12] that altitude changes in urban airspace create additional conflicts that can destabilise the airspace. Therefore, we assume that aircraft remain at a specific height en-route to their destination. Our research focuses on the implementation of vertical take-off and landing (VTOL) operations using small uncrewed aerial vehicles (UAVs).

The process begins by extracting the city graph from open geospatial data sources such as Open-

StreetMap [13], representing the street network as a collection of nodes (intersections) and edges (street segments). We then process the graph by eliminating features such as redundant streets, tunnels, or pedestrian streets. An example of the outcome of this operation is shown in Figure 1 for the city centres of Vienna, Austria, and Rotterdam, The Netherlands.

Figure 1. Examples of street network graphs extracted for the city centres of Vienna (a) and Rotterdam (b).

Previous research has shown that the use of one-way networks significantly reduces the risk of conflicts and intrusions (defined in Figure 2). The reduction in these events is an effect of the increased aircraft alignment that one-way streets produce [6]. Thus, once the street network is cleaned, we further process it to enable the allocation of singular directions of travel along the edges. To reduce the complexity of the directionality problem, we first apply the Continuity in Streets (COINS) algorithm [14], which groups streets into continuous strokes based on geometric continuity, categorised by colour in Figure 3.

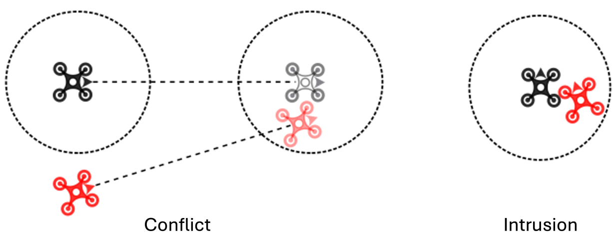

Figure 2. Conflict and intrusion diagram. A conflict occurs when an intruder (red drone) is predicted to breach the minimum separation distance (dashed circle) of the ownship (black drone). An intrusion occurs then the minimum separation distance is breached.

We then employ a genetic algorithm to define the directionality of the network. The algorithm prioritises configurations that ensure strong connectivity (i.e., any node is reachable from any other node) while minimising the average travel distance between any two nodes. Figure 3 shows the outcome of such an optimisation, where arrows represent the directionality of each stroke.

Lastly, segmentation and alignment are two key elements of promoting safety in airspace design [15]. The Metropolis project applied this principle to urban airspace by creating a layered structure

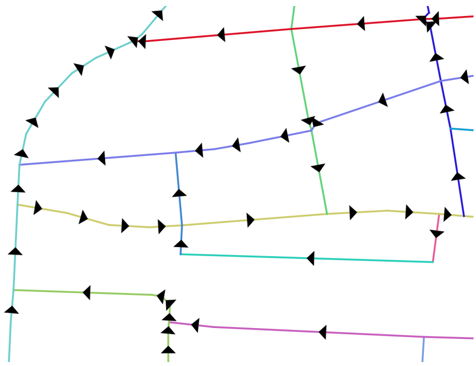

Figure 3. Example of the use of the existing street network to create a unidirectional airspace structure. Edges are coloured in function of their grouping into strokes, and the arrows indicate the allocated direction.

in which aircraft with different heading ranges cruise at different altitudes [16]. Similarly, the concept presented in this work includes the vertical separation of aircraft through the use of cruising layers along all streets of the network. As our research mainly concerns the cruise phase of U-space operations, aircraft must maintain their allocated cruise altitude throughout the whole flight.

2.2 Pre-departure flow-based strategic planning

In general, efforts to develop pre-departure strategic planning have been focused on 4D trajectory optimisation methods that aim to predict and resolve all conflicts at a flight plan level. However, the results of our work [17] indicate that methods focusing on efficiency are not resilient towards uncertainties that lead to aircraft deviating from their flight plan due to traffic over-optimisation (i.e., the reduction of safety margins as a result of increasing efficiency) [18]. While a solution to this could be increasing the emphasis on safety (e.g., by increasing safety buffers), this could lead to an increase in optimisation complexity, as a system that decides the level of safety in function of the uncertainty level would be needed.

To address this, we developed and tested a different approach to the issue of operational uncertainty (i.e., wind, departure delay) that could also lower the complexity of the U-space CD&R module. Similar to the method presented by Levin et al. [19], we propose a pre-departure strategic optimisation framework that focuses on enforcing traffic flow limits at each node of the network graph such that the frequency and complexity of conflicting situations are lowered. Then, the remaining conflicts can be solved more effectively by the tactical CD&R module. The following sections present the optimisation problem formulation for the proposed pre-departure strategic planning method. A more in-depth version of this can be found in [10].

2.2.1 Route generation

We employed the same route generation method of Bereziat et al. [20], where aircraft can be allocated a flight path from an existing set of routes. An optimisation problem can be formulated that aims to assign paths so that the total travel time is minimised. Then, the flight requests can be processed so that the predicted traffic flow at each node within the graph of the constrained airspace network does not exceed the imposed threshold. The set of routes that can be assigned to aircraft is created by generating alternatives avoiding parts of the nominal flight path, as shown in Figure 4. Thus, the first alternative avoids the first half of the nominal route, the second alternative avoids the middle section, the third alternative avoids the last section, and the fourth alternative attempts to avoid the nominal route altogether.

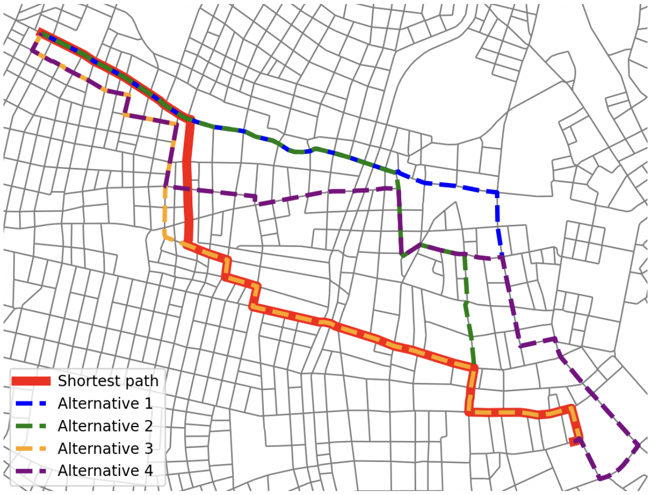

Figure 4. Alternative routes are generated such that sections of the optimal route can be efficiently avoided if needed.

2.2.2 Assumptions

The optimisation problem is implemented using several simplifying assumptions to prevent flight plan over-optimisation and reduce its complexity:

- Aircraft do not change altitude during the cruise phase.
- Take-off and landing manoeuvres are not accounted for within the flow capacity measure.
- Aircraft intended departure time is not modified.

2.2.3 Traffic flow management

In the optimisation problem at hand, the traffic flow management is coordinated through the use of time windows. Thus, the number of aircraft that can traverse a node within the graph at a certain altitude within each time window is limited, as shown in Figure 5. This way, the aircraft are planned such that the capacity at intersections is respected.

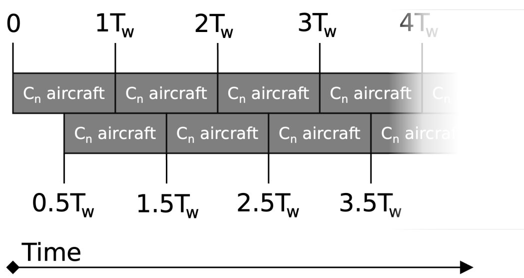

Figure 5. Visualisation of time window configuration at each intersection and altitude level of the urban airspace area. Within each time window, the flow capacity is set at C_n aircraft. Overlapping time windows are used to reduce the occurrence of local congestion peaks at the interval edges.

In contrast to methods that use separation minimums as an optimisation parameter, this method only focuses on traffic flow through intersections. This allows for more flexible planning, and distributes traffic more evenly within the network. It is assumed that, if conflicts still occur due to the planning, the tactical conflict detection and resolution module will resolve them.

2.2.4 Model parameters

The following parameters are used within the optimisation problem, describing characteristics such as the requested missions, the set of alternative routes, and the allowable flow capacity for each node within the airspace network graph.

- 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, $\forall f \in F, \forall p \in P_f$
- $x_{f,p,n,\theta} \in \{0,1\}$: 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, $\forall n \in N$
- $\delta_{f,y}$: estimated time for flight f to ascend to and descent from flight level y, $\forall f \in F, \forall y \in Y$

2.2.5 Decision variables

The optimisation problem is governed by one decision variable, which encompasses the route and cruise flight level choice for each mission.

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

2.2.6 Constraints

The first set of constraints ensure that all aircraft are allocated a route and a flight level.

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

The second set of constraints enforce the flow capacity limit at each node of the street network.

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

2.2.7 Objective function

The optimisation problem aims to minimise the mission travel time (Eq. 3), which consists of the estimated take-off and landing time, as well as the travel time associated with the selected route.

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

2.2.8 Problem feasibility

The constraint presented in Eq. 1 implies that all flight plans are accepted. However, in combination with the constrained presented in Eq. 2, this could potentially lead to problem infeasibility. Thus, the constraint in Eq. 2 can be relaxed to allow for small violations, but ensure feasibility. This allows for such violations (conflicts) to be resolved locally by the tactical conflict detection and resolution module. The constraint violation value can be employed as a decision variable and included in the objective function.

Thus, the relaxed flow constraint is presented in Eq. 4:

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

with the following decision variable being introduced, representing the constraint violation at each node of the graph, for every time window and altitude:

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

Thus, the objective function is modified to include the minimisation of the flow constraint violations, as presented in Eq. 6.

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

2.3 Dynamic capacity management

Dynamic capacity management is a U-space service for areas where traffic density is expected to be high and potentially difficult for a strategic planner to handle [2]. Previous work based on traditional air traffic management [21] aimed to create dynamic airspace sectors based on local traffic density. In our work [9] we use a similar approach and apply it to urban air traffic to develop a dynamic capacity management method where individual aircraft are in charge of re-routing around areas of high-traffic complexity.

In the absence of additional constraints, the shortest route between an origin and a destination is generally preferred. As a consequence, some travel legs are preferred more than others, especially in a topologically organic (i.e., non-orthogonal) constrained airspace network. These conditions create traffic hot spots that lead to increased conflicts and intrusions due to the higher local traffic density and complexity.

In our work [9], we attempted to mitigate these hotspots using a dynamic capacity management method. The method uses up-to-date aggregate flow information of conflict locations and makes it available to individual aircraft. These then make the decision whether to alter their current route in a decentralised manner. The goal is to incentivise aircraft to take alternate and less congested routes to their destination to lower the local traffic density and complexity. The method is illustrated in Figure 6, and the overall steps are as follows: (1) The current position of aircraft in a conflict are gathered into clusters, (2) the clusters are classified as high or low complexity based on their relative density and an additional cost of travel is applied to high-complexity areas, (3) aircraft check if their current route intersects high-density areas, (4) aircraft search for new a new optimal plan. Note that these steps are continuously repeated during flight, which allows aircraft to consider a recent snapshot of the airspace situation when making new plans.

Dynamically rerouting aircraft around conflict hotspots resulted in a greater safety level compared to a baseline case where aircraft do not re-route and always fly the shortest route. At high traffic demand levels, this method was able to reduce the number of intrusions by up to 30% while only increasing the average travel distance by less than 6%.

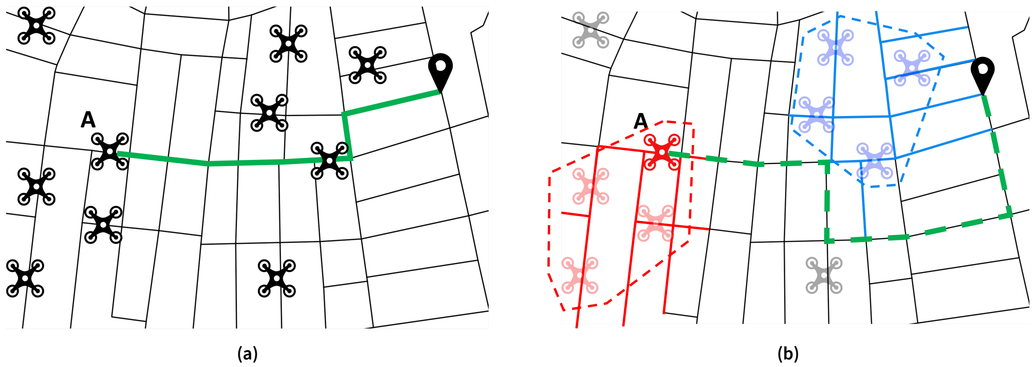

Figure 6. Drone A initially takes the shortest route to its destination (a). Then, high-cost cluster areas are created based on the position of aircraft in a conflict. Drone A observes that their current route goes through the zone with increased cost, so it dynamically creates a new plan (b).

2.4 Worst-case tactical CD&R

State-based CD&R methods (i.e., linear extrapolation of current state to predict future conflicts) such as Modified Voltage Potential (MVP) [22] or ACAS Xu [23], have been shown to perform well when employed in open airspace [16] as well as orthogonal street networks [6]. However, the results of our previous work show that such methods are less suitable in the case of organic street networks such as the ones presented in Figure 1 due to the higher prevalence of heading changes.

We thus developed and tested a conservative tactical CD&R method that uses airspace topology information to improve the conflict detection process while requiring no intent information from other aircraft. Aircraft consider for all possible conflict nodes with potential intruders in the vicinity, as shown in Figure 7a. Then, a halt resolution manoeuvre is selected by the aircraft further away from the intersection such that the most immediate conflict would be resolved (Figure 7b). The stopping location is selected such that the minimum separation threshold between the aircraft is not breached.

The use of halting manoeuvres allows aircraft delay acting upon a detected conflict, as a resolution velocity is not immediately adopted. Instead, aircraft only start decelerating just in time to stop at the required distance from the conflict intersection, allowing for some false-positive detections to be cleared and thus reduce disruptive and unnecessary manoeuvring. Speed-matching manoeuvres are used when aircraft are travelling along the same street. When compared to other methods in literature such as state-based [24] or intent-based methods [8], the worst-case method performed significantly better in constrained airspace, or matched the performance in case of the intent-based methods, but with less information exchanging requirements between aircraft.

It is important to note that the worst-case tactical CD&R method presented in this work assumes that all aircraft are cooperative, with fully functioning communication capabilities. While the handling of uncooperative aircraft is an important service within a U-space/UTM system, we consider that it should be implemented as a stand-alone detect and avoid (DAA) service, similar to the traffic collision avoidance system (TCAS) in classical aviation.

2.5 Traffic scenario generation and simulation

The traffic demand scenarios we used to simulate VLL urban airspace operations attempt to emulate point-to-point missions such as parcel deliveries and air taxiing. The scenarios are generated over several levels of predicted traffic demand levels [25]. They cover a wide range of traffic situations, as

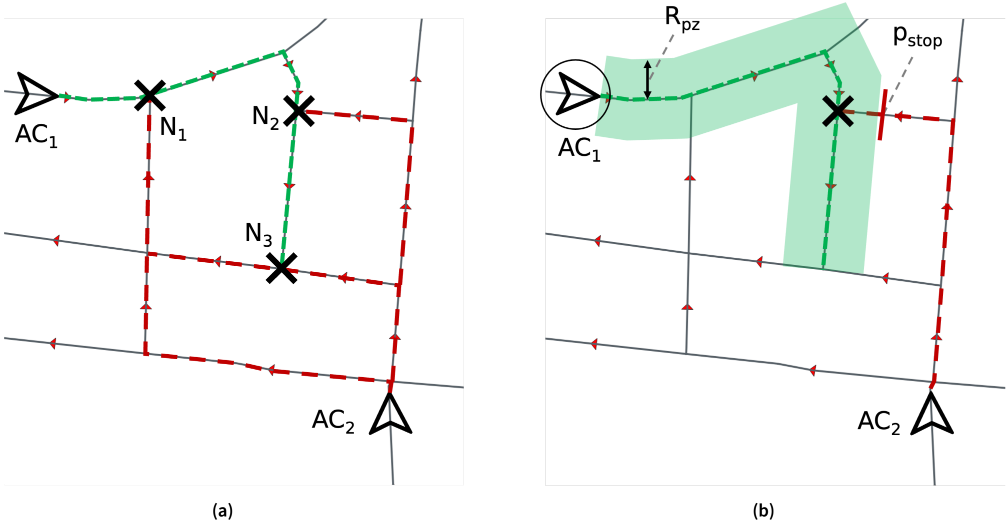

Figure 7. Functioning principle of the Worst-case CD&R method. The ownship (AC$_1$) accounts for all possible paths that the intruder (AC$_2$) could take, and determines all possible conflict nodes (N$_1$, N$_2$, and N$_3$). The intruder resolves the conflict by stopping at p_{stop} ahead of the most immediate conflict node, ensuring the minimum separation distance R_{pz}.

origin-destination pairs are randomly selected from the set of nodes of the street graph, as presented in Figure 1.

The traffic scenarios are then simulated using the BlueSky Open Air Traffic Simulator [26], chosen due to its prevalent use in the U-space field (e.g., [27, 28, 29, 30]). Its open-source implementation allows for the development and testing of CD&R plugins. One major assumption in our simulations is the use of a single type of drone, based on the DJI Matrice 600. This was done to reduce the probability of confounding factors affecting the performance results of the studied CD&R methods. It is also expected that aircraft will fly at similar velocities within each cruise flight level, as that has been shown to greatly increase safety [16].

Another particular characteristic of the simulations is the in-flight turning procedure during the cruise phase. To guarantee that drones do not collide with urban obstacles such as buildings, they must slow down ahead of turns to achieve an appropriate turn radius requirement, as shown in Figure 8. Thus, drones decelerate from their cruise speed V_{cruise} to the turn speed V_{turn}, then perform the turning manoeuvre of turn radius R_{turn}. Then, they resume nominal cruise flight.

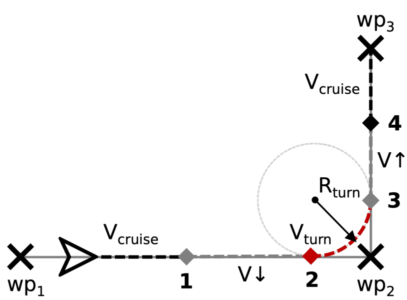

Figure 8. Turning procedure implemented within BlueSky: an aircraft must start decelerating in due time (point 1) to perform the turn with the required turning velocity (point 2 to point 3); then, cruise operations are resumed.

The characteristics of this manoeuvre (turning speed, turn rate, etc.) will mainly depend on the turn angle, but will also be influenced by factors such as wind or path geometry. Thus, the use of these manoeuvres reduces the temporal predictability of the trajectory of the aircraft, a phenomenon also expected within actual VLL airspace U-space operations.

Another particular aspect of our modelling approach is the exclusion of the take-off and landing manoeuvres of missions from the dynamic simulations. This is an important limitation of our approach, as the manner in which these flight phases are performed can greatly influence other flight procedures, such as the pre-departure strategic planning. However, while this aspect needs to be tackled in future work, we believe that limiting the scope of our investigations benefited the robustness and clarity of our results.

Lastly, the simulations include factors such as wind and departure delay to test the robustness and performance of conflict detection and resolution methods in dynamic and uncertain environments. Wind is simulated by projecting a global wind vector onto every street in function of its bearing, similarly to results gathered through live measurements [31]. This results in aircraft flying at different airspeeds, and also affects their performance envelope. Delay is randomly sampled from an exponential distribution with a specified average and applied to the intended departure time of missions. These models are more extensively explained in [8].

2.6 Simulation results and safety performance comparison

The following section presents a selection of results obtained by testing the aforementioned deconfliction methods within simulated U-space traffic scenarios. The experiments are focused on the performance of the pre-departure flight planning and the dynamic capacity planning modules under various levels of uncertainty (i.e., departure delay and wind) compared to equivalent established methods from literature. Please note that the aim of the portrayal of the results is not to compare methods in terms of absolute safety performance, but to mainly study the interactions between the different components of a CD&R system.

2.6.1 Pre-departure flight planning and worst-case tactical CD&R

The flow-capacity flight planning strategy is compared to a representative 4D trajectory (4DT) planning from literature [20]. Three flow-control configurations are used, in increasing order of planing flexibility: one aircraft every 20 seconds ($T_w = 20s, C_n = 1$), two aircraft every 40 seconds ($T_w = 40s, C_n = 2$), and three aircraft every 60 seconds ($T_w = 60s, C_n = 3$). The first set of results is presented in Figs. 9 and 10, which highlight the differences in the level of safety between the planning methods when subjected to various levels of wind. Then, Figs 11 and 12 present the safety and efficiency performance of the methods when the simulated traffic is subjected to departure delay.

Firstly, the results shown in Fig 9 show that the flow capacity strategic planning method outperforms the 4D trajectory method across all wind uncertainty levels when performed using a time window (T_w) value of 20 seconds and a node capacity (C_n) value of 1 aircraft. The number of intrusion events modestly increased with higher wind levels regardless of method used, showing that the operations are overall robust towards this kind of uncertainty. However, the source of this robustness for the 4DT method is that aircraft actively adjust their velocity to ensure flight plan compliance, thus being able to "catch up". For the flow capacity management methods, aircraft only attempt to maintain the nominal cruise airspeed (not ground speed, for optimal performance) regardless of whether the flight is still compliant with the flight plan. This effect can be observed in Figure 10, as the average flight time for the 4DT method only increases at high wind levels, while the other methods experience a steady increase due to wind. This suggests that the latter set of methods can provide similar safety performance as established strategies while also enhancing airspace stability by not requiring strict flight plan compliance.

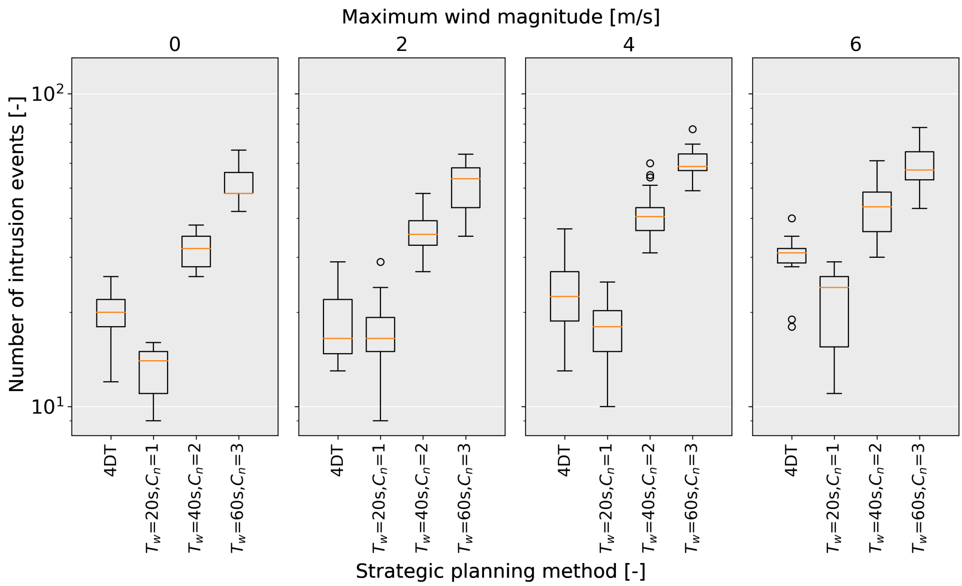

Figure 9. Comparison of the number of intrusion events in function of strategic deconfliction strategy at various levels of maximum wind magnitude. Wind is projected along the direction of streets. The worst-case tactical resolution algorithm is used in all conditions.

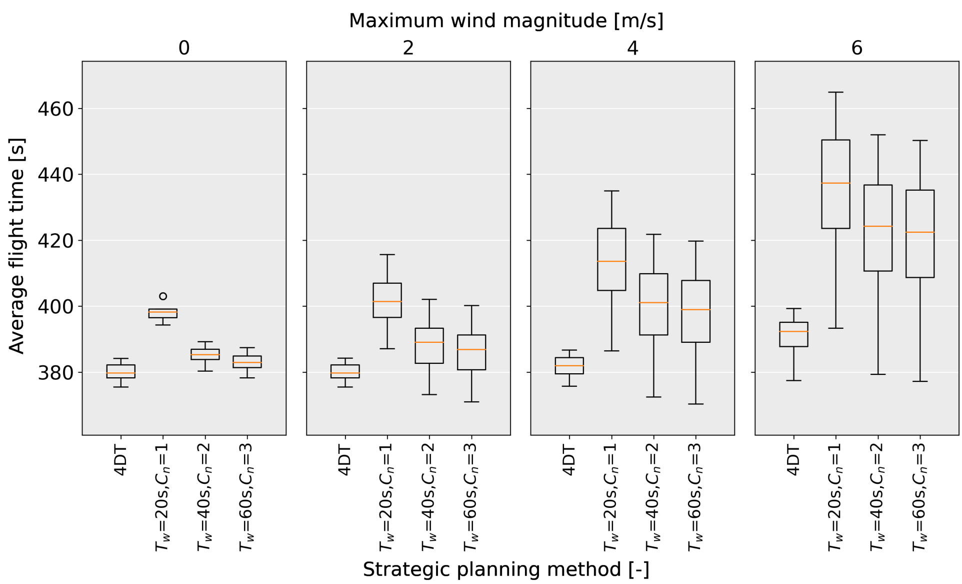

Figure 10. Comparison of the average mission duration in function of strategic deconfliction strategy at various levels of maximum wind magnitude. Wind is projected along the direction of streets. The worst-case tactical resolution algorithm is used in all conditions.

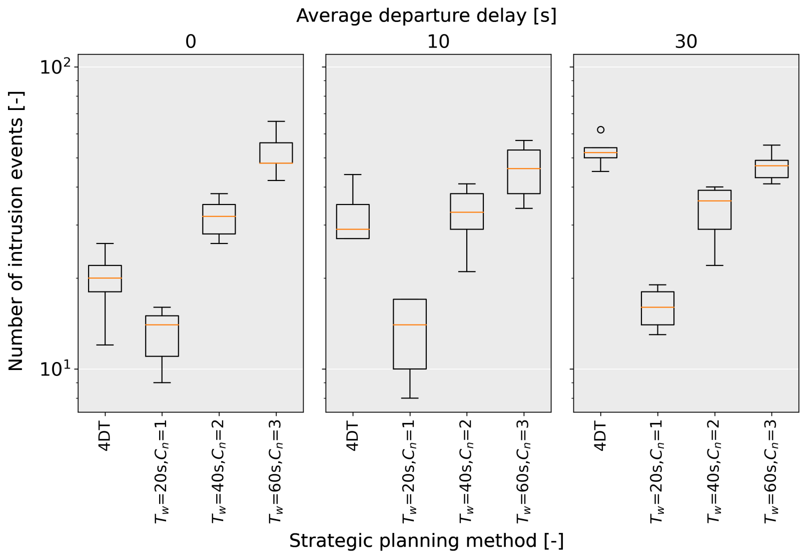

Figure 11. Comparison of the number of intrusion events in function of strategic deconfliction strategy at various levels of average departure delay. A third of departing aircraft experience the indicated average delay before departure. The worst-case tactical resolution algorithm is used in all conditions.

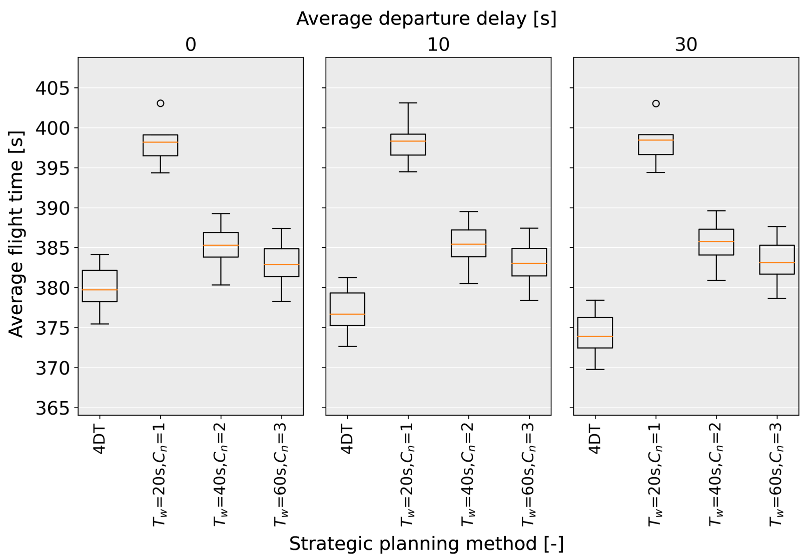

Figure 12. Comparison of the average mission duration in function of strategic deconfliction strategy at various levels of average departure delay. A third of departing aircraft experience the indicated average delay before departure. The worst-case tactical resolution algorithm is used in all conditions.

The differences between the strategic planning methods are more prevalent when departure delay is introduced within the simulated traffic scenarios. Figure 11 highlights the sensitivity of the 4DT method to the presence of departure delay, as the number of intrusions increased to, or surpassed those of the higher flexibility flow-based capacity planning configurations. This is due to the "catching-up" effect inducing higher velocities for flights planned using the 4DT method, resulting in lower flight times with increasing delay, as seen in Figure 12. On the other hand, regardless of the configuration, the flow capacity management set of methods is mostly unaffected by the presence of departure delay. This highlights the potential of flow capacity methods to outperform established 4D trajectory planning methods that rely on strict flight plan compliance in environments with moderate delay conditions.

2.6.2 Dynamic capacity planning and state-based tactical CD&R

The dynamic capacity planning module is tested similarly to the previous experiment. Two conditions are investigated: including and excluding the dynamic capacity management module. Aircraft always use the shortest route to their destination and do not change their route in the case where the dynamic capacity management module is excluded. In both cases, a conventional state-based tactical conflict resolution algorithm is used, as presented in [8]. The results of the experiment are presented in Figs. 13a and 13b.

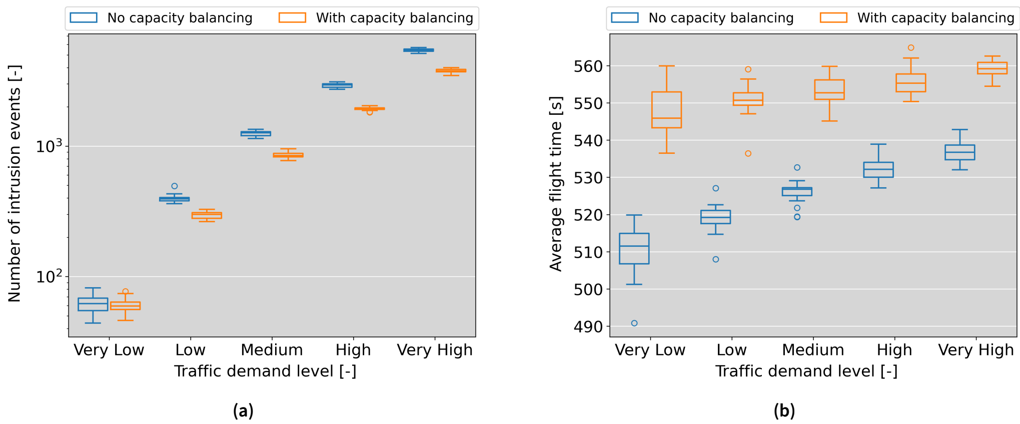

Figure 13. Comparison of the number of intrusion events and flight time with and without dynamic capacity balancing in Rotterdam. The state-based tactical conflict resolution algorithm is used in all conditions.

Figure 13 shows the number of intrusion events (Figure 13a) and the average flight time (Figure 13b). Both are plotted with increasing traffic demand level. These results are measured from the simulated urban environment of Rotterdam, shown in 1b.

Figure 13a shows that at most traffic demand levels, using capacity balancing reduces the number of observed intrusions in the airspace. At very low demand levels, the number of intrusions is similar with and without capacity balancing. Figure 13b shows that the average flight time when using capacity balancing is always higher than without capacity balancing. This is because in the case with capacity balancing, aircraft do not always take the shortest route to their destination.

At very low demand levels, there are not enough recent conflicts in the airspace to effectively identify areas of high traffic complexity. These replans are effectively useless because there is no improvement in safety and an increase in the average flight time. However, as the traffic density increases and more conflicts occur, problem areas are correctly identified and aircraft are able to replan around them. This means that extra flight time comes with a benefit in safety. However, note that the relative increase in flight time decreases with the demand level when comparing the cases (with and without capacity balancing). Refer to [9] for more in-depth results of this dynamic capacity balancing method.

2.7 Resulting CD&R system architecture

To summarise the section at hand, the proposed CD&R system architecture is shown in Figure 14. The three modules investigated in the work at hand are placed on the left side, and the information flow between them and the air traffic is conveyed using arrows. An important note is that the dynamic capacity management and the tactical CD&R modules can be deployed both in a distributed and centralised manner.

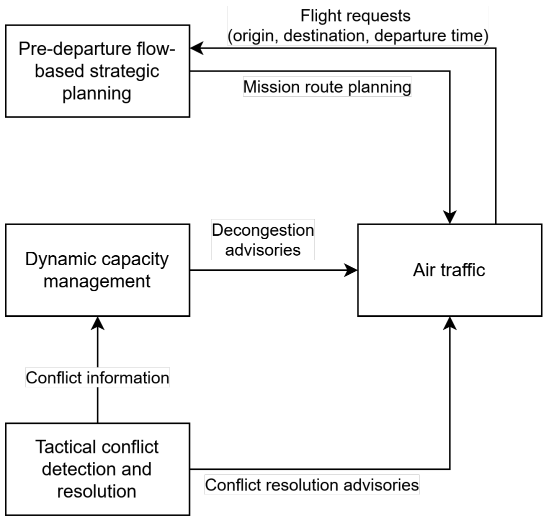

Figure 14. Proposed CD&R system architecture for U-space operations.

3. Analysis and discussion

The following section presents an analysis of the benefits and shortcomings of the presented CD&R methods. A comparison with other work from existing literature is used to suggest directions for future research and development.

3.1 VLL urban airspace structure design

The method for urban airspace design presented in this work provides a rapid and low-complexity framework for structuring a VLL urban airspace, based on previous airspace structuring experiments and analysis performed by Doole et al. [6]. However, it is limited in leveraging the characteristics of the urban environment and requires a considerable manual post-processing effort, mainly serving as a functional starting point for further design iterations. For example, the strategy to optimise for uniform connectivity across all nodes within the graph could be unsuitable in cities where traffic patterns emerge between specific locations. In such situations, the directionality of the streets should be set such that the capacity between nodes matches the demand.

Similar variations of this method have been previously applied [32, 33, 19], as using the existing street network as a foundation inherently avoids buildings, thereby mitigating safety risks. It also aligns well with privacy considerations, as aircraft would primarily operate within publicly accessible spaces. However, flights could be performed more efficiently if aircraft were able to fly above buildings where possible. An approach that would enable this is the use of geofencing (i.e., restricting access to certain areas) [34, 35] to more precisely delimit restricted airspace in the altitude dimension, and thus expand the routing flexibility for U-space operations.

On the other hand, the results of our research [8] show that the use of a geospatial network graph for defining VLL constrained urban airspace can benefit safety by increasing action predictability. As agents are generally expected to follow the geometry of air paths, the risk of the occurrence of a conflict can be better assessed and accounted for. This strategy can also be used if geofences are included within the definition of allowable airspace by adapting the network graph to include altitude-dependent edge weights that allow flying over buildings where permitted. Thus, we suggest that future iterations of VLL urban airspace designs should investigate combining the street network graph approach with that of geofencing to expand the capacity and efficiency of operations while enhancing predictability.

3.2 Pre-departure strategic planning

Existing research on strategic planning for U-space operations has concentrated on developing 4D trajectory planning methods as a pre-departure traffic management strategy. The U-space concept of operations [4] mentions the results of the BUBBLES project [36] as a promising approach, suggesting the use of protection zones whose areas adapt dynamically based on the assessed risk level and can thus accommodate the heterogeneous traffic and adapt to dynamic and uncertain conditions. Perez et al. [37] investigate how tactical manoeuvring can also be integrated within such a system that emphasises flight prioritisation.

However, this approach implies the existence of a central agent that manages the strategic and tactical routing of aircraft, which might lead to a high level of workload for air traffic controllers, or system supervisors if a high degree of automation is employed. One method to mitigate this would be decentralisation, as proposed by Ho et al. [38], where flight paths are deconflicted through iterative negotiation among the involved agents. Another issue with using 4D trajectory deconfliction methods, identified by Joulia et al. [18], is the decreased resilience against uncertainties due to the over-optimisation of flight plans.

Our approach to this problem, presented in this work, delegates a considerable part of the deconfliction task to the agents themselves. Then, the pre-departure strategic planning module is focused more on managing flow and capacity. This offers the benefit of reducing the complexity of the U-space air traffic management system by not requiring strict adherence to 4D trajectories. Furthermore, it offers increased resilience against uncertainties like wind and departure delays by mitigating traffic density and potential conflict zones. However, a limitation of this method is a reduction in operational efficiency: at higher traffic densities, many aircraft are assigned less-than-optimal routes, leading to increased average mission travel times (our experiments show an increase of 6%). Furthermore, this also poses issues on how such routes should be fairly allocated among flights.

We suggest future research to focus on finding a better balance between centralised and decentralised systems for the management of U-space operations. We obtained promising results by combining flow capacity management (centralised) with a local tactical deconfliction algorithm (decentralised), as the latter is better equipped to handle conflicts locally, where situational awareness is higher, and the prediction horizon is shorter. Other methods, such as the one proposed by Ho et al. [38], promise to further reduce the U-space traffic management system complexity and reduce the workload on air traffic controllers. Alternative routing could also be generated using historical traffic and conflict data, which could produce more efficient routing that only minimally deviates from the shortest route and thus be more fair towards the involved parties.

3.3 Dynamic capacity management

Our proposed method has an important limitation: it is a reactive method that relies on the existence of conflict events to solve future conflict events. This limitation is especially clear in low demand levels, where there was no significant improvement over the baseline. Therefore, adding historical data to the decision-making, similar to Patrinopoulou et al. [39], could help improve the safety level at low demand levels.

However, in a broader sense, the method should be treated as one component of a more proactive strategic approach. Such a strategy could benefit from real-time cluster information and propose routes that avoid congested regions. Additionally, other types of demand capacity balancing actions should be studied. Tang et al.[40] suggested dynamic airspace configuration in addition to modifying routes. Other works by Chen et al. [41, 42] propose solutions that delay aircraft departures.

The types of actions proposed to act on capacity balancing have implications on the degree of centralisation. For example, in our work, the individual aircraft are the ones that ultimately decide which routes to take. However, in the work of Yang et al. and Chen et al. [40, 41, 42], a central actor decides what route to take or the magnitude of the take-off delay. However, a centralised plan could make it difficult to ensure fairness in delays due to the impromptu nature of missions. A centralised system also raises privacy concerns, as it might require stakeholders to publicise their routing strategy. Therefore, we suggest future research to focus on (1) learning how different combinations of actions in capacity balancing affect the safety and efficiency of air operations, (2) studying how the effectiveness of different actions changes with different demand levels, and (3) who should oversee these actions (the central agent or individual aircraft). It might be possible that a centralised actor is not needed at lower demand levels. However, at very high-demand levels, the central actor could be overwhelmed by the very high traffic demand levels and would benefit from decentralisation.

3.4 Tactical conflict detection and resolution

The U-space concept of operations [4] proposes a centralised approach to tactical deconfliction performed by air traffic controllers (or an equivalent system of higher automation). The BUBBLES project [43] presents a method through which tactical deconfliction is achieved by designating one of the aircraft of a conflict pair as the separator (i.e., lower priority, thus must give right of way). Jover et al. [44] build on this concept and developed a centralised algorithm that explicitly assigns priority to aircraft in conflicting situations.

However, as in the case of pre-departure strategic planning, a centralised approach to tactical deconfliction might limit the overall capacity of the airspace due to factors such as air traffic controller workload or system complexity. Thus, research has also been focused on investigating the feasibility of decentralising or automating the tactical CD&R service for VLL U-space operations. Von Roenn et al. [45] proposed an automated and decentralised deconfliction procedure for electric vertical take-off and landing (eVTOL) operations that maintains communication with a central traffic management authority. Ribeiro et al. [46] and Isufaj et al. [47] use reinforcement learning techniques to study the behaviour of aircraft when cooperative tactical CD&R manoeuvring is used.

In this work, we proposed a highly conservative tactical deconfliction method that enables aircraft to dynamically assess the local traffic situations and account for all possible conflicting situations. Compared to previous work, the Worst-case CD&R algorithm is developed to be compatible with the flow management module used to plan mission routes strategically. The results of our simulations indicate that this combination can achieve a higher level of safety and robustness against uncertainties by delegating the local deconfliction task to the tactical module. However, this outcome is dependent on the structure of the airspace and how VLL constrained urban airspace operations will be conducted, and should thus be further investigated in a wider variety of configurations.

Firstly, the proposed worst-case method assumes that aircraft follow predictable trajectories given by a graph-based network. If another airspace structure is to be used (e.g., geofencing), then further adaptations are needed to achieve an equivalent safety level. Moreover, while the results of our work indicate that vertical manoeuvring should be discouraged, the tactical CD&R module should nonetheless be able to resolve such situations. Lastly, a wider range of uncertainties and operational conditions need to be studied. Factors such as hyper-local weather effects, aircraft prioritisation, and traffic heterogeneity could affect the performance of the tactical CD&R module and challenge our current understanding of these systems.

Based on these research findings, we suggest future research to focus on improving the synergy between the tactical deconfliction and strategic planning modules. This approach can lower the system complexity of the VLL constrained urban airspace air traffic management service by enabling the use of high-level automation and the distribution of the deconfliction task among all in-flight aircraft. Tactical CD&R methods should also be adapted to account for all aspects of VLL U-space operations, including vertical manoeuvres, take-off and landing, and a wider range of uncertainties. This might lower the workload of air traffic controllers, and should thus increase safety [48].

3.5 Simulation of U-space operations

One of the strengths of our methodology for developing and testing the proposed CD&R methods is the use of simulations that aim to closely represent future implementations of VLL constrained urban airspace operations based on current traffic estimations [25]. The live demonstrations of U-space operations performed by the Metropolis 2 project [49] show that the BlueSky Open Air Traffic Simulator is capable of modelling drones with high accuracy.

However, the simulations we performed were still limited in capturing a complete picture of urban airspace operations. Assumptions such as homogenous traffic, exclusion of take-off and landing phases from the tactical phase, and the use of simplified uncertainty models [8, 17, 10] might have a significant and unpredictable impact on the performance of a complete U-space system. This limitation (i.e., the exclusion of some U-space services) can be found in other work in this domain as well. Joulia et al. [18] developed a simulation framework specifically for tactical CD&R services that only captures the services required for Phase U1 of U-space deployment. An approach towards better understanding the interactions between services in realistic settings is the use of live demonstrations. While the increasing prevalence of such research is a positive factor, they are still severely limited in scope and representativeness due to the restrictiveness of local laws and their limited scale [50, 51].

We thus recommend that, until the opportunity for larger-scale testing arises, a unified simulation platform is developed to simulate the implementations of all U-space services. As the use of the BlueSky is already prevalent in this domain [27, 28, 29, 30] due to being open-source and continuously adapted to match the newest developments, it is a suitable candidate to serve as a foundation for higher-fidelity simulations. An example of such an implementation was created by Fremond et al. [52] by integrating the use of BlueSky into a larger simulation framework that includes other U-space services such as flight plan processing and risk assessment, and the interfaces between them.

3.6 Unified CD&R development approach

To further emphasise the necessity for a unified strategy in the development of CD&R methods, it is important to use an integrated approach towards system design and development as a whole rather than treating each component in isolation. Within our work, we attempted to pair CD&R components (e.g., combining and studying the interactions between tactical CD&R and strategic planning [17] or dynamic capacity planning [9]). However, this is insufficient for studying the interactions between all system components, as, for example, the airspace structure design could influence what strategic and tactical deconfliction strategies can be used. Dynamic capacity planning could also influence the resilience of the pre-departure flight planning method against uncertainties, as new routes might be allocated that reduce the effectiveness of the optimisation.

Furthermore, the manner in which U-space operations are conducted within VLL constrained airspace is dependent on unique characteristics of the urban environment itself, which can greatly vary even within a single city. For example, the structure of the street network may be either highly orthogonal or non-orthogonal [53]. This makes it challenging to develop generally applicable CD&R methods that can be applied within all airspace structures and urban topologies. However, operational consistency can be achieved through the use of a unified and standardised design framework that can be applied to most urban environments. Through this, it becomes possible to identify the key aspects of a city that are important when formulating effective CD&R strategies.

4. Conclusion

The past decade has seen great progress towards defining the framework for implementing very-low-level (VLL) U-space operations within urban environments. Research has been dedicated towards solving the associated challenges, including how to structure and navigate the airspace, as well as the creation of novel procedures for the management and deconfliction of traffic.

Within this paper, we presented and critically analysed the methods we developed and investigated for air traffic management within constrained VLL urban airspace. We primarily focused on the cruise phase of missions, and attempted to develop and improve concepts for urban airspace structure design, pre-departure strategic planning, dynamic capacity management, and tactical conflict detection and resolution (CD&R). Then, acknowledging the limitations of our work and comparing it with other approaches found in literature, we converged on the following considerations and recommendations for future research within this domain:

1. Utilising the airspace above the existing street network is a viable option for VLL U-space operations in urban areas. This approach should be factored into future planning, especially for areas with prevalent high-rise structures.
2. Over-reliance on 4D trajectory planning for conflict resolution can lead to the over-optimisation of flight plans when mission efficiency is emphasised, which negatively affects the resilience of U-space operations against uncertainties (e.g., wind, delay).
3. The design of dynamic capacity management systems needs to account for the potential emergence of undesirable behaviour and the subsequent destabilisation of the airspace system.
4. Tactical CD&R manoeuvring should be considered and used as an integral part of future system developments instead of being seen as a last-resort module, as it can lower the overall system complexity and interdependency, and reduce air traffic controller/supervisor workload.
5. More research should focus on understanding the effects of uncertainties such as weather and delay, and investigating ways in which these can be predicted and mitigated, as they greatly affect the effectiveness of pre-departure strategic planning.
6. A unified, open-source, and open-data simulation environment should be developed to better test and integrate all U-space services and ensure their compatibility.

These recommendations should be applied and considered in function of the U-space operational environment characteristics, including expected traffic densities, communication, navigation, and surveillance (CNS) system performance, or required safety and efficiency levels.

In conclusion, this paper analysed the current state of research on air traffic management in constrained VLL urban airspace and highlighted the crucial areas for future exploration. By addressing the complexities of uncertainty, exploring decentralisation and automation, and developing a unified research environment, progress can be made towards the safe and efficient integration of VLL operations into our urban landscapes.

Author contributions

- C.A. Badea: Conceptualisation, Data Curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualisation, Literature Review, Writing (Original Draft), Writing (Review and Editing)
- A.M. Veytia: Conceptualisation, Data Curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualisation, Writing (Original Draft), Writing (Review and Editing)
- A. Vidosavljević: Conceptualisation, Software, Investigation, Methodology, Validation, Supervision, Writing (Review and Editing)
- J. Ellerbroek: Conceptualisation, Software, Supervision, Funding Acquisition, Writing (Review and Editing)
- J. Hoesktra: Software, Supervision, Funding Acquisition, Writing (Review and Editing)

Open data statement

The source code and results of the concepts presented in this work are openly available online

- Flow-based strategic deconfliction software and dataset:
  https://doi.org/10.4121/1026b811-96cc-47a1-85ed-aaa217343d70
- Dynamic capacity management software and dataset:
  https://doi.org/10.4121/54825f14-8743-447d-8346-3afa46d319d6
- Worst-case tactical deconfliction software and dataset:
  https://doi.org/10.4121/4caadece-1cbe-4eee-824f-e8ebf7055c07

The closed-source Gurobi optimiser [54] was used for the flow-based strategic deconfliction experiments. However, the models generated through Gurobi are available as open `.mps` files that can be run using most open-source solvers (e.g., HiGHS). Code examples are also available within the repositories to enable this.

Reproducibility statement

There are two experiments presented in this article, each with their source code repositories.

The flow-based strategic deconfliction software and dataset are available at
https://doi.org/10.4121/1026b811-96cc-47a1-85ed-aaa217343d70.

The dynamic capacity management software and dataset are available at
https://doi.org/10.4121/54825f14-8743-447d-8346-3afa46d319d6.

To reproduce the flow-based strategic deconfliction experiments, the following steps should be taken:

1. Create a new Python virtual environment (conda is preferred).
2. Install the requirements contained within the requirements.txt files in the optimiser and bluesky directories.
3. The optimiser is run by executing `solve_all.py`. By default, it uses the Gurobi optimiser. However, the .mps files of the models are available in the `data/output` directory to be run using open-source solvers (e.g., HiGHS). The optimiser outputs traffic scenarios which can then be simulated in BlueSky.

4. BlueSky can be run by executing `BlueSky.py`. The experiments are run by using the following command in BlueSky: `BATCH flowbatch.scn`.
5. The results figures can be generated by copying the output logs from `bluesky/output` to `Results/output` and running `main.py`.

To reproduce the dynamic capacity management experiments, the following steps should be taken:

1. Create a new Python virtual environment (conda is preferred).
2. Download and extract `python_environment.zip`. Refer to the `README.md` instructions to install the necessary packages.
3. Download and extract `bluesky.zip` for the BlueSky code used in the dynamic capacity management experiments.
4. Download and read `HOWTOSCENARIOS.md` to understand how to run the scenarios. Note that only some of the city-wide scenarios should be run for this work. From the city-wide scenarios, only run the Baseline (no capacity balancing) and the Conflict-based (with capacity balancing).
5. BlueSky can be run by executing `BlueSky.py`. The experiments are run by using the following commands in BlueSky: `BATCH citywidebaselinebatch.scn` to run experiments with no capacity balancing, and `BATCH citywideconflictbatch.scn` to run experiments with capacity balancing.
6. Download and extract `main_experiment_post_processing.zip` then place the logs from `bluesky/output` inside `logs`. Download `HOWTOCREATEPLOTS.md` and read the section on generating the city-wide scenario plots.

References

[1] Adam P. Cohen, Susan A. Shaheen, and Emily M. Farrar. "Urban Air Mobility: History, Ecosystem, Market Potential, and Challenges". In: *IEEE Transactions on Intelligent Transportation Systems* 22.9 (2021), pp. 6074–6087. DOI: 10.1109/TITS.2021.3082767.

[2] Cristina Barrado, Mario Boyero, Luigi Brucculeri, Giancarlo Ferrara, Andrew Hately, Peter Hullah, David Martin-Marrero, Enric Pastor, Anthony Peter Rushton, and Andreas Volkert. "U-Space Concept of Operations: A Key Enabler for Opening Airspace to Emerging Low-Altitude Operations". In: *Aerospace* 7.3 (2020). DOI: 10.3390/aerospace7030024.

[3] Victor Alarcon, Manuel Garcia, Francisco Alarcon, Antidio Viguria, Angel Martinez, Dominik Janisch, Jose Joaquin Acevedo, Ivan Maza, and Anibal Ollero. "Procedures for the Integration of Drones into the Airspace Based on U-Space Services". In: *Aerospace* 7.9 (2020). DOI: 10.3390/aerospace7090128.

[4] CORUS-XUAM consortium. *U-space Concept of Operations Fourth Edition*. Edition 01.00.02. SESAR Joint Undertaking, 2023.

[5] Sebastian Wandelt and Changhong Zheng. "Toward Smart Skies: Reviewing the State of the Art and Challenges for Intelligent Air Transportation Systems (IATS)". In: *IEEE Transactions on Intelligent Transportation Systems* (2024). DOI: 10.1109/TITS.2024.3415588.

[6] Malik Doole, Joost Ellerbroek, Victor L. Knoop, and Jacco Hoekstra. "Constrained Urban Airspace Design for Large-Scale Drone-Based Delivery Traffic". en. In: *Aerospace* 8.2 (2021). DOI: 10.3390/aerospace8020038.

[7] C.A. Badea, A.M. Veytia, N. Patrinopoulou, I. Daramouskas, J. Ellerbroek, V. Lappas, V. Kostopoulos, and J. Hoekstra. "Unifying Tactical Conflict Prevention, Detection, and Resolution Methods in Non-Orthogonal Constrained Urban Airspace". In: *Aerospace* 10.5 (2023), p. 423. DOI: 10.3390/aerospace10050423.

[8] C.A. Badea, J. Ellerbroek, and J. Hoekstra. "The Benefits of Using Intent Information in Tactical Conflict Resolution for U-space/UTM Operations". In: *IEEE Transactions on Intelligent Transportation Systems* (2024). DOI: 10.1109/TITS.2024.3505981.

[9] Andres Morfin Veytia, Joost Ellerbroek, and Jacco Hoekstra. "Decentralised Traffic Management for Constrained Urban Airspace: Dynamically Generating and Acting Upon Aggregate Flow Data". In: *Journal of Open Aviation Science* 2.1 (2024). DOI: 10.59490/joas.2024.7716.

[10] C.A. Badea, J. Ellerbroek, and J. Hoekstra. "Robust Conflict Detection and Resolution for High-Uncertainty Very-Low-Level Constrained Urban Airspace Operations". 2024. DOI: 10.4121/d3855a88-7ab8-40ae-93ae-09c0c5ab1fca.

[11] A.M. Veytia et al. "Metropolis II: Benefits of Centralised Separation Management in High-Density Urban Airspace". In: *12th SESAR Innovation Days*. 2022.

[12] Emmanuel Sunil, Joost Ellerbroek, Jacco M. Hoekstra, and Jerom Maas. "Three-dimensional conflict count models for unstructured and layered airspace designs". In: *Transportation Research Part C: Emerging Technologies* 95 (2018), pp. 295–319. ISSN: 0968-090X. DOI: https://doi.org/10.1016/j.trc.2018.05.031.

[13] OpenStreetMap contributors. *Planet dump retrieved from https://planet.osm.org*. https://www.openstreetmap.org. 2017.

[14] Pratyush Tripathy, Pooja Rao, Krishnachandran Balakrishnan, and Teja Malladi. "An open-source tool to extract natural continuity and hierarchy of urban street networks". In: *Environment and Planning B: Urban Analytics and City Science* (2020). DOI: 10.1177/2399808320967680.

[15] J. Hoekstra, J. Ellerbroek, E. Sunil, and J. B. Maas. "Geovectoring: Reducing Traffic Complexity to Increase the Capacity of UAV airspace". en. In: *2018 International Conference on Research in Air Transportation* (2018).

[16] Emmanuel Sunil, Jacco Hoekstra, Joost Ellerbroek, Frank Bussink, Dennis Nieuwenhuisen, Andrija Vidosavljevic, and Stefan Kern. "Metropolis: Relating Airspace Structure and Capacity for Extreme Traffic Densities". en. In: *ATM seminar 2015, 11th USA/EUROPE Air Traffic Management R&D Seminar*. 2015.

[17] C.A. Badea, J. Ellerbroek, and J. Hoekstra. "Evaluating the Synergy of Conflict Detection and Resolution Services for U-space/UTM Operations". 2024. DOI: 10.1109/OJITS.2025.3530516.

[18] Antoine Joulia and Thomas Dubot. "A simulation framework for U-space tactical conflict detection and resolution services". In: *AIAA AVIATION 2022 Forum*. Chicago, United States: American Institute of Aeronautics and Astronautics, 2022. DOI: 10.2514/6.2022-3543.

[19] Michael W. Levin and David Rey. "Branch-and-Price for Drone Delivery Service Planning in Urban Airspace". In: *Transportation Science* 57.4 (2023), pp. 843–865. DOI: 10.1287/trsc.2022.1175.

[20] Denis Bereziat, Sonia Cafieri, and Andrija Vidosavljevic. "Metropolis II: Centralised and strategical separation management of UAS in urban environment". In: *12th SESAR Innovation Days*. 2022.

[21] Karl Bilimoria and Hilda Lee. "Analysis of Aircraft Clusters to Measure Sector-Independent Airspace Congestion". In: *AIAA 5th ATIO and16th Lighter-Than-Air Sys Tech. and Balloon Systems Conferences*. Arlington, Virginia, 2005.

[22] J. Hoekstra and F. Bussink. "Free flight: how low can you go? [ATC]". In: *The 21st Digital Avionics Systems Conference*. Vol. 1. 2002. DOI: 10.1109/DASC.2002.1067889.

[23] Michael P. Owen, Adam Panken, Robert Moss, Luis Alvarez, and Charles Leeper. "ACAS Xu: Integrated Collision Avoidance and Detect and Avoid Capability for UAS". In: *2019 IEEE/AIAA 38th Digital Avionics Systems Conference (DASC)*. 2019, pp. 1–10. DOI: 10.1109/DASC43569.2019.9081758.

[24] Jacco Hoekstra and Joost Ellerbroek. "Aerial Robotics: State-based Conflict Detection and Resolution (Detect and Avoid) in High Traffic Densities and Complexities". en. In: *Current Robotics Reports* 2.3 (2021), pp. 297–307. DOI: 10.1007/s43154-021-00061-6.

[25] Malik Doole, Joost Ellerbroek, and Jacco Hoekstra. "Estimation of traffic density from drone-based delivery in very low level urban airspace". en. In: *Journal of Air Transport Management* 88 (2020), p. 101862. DOI: 10.1016/j.jairtraman.2020.101862.

[26] J. Hoekstra and J. Ellerbroek. "BlueSky ATC Simulator Project: an Open Data and Open Source Approach". In: *International Conference for Research on Air Transportation*. 2016.

[27] *USEPE: U-space Separation in Europe*. https://cordis.europa.eu/project/id/890378/results. The Community Research and Development Information Service. 2022. (Visited on 05/01/2023).

[28] Aurelie Aurilla Arntzen Bechina, Esther Nistal Cabañas, Serkan Güldal, Ole Henrik Dahle, Jerónimo Bueno, Martin Dullweber, Sebastian Giersch, and Manon Coyne. "A Model for a Safer Drone's Operation in an Urban Environment". In: *2022 International Conference on Unmanned Aircraft Systems (ICUAS)*. 2022, pp. 73–77. DOI: 10.1109/ICUAS54217.2022.9835715.

[29] Rina Komatsu, Aurelie Aurilla Arntzen Bechina, Serkan Güldal, and Merivan Sasmaz. "Machine Learning Attempt to Conflict Detection for UAV with System Failure in U-Space: Recurrent Neural Network, RNNn". In: *2022 International Conference on Unmanned Aircraft Systems (ICUAS)*. 2022, pp. 78–85. DOI: 10.1109/ICUAS54217.2022.9836147.

[30] Junjie Zhao, Christopher Conrad, Rodolphe Fremond, Anurag Mukherjee, Quentin Delezenne, Yu Su, Yan Xu, and Antonios Tsourdos. "Co-simulation Digital Twin Framework for Testing Future Advanced Air Mobility Concepts: A Study with BlueSky and AirSim". In: *2023 IEEE/AIAA 42nd Digital Avionics Systems Conference (DASC)*. 2023. DOI: 10.1109/DASC58513.2023.10311124.

[31] C.A. Badea, A. Morfin Veytia, J. Ellerbroek, and J. Hoekstra. "Urban Wind Measurement and Modelling for U-space Operations". In: *Proceedings International Conference on Research in Air Transportation 2024*. 2024.

[32] Felix Mora-Camino, Bruno Lamiscarre, and Georges Mykoniatis. "Structuring Air Logistics Networks in the Urban Space". In: *SMART2021, The Tenth International Conference on Smart Cities, Systems, Devices and Technologies*. Valencia, Spain, 2021.

[33] Nikolas Hohmann, Sebastian Brulin, Jürgen Adamy, and Markus Olhofer. "Multi-Objective Optimization of Urban Air Transportation Networks Under Social Considerations". In: *IEEE Open Journal of Intelligent Transportation Systems* (2024). DOI: 10.1109/OJITS.2024.3443170.

[34] Joseph Kim and Ella Atkins. "Airspace Geofencing and Flight Planning for Low-Altitude, Urban, Small Unmanned Aircraft Systems". en. In: *Applied Sciences* 12.2 (2022), p. 576. DOI: 10.3390/app12020576. (Visited on 08/26/2024).

[35] Giancarmine Fasano, Flavia Causa, Armando Franzone, Carmela Piccolo, Livio Cricelli, Alberto Mennella, and Valerio Pisacane. "Path planning for aerial mobility in urban scenarios: the SMARTGO project". In: *2022 IEEE 9th International Workshop on Metrology for AeroSpace (MetroAeroSpace)*. 2022, pp. 124–129. DOI: 10.1109/MetroAeroSpace54187.2022.9855956.

[36] Thomas Dubot and Antoine Joulia. "Towards U-space conflict management services based on 4D protection bubbles". In: *AIAA AVIATION 2021 FORUM*. American Institute of Aeronautics and Astronautics, 2021. DOI: 10.2514/6.2021-2347.

[37] Hector Perez-Leon, Jose Joaquin Acevedo, Ivan Maza, and Anibal Ollero. "Integration of a 4D-trajectory Follower to Improve Multi-UAV Conflict Management Within the U-Space Context". In: *Journal of Intelligent & Robotic Systems* 102.3 (2021), p. 62. DOI: 10.1007/s10846-021-01415-0. (Visited on 08/27/2024).

[38] Florence Ho, Rúben Geraldes, Artur Gonçalves, Bastien Rigault, Benjamin Sportich, Daisuke Kubo, Marc Cavazza, and Helmut Prendinger. "Decentralized Multi-Agent Path Finding for UAV Traffic Management". In: *IEEE Transactions on Intelligent Transportation Systems* 23.2 (2022), pp. 997–1008. DOI: 10.1109/TITS.2020.3019397.

[39] Niki Patrinopoulou, Ioannis Daramouskas, Calin Andrei Badea, Andres Morfin Veytia, Vaios Lappas, Joost Ellerbroek, Jacco Hoekstra, and Vassilios Kostopoulos. "Dynamic Capacity Management for Air Traffic Operations in High Density Constrained Urban Airspace". In: *Drones* 7.6 (2023). DOI: 10.3390/drones7060395.

[40] Yiwen Tang, Yan Xu, and Gokhan Inalhan. "An Integrated Approach for On-Demand Dynamic Capacity Management Service in U-Space". In: *IEEE Transactions on Aerospace and Electronic Systems* 58.5 (2022), pp. 4180–4195. DOI: 10.1109/TAES.2022.3159317.

[41] Shulu Chen, Antony D. Evans, Marc Brittain, and Peng Wei. "Integrated Conflict Management for UAM With Strategic Demand Capacity Balancing and Learning-Based Tactical Deconfliction". In: *IEEE Transactions on Intelligent Transportation Systems* 25.8 (2024), pp. 10049–10061. DOI: 10.1109/TITS.2024.3351049.

[42] Shulu Chen, Peng Wei, James C. Jones, and Antony D. Evans. "Rolling Horizon Demand Capacity Balancing in UAM: Integrating Machine Learning for Conflict Resolution". In: *AIAA AVIATION FORUM AND ASCEND 2024*. 2024. DOI: 10.2514/6.2024-3852.

[43] Cecilia Claramunt Puchol, Norberto Vera Vélez, Juan Vicente Balbastre Tejedor, and Joan A. Vila Carbó. "BUBBLES: A new concept of operations for separation management in the U-space". In: *Journal of Physics: Conference Series* 2526.1 (2023), p. 012092. DOI: 10.1088/1742-6596/2526/1/012092.

[44] Jesús Jover, Aurelio Bermúdez, and Rafael Casado. "Priority-Aware Conflict Resolution for U-Space". en. In: *Electronics* 11.8 (2022), p. 1225. DOI: 10.3390/electronics11081225.

[45] Luca von Roenn, Timo Häckel, Nemo Juchmann, Tobias Grebner, Daniel Kloock-Schreiber, Tim Tiedemann, Volker Gollnick, Rinie Akkermans, and Alexander Fay. "Concept for a Decentralized Tactical Conflict Management in a U-space Ecosystem". In: *2024 New Trends in Civil Aviation (NTCA)*. 2024, pp. 59–66. DOI: 10.23919/NTCA60572.2024.10517828. (Visited on 09/02/2024).

[46] Marta Ribeiro, Joost Ellerbroek, and Jacco Hoekstra. "Improving Algorithm Conflict Resolution Manoeuvres with Reinforcement Learning". en. In: *Aerospace* 9.12 (2022), p. 847. DOI: 10.3390/aerospace9120847. (Visited on 09/02/2024).

[47] Ralvi Isufaj, Marsel Omeri, and Miquel Angel Piera. "Multi-UAV Conflict Resolution with Graph Convolutional Reinforcement Learning". In: *Applied Sciences* 12.2 (2022), p. 610. DOI: 10.3390/app12020610.

[48] Savvy Verma, Victoria Dulchinos, Robert Dan Wood, Amir Farrahi, Richard Mogford, Megan Shyr, and Rania Ghatas. "Design and Analysis of Corridors for UAM Operations". In: *2022 IEEE/AIAA 41st Digital Avionics Systems Conference (DASC)*. 2022. DOI: 10.1109/DASC55683.2022.9925820.

[49] Metropolis 2 consortium. *Metropolis 2: A unified approach to airspace design and separation management for U-space | Results*. 2022. URL: https://cordis.europa.eu/project/id/892928/results (visited on 09/02/2024).

[50] Vaios Lappas et al. "EuroDRONE, a European Unmanned Traffic Management Testbed for U-Space". In: *Drones* 6.2 (2022). DOI: 10.3390/drones6020053.

[51] Miguel-Angel Fas-Millan, Andreas Pick, Daniel Gonzalez del Rio, Alejandro Paniagua Tineo, and Ruben Garcia Garcia. "Implementing and Testing a U-Space System: Lessons Learnt". In: *Aerospace* 11.3 (2024), p. 178. DOI: 10.3390/aerospace11030178.

[52] Rodolphe Fremond, Yiwen Tang, Prithiviraj Bhundoo, Yu Su, Arinc Tutku, Yan Xu, and Gokhan Inalhan. "Demonstrating advanced U-space services for urban air mobility in a co-simulation environment". In: *12th SESAR Innovation Days* (2022).

[53] Geoff Boeing. "Urban spatial order: street network orientation, configuration, and entropy". In: *Applied Network Science* 4.1 (2019). DOI: 10.1007/s41109-019-0189-1.

[54] Gurobi Optimization, LLC. *Gurobi Optimizer Reference Manual*. 2024. URL: https://www.gurobi.com.