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# Impact assessment of the Strategic Planning performance in Shared U-space volumes

Juan José Ramos González[1], Zhiqiang Liu[2], Jose Luis Muñoz Gamarra[3], Enric Pastor Llorens [4], Cristina Barrado[5]

[1] corresponding author juanjose.ramos@uab.cat, Aeronautics and Logistics department unit, Universitat Autònoma de Barcelona, Spain; 0000-0002-0881-7205
[2] Aeronautics and Logistics department unit, Universitat Autònoma de Barcelona; 0000-0001-7721-6035
[3] Aeronautics and Logistics department unit, Universitat Autònoma de Barcelona, Spain; 0000-0003-3213-0558
[4] Dep. Computer Architecture, Universitat Politècnica de Catalunya, Spain; 0000-0002-7587-8702 [5] 0000-0003-0100-724X

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## Abstract

This work analyses how the different U-space service providers (USSPs) managing a shared airspace volume will impact on the other's performance. The paper demonstrates how the various strategic planning USSPs capabilities, ranging from procedures and policies, trajectory representation, as well as the deconflicting strategies, impact on the use of this common resource in terms of effective airspace capacity. The paper brings to practice the concept of Reasonable Time to React by proposing a planning timeline with common milestones for the implementation of the required authorization procedures prior to the flight. The paper analyses how these milestones impact on the effective airspace capacity. Also, the First-Come First-Served planning policy is compared with respect to a more efficient batch planning policy, where flight plan batches are processed to mitigate the potential conflicts existing at the strategic phase. Furthermore, the paper discusses how the capabilities supported by the USSP to represent the trajectory and its associated uncertainty will be also key to optimize the use the airspace. Based on a CORUS-XUAM VLD scenario, a simulation analysis will assess how the USSPs' capabilities to manage flight planning activities impact on the effective occupation of airspace, jeopardizing in some cases not just the own performance but also that of other airspace users.

# 1 Introduction

U-space (Eurocontrol, 2016) was born as the framework to ensure the creation of safe, efficient and secure Very Low Level (VLL) airspace, accommodating a very large variety of new aircrafts: Unmanned Aerial Vehicles (UAVs). It is composed of a set of new services and specific procedures designed to support access to airspace. These new services are provided by U-space service providers (USSPs) in an open market that tries to encourage a high quality and competitive market that leads to safe and sustainable operations in the European U-space. Once certified, USSP will be able to offer their services in any U-space volume. A scenario in which more than one USSPs are providing services in the same volume under the coordination of a Common Information Service Provider (EASA, 2020) (CISP) could be possible according to existing legislation (see Figure 2, each USSP will offer their operators safe access to a shared airspace).

However, it will be key to ensure that all USSPs using the VLL volume will show comparable efficiency managing their shared airspace capacity, considering the uncertainty inherent to each mission. A set of questions raise in this shared airspace scenarios: Could a mission be accepted or rejected due to a non-optimal performance of a different USSP capabilities in a shared airspace? Can a USSP jeopardize the level of service of other USSPs offering their services in a shared airspace? Should a minimum performance level be required from USSPs and their services according to the complexity of the airspace where the service is provided? Should USSP certification requirements be adapted to the airspace complexity?

To answer these relevant questions, this work proposes a simulation-based analysis to assess how the planning process carried out by several USSPs impacts each other from the airspace capacity utilization perspective. Specifically, focused on the way flight intents (or mission plans) are defined depending on the USSP capabilities to process them and deconflict the airspace. The paper is organized as follows: section 2 introduces the scenario (based on CORUS-XUAM Spanish demo) that will be the airspace structure based of the simulations; section 3 will introduce the main concepts of the strategic conflict management that will be used in the simulation study. Section 4 will present the methodology used in the simulation study and section 5 its main results. To conclude, the impact of the result obtained in a future shared USSPs deployment will be discussed.

# 2 Scenario Description

The simulated scenario is based on the CORUS-XUAM (CORUS-XUAM, 2020) Spanish demo performed in Castelldefels (Barcelona). The Spanish demonstration exercise was aimed at demonstrating the U-space system capabilities of managing UAS logistic operations within mid-size urban and suburban areas within controlled airspace.

The exercise recreated a network of vertiports (4 in total, each one assigned to a specific operator) from which four different Drone Operators managed the take-offs and landings of their flights, executing last-mile delivery missions (see Figure 1 left). The vertiports (Points of Departure – PODs) also represented logistic hubs where drones were loaded with cargo received via other transport means to be delivered to one of the thirteen delivery points distributed along the 3 km. Two USSPs, interoperating through the CISP, were deployed to support two drone operators each.

The flights were channelled through an airspace structure designed explicitly for serving last-mile delivery missions, where multirotors were continuously executing deliveries in the area and using the vertiports for the turnaround. The airspace structure was articulated around four air corridors, two in the west direction and two in the east direction. The corridors are aligned in a parallel direction. Each corridor is assigned a different altitude within the available envelope for safe separation (BUBBLES, 2020; Sunil et al., 2017). West corridors operate at both 30 and 70 meters altitude, while the East corridors operate at both 40 and 80 meters altitude (see Figure 1 right). The selection of different altitudes allowed for a safe crossing of corridors from/to vertiports and delivery points. Moreover, corridors have an additional horizontal offset added to them. This offset

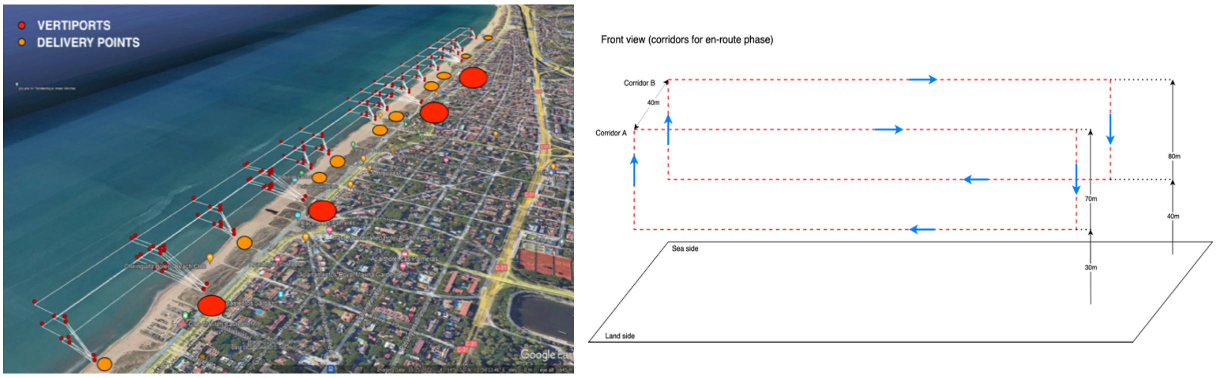

*Figure 1. Schematic representation of several USSPs sharing a U-space volume and their performance and capacity used (left). Corridor-based airspace structure used in the Spanish demonstrations in the CORUS-XUAM project (right)*

is intended to increase the safety of any vertical climb occurring on any corridor. In that way, unplanned vertical climbs, generally associated with loss-link RTL manoeuvres, can be executed without interfering with other vehicles that are coincidentally operating at higher altitudes.

In this work the same type of operation is emulated, but with a much higher traffic density compared with the real flown scenario. This work focusses on the impact of trajectory representation and planning strategies. For these experimentation goals, three USSPs will be used in this case, each of them showing different capabilities in terms of the flight intent description. All flight operations will have the same structure: depart from the vertiport, fly to the delivery point and return to the vertiport, but the representation of these operations will be different depending on the capabilities of the USSP used by the drone operator. Experiments aim to assess the mutual impact of these capabilities on the airspace efficiency in terms of occupancy ratios. Each drone operator will submit their flight authorization requests to its assigned USSP according to the planning strategy set for the experimentation goals. The rate of acceptance (approved operations) will be measured to assess the impact of the various USSP performance, as well as the different planning policies, on the airspace efficiency.

# 3 Strategic management of U-space volumes

The safe and efficient deployment of U-space will be based on the safe arrangement of U-space volumes. The U-space regulation introduces the concept of U-space airspace as a geographical zone (EASA, 2020a) where UAS operations are not allowed unless they are supported by several U-space services.

U-space volumes will be “equipped” with a set of U-space services to ensure the safe and efficient deployment of the U-space in these specific volumes (EU, 2021). It will be mandatory to provide Network identification, Geo-awareness, UAS flight authorization service and traffic information. Optionally, the entities providing these services (USSPs) may offer weather information and conformance monitoring services. It is expected that more than one USSP will offer its services in U-space volumes. They will coordinate their interactions through CISP, that will oversee spreading the common information required to enable the operation and provision of the U-space services. Figure 2 illustrates the deployed U-space architecture.

In this work, the USSP platform DronAs by Aslogic[1] will be used. This platform was one of the USSP systems deployed at CORUS-XUAM demonstrations. In addition to providing U-space services in real scenarios, the platform has simulation capabilities for the analysis of demand-capacity balance. For the paper experimentation purposes, it will be used to emulate the three USSP interoperating through the CISP, each of them showing different capabilities for the strategic

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[1] Aslogic is a Universitat Autònoma de Barcelona startup company

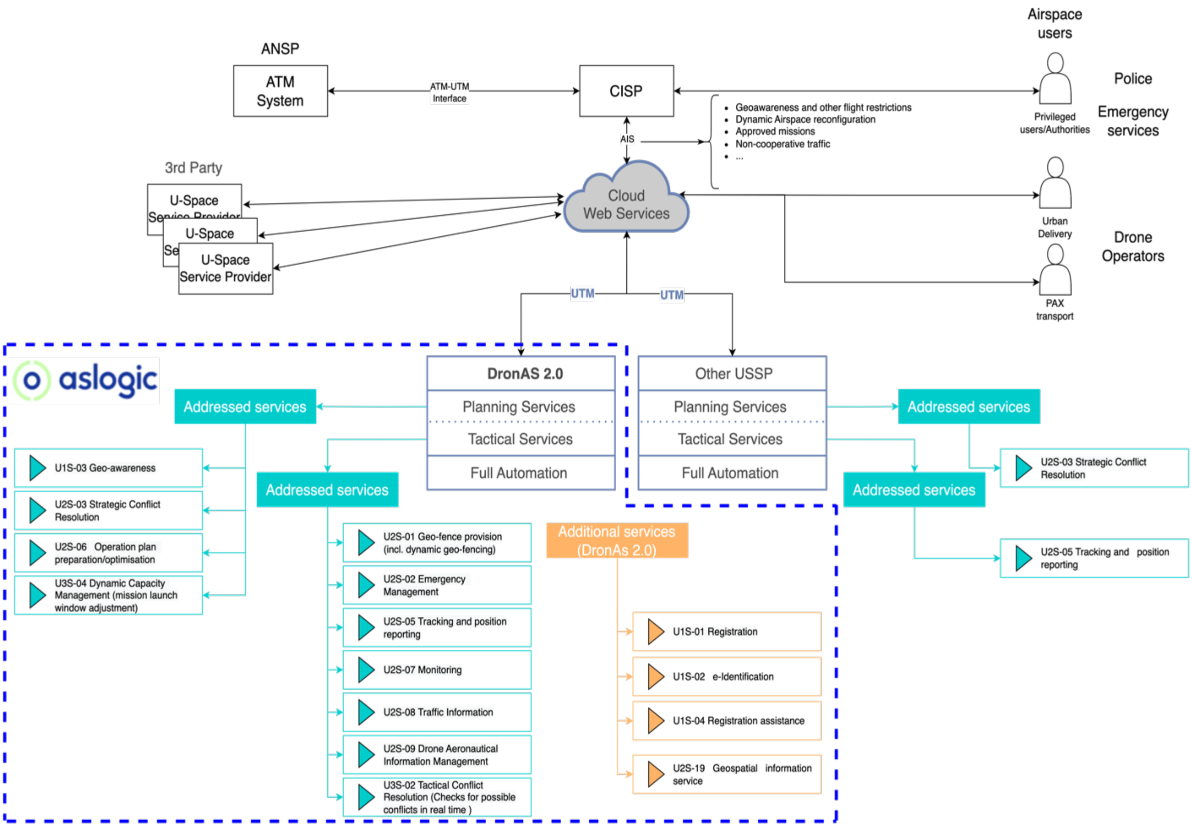


*Figure 2. Cloud based architecture of USSP interoperating through the CISP.*

planning in managing the flight plan representation, as it is described next. Each USSP will receive the flight plan authorization requests from their drone operators. The USSP gets the geoawareness information from the CISP, as well as the operations that have been already approved, to check for conformance and deconflict the received request or reject otherwise.

So, it is clear that all USSPs will manage a common resource of the U-space: the capacity of the airspace volume. The performance of each USSP managing this resource will have a deep impact on the other entities providing services. A USSP that produces high latent capacity (airspace booked but not used) will reduce the capacity available for the other USSP, which could be translated in less operator missions accepted, or more missions' modifications, to ensure that the approved flight plans are free of conflict. While this may not be a problem in rural environment where a low traffic density is expected, it could become a bottleneck in urban areas with high density scenarios. The urban scenarios will have additional restrictions due to the ground obstacles, so it would be mandatory to get the maximum of the available airspace.

To tackle this point, three main topics should be covered at the strategic phase: flight intent description, strategic deconflicting strategies and policies, and a seamless operator-USSP and CISP interoperability. Being the third one also relevant to efficiency, it is considered as a technological concern rather than a conceptual and methodological challenge. This paper focuses on the USSP capabilities to handle different flight intent representations and on the features of the strategic planning services. The impact will be measured in terms of the effective use of the airspace capacity using the average acceptance ratio as the main metric, that is the percentage of authorized fling plans with respect to the number of requested operations. So far, there is not a common understanding for measuring the airspace capacity in U-space. Other works like DACUS project (DACUS, 2020), focused on the definition of Demand and Capacity Optimization, propose that "capacity" in U-space should be a function of uncertainty, noise and visual nuisance, safety thresholds and collision risk (Janisch et al., 2021), estimating capacity imbalances based on risk indicator based on trajectories uncertainty modelling.

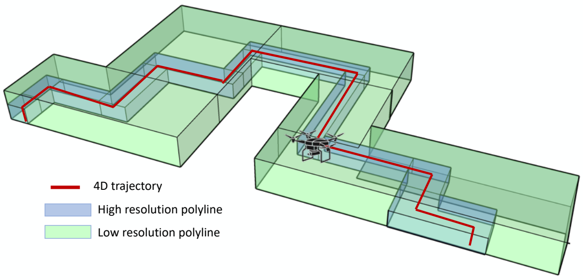


*Figure 3. Schematic representation of 4D and polyline mission format.*

A stochastic simulation of the demand is proposed for the impact assessment of the USSP performance with these regards. Realistic flight operations will be randomly generated according to the logistics operational context described in Section 2. The simulation will demonstrate the abilities and limitations of three USSPs with different capabilities, both in terms of their own performance as well as of their mutual impact on the other USSPs and airspace users.

## 3.1 Flight trajectory description

The flight trajectory representation is the source of information on which strategic management of the airspace is performed. Figure 3 shows alternative descriptions of a mission with different levels of uncertainty. The simulation experiments will demonstrate that the more detailed the information is provided, the more efficient and advanced functionalities could be provided by USSPs and more efficient use of the airspace might be achieved.

In the scope of the Risk Assessment Model for UAS operations, the European Regulation defines the operational volume as the composition of the flight trajectory (missions) and the contingency volume (EASA, 2020a).The flight trajectory means the volume(s) of airspace defined spatially and temporally in which the UAS operator plans to conduct the operation under normal procedures and the contingency volume means the volume of airspace outside the flight trajectory where contingency procedures defined will be applied.

Furthermore, the operational volume shall be characterized by the position-keeping capabilities of the UAS in 4D space (latitude, longitude, height and time), in particular:

- Navigation performance
- Flight technical error (the flight technical error is the error between the actual track and the desire track) of the UAS
- Path definition error (e.g. map errors)
- Latencies

UAS missions can be defined using three different formats, or a combination of them, schematically represented in Figure 3:

- Font Volume format: specifying the airspace volume that contains the mission, without providing any additional details, and booking this volume for the entire time interval in which it is expected to be flying.
- Polyline format: as specified in Commission implementing regulation 2021/664 (EU, 2021), flight trajectory as a series of one or more 4D volumes expressed in height (base, ceiling), longitudinal and lateral limits, and duration (entry and exit times). Each dimension includes the uncertainty of the flight, considering the UAS operational performance, and the assumptions on the operator proficiency and weather conditions. The discretization of these polyline volume can vary considerably, changing the level of detail of the mission description (see Figure 3).

- 4D format: a set of 4D points providing the latitude, longitude, altitude, and time of all the waypoints making up the trajectory. Associated to each of these points there is an uncertainty value that models its temporal and position uncertainty.

In some circumstances it will be the nature of the mission itself that will set the level of description of the mission. For example, a surveillance mission for characterizing a cultivation area will require a great deal of flexibility that will make it suitable for a volume mission format. However logistic missions, where the origin, destination and trajectory are known since the planning phase, could be described in 4D format. Note that the 4D format is also aligned with the 2021/664 regulation. It provides an uncertainty volume attached to the envisioned 4D position of the aircraft with a time interval when it is expected to be within. However big differences are found between polyline and 4D format. As it will be demonstrated in results section, it deeply impacts the efficiency of the airspace as increases the volume (used or not) that a mission needs in its definition phase. 4D format mission strictly reserve the uncertainty envelop of the position and time uncertainty, while polyline representation occupies one segment of the mission for a time interval.

Note that flight trajectory description also impacts some main functionalities of U-space services:

- DACUS project (DACUS, 2020) focused on the DCB U-space service, that it based on developing a "consolidated demand picture" considering mission planned and forecasting future demand. The quantification of uncertainty will be an essential component of the service and the effectiveness of the DCB measures, and the operational capacity will strongly depend on the mission description format (they defined as "the single point of truth") crease.
- BUBBLES (BUBBLES, 2020) defines a protection volume around each aircraft, so that a breach of separation minima is triggered by the overlap of these volumes. During the strategic phase a probabilistic 4D trajectory is extracted from the operation plan, when the probability of a bubble intersection exceeds some predefined value then a conflict is declared. It is clear that high uncertainty values could reach to the detection of false conflicts.

Though it might seem obvious, operations described as volumes will have a higher negative impact on airspace occupancy compared with polyline description, and even more with 4DT description. One of the main contributions of this work is to quantitatively assess this impact by focusing on the airspace occupancy in terms of the mission accepted/rejected ratio as an efficiency metric. For this purpose, each of the USSPs will show different capabilities for processing the operator's flight intent. USSP named A will be able to work with 4DT trajectories, as illustrated by the left image in Figure 4. USSP named B will be able to work with polyline trajectories, as illustrated by the middle image in Figure 4. USSP named C will be able to work with volume trajectories, as illustrated by the right image in Figure 4.

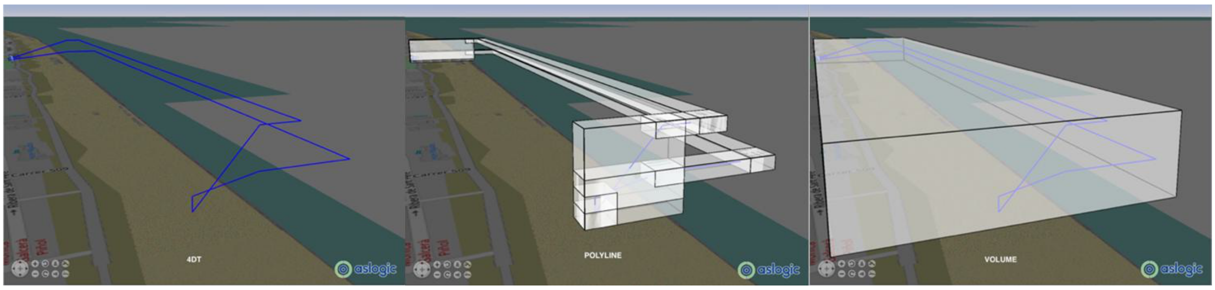
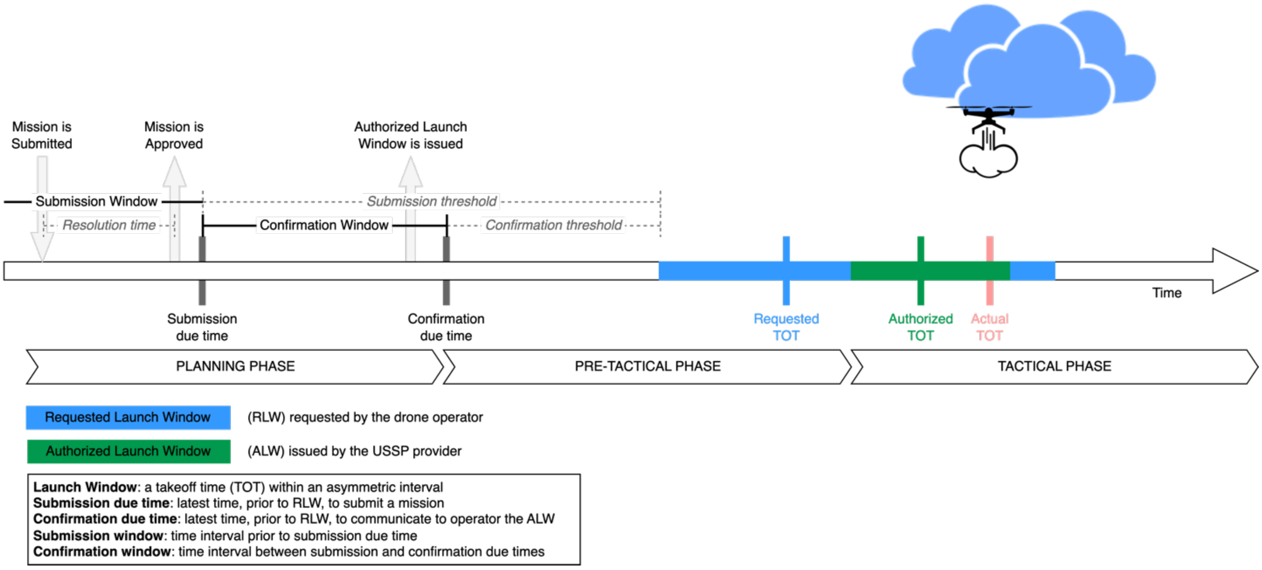


*Figure 4. The three flight trajectory representations to be evaluated: 4DT (left), Polyline (center) and Volume (right)*

### 3.2 *Strategic deconfliction service*

The strategic deconfliction service is part of the UAS flight authorization service. The EASA U-space regulation relies on the pre-flight strategic conflict resolution by the Flight authorization service in the pre-flight phase (EASA, 2020b). To get a flight authorization, a flight plan must be



**Launch Window**: a takeoff time (TOT) within an asymmetric interval
**Submission due time**: latest time, prior to RLW, to submit a mission
**Confirmation due time**: latest time, prior to RLW, to communicate to operator the ALW
**Submission window**: time interval prior to submission due time
**Confirmation window**: time interval between submission and confirmation due times

*Figure 5. Timeline for planning and executing a mission.*

strategically deconflicted from any other conflicting flight plan. Strategic conflict resolution services are based on predictions of conflicts.

A number of approaches have been proposed for strategic deconfliction in UAS Traffic Management (UTM) (J.Rios, 2018; Rios et al., 2020; Rodriguez et al., 2017), with the most widely demonstrated being a de-centralized architecture (Sesar, 2023) with volume-based trajectory representation (Egorov et al., 2021; A. Evans et al., 2023; A. D. Evans et al., 2023). Conflict resolution compares the submitted operation plan with the already approved ones. It is triggered when the probability of loss of separation is above a given threshold, based on the most likely predicted trajectory for each aircraft, proposing a set of solutions. These solutions go from changing a portion of the planned trajectory to avoid the volume in conflict (Ribeiro et al., 2020) up to modifying the time interval in which the mission will be executed to ensure that the aircraft respect the separation minima values (A. Evans et al., 2020). Simpler strategic conflict resolution service just rejects the last submitted mission if it conflicts with the previous ones.

In this work a time-based separation mitigation strategy will be used. This separation strategy basically consists in adjusting the takeoff time of the missions in conflict. The main reason for using this mitigation strategy is to propose a suitable solution for the drone operator (DO) without additional modifications on the requested flight trajectory. DronAs implements an optimization set of algorithms to coordinate the takeoff time windows for deconflicting the different missions in conflict. This method was first developed for ATM traffic in the PARTAKE project (PARTAKE, 2016). A detailed view of the optimization methods can be found in (DACUS, 2020), (Schefers et al., 2018), (Schefers et al., 2020), and (Schefers et al., 2016).

Figure 5 illustrates the timeline from the planning phase until the tactical phase (when approved mission departs). The drone operator (DO) issues the Flight Plan (FP) including the flight trajectory and the Requested Launch Window (RLW), a time window of a given size surrounding the Requested Takeoff Time (RTOT). The start time of the RLW is the reference for the remaining milestones.

The planning phase involves the following steps:

1. Authorization of the FP must be requested to the strategic conflict resolution service during the Submission Window, that is, prior to the so-called Submission Due Time (common to all airspace users).
2. The USSP applies the conflict detection & resolution algorithms to determine potentially existing conflicts and the existence of, at least, one Authorized Launch Window (ALW).

The ALW time window defines the time interval when the takeoff of the mission can safely happen in the sense of not having conflicts with other missions already approved.

3. Almost instantaneously (response latency is negligible), the FP is either rejected (no strategic deconfliction measure exists) or approved (at least one ALW exists). The result of the requested authorization is communicated to the DO. The ALW is shorter than, and contained by, the RLW to preserve DO preferences.
4. The ALW of an approved mission is not communicated to the DO until the Confirmation Due Time. The window between the confirmation due time and the start of the ALW is also named as Reasonable Time to React (Sesar, 2023). The so-called Confirmation Window (between approval time and confirmation due time) is used by the USSP strategic deconflicting algorithms to have the possibility to still recalculate new feasible ALW to accommodate new FP approval requests arriving before the expiration of the confirmation due time.

Once the ALW is issued to the DO, the pre-tactical phase for preparing the flight starts. The ALW start time determines the tactical phase start. DO is supposed to follow the rules and takeoff within the allocated ALW, being sure that the mission has no strategic conflicts (loss of separation minima) with other planned missions. Some of these time windows and planning milestones have a strong impact on the airspace use efficiency (Liu et al., 2023). A deeper discussion on these efficiency concerns is also presented later in this paper.

### 3.3 USSP planning strategies and policies

The USSPs share a common picture of missions under consideration or approved thanks to the CISP, which has a common database with this information. Nevertheless, the USSPs sharing the airspace can show different approaches in the view of their planning strategies and policies.

For whatever timeline and procedures set for the UAS flight authorization process, different strategies can be adopted to set a trade-off between the optimization of the airspace occupancy and the flexibility usually required by operators. For the goals of this paper, these strategies will be analysed in order to assess their impact on the effective airspace occupancy. The DronAs USSP deploys the flight authorization process as described in in Section 3.2. All the time parameters can be tuned in the platform by the airspace manager (AM) to set the balance between the use of the airspace capacity optimization and the flexibility enabled to DO for their planning activities. Note that, for instance, the takeoff can happen at any moment within the ALW, so the longer the ALW (good for the DO) the more airspace capacity is ‘consumed’ by the flight (not as good for the AM). In fact, the values of these parameters, some of them tightly related to the Safety Target Level (BUBBLES, 2020), have a strong impact on airspace capacity as well as on the DO flexibility. Part of the simulation study in this paper is devoted to analysing the impact of these parameters on the airspace occupancy metric.

A second important factor concerning airspace capacity is the planning policy supported by the USSP. Nowadays, in the face of several missions of the same priority (thus eliminating any missions of state and law enforcement bodies), a policy of “first come first served” (FCFS) is used to process the planned missions. In the view of the airspace occupancy maximization, this policy suffers from the same limitations as any stochastic planning activity: decisions are made based on the latest request for approval, so the order of arrival of requests determines the capability to optimize the use of airspace. With FCFS, only the time adjustments of the ALW can be applied to those approved missions which are still within the Confirmation Window in order to accommodate a new approval request. The new operation request is simply rejected if no such adjustments are found. Much higher occupancy rates could be achieved if more than one single approval request are processed at the same time, so their order of arrival does not impact on the optimal solution. This alternative policy, where the requests arriving during a given time interval form a batch of missions, would enable the use of optimization algorithms able to adjust the ALW of all of them, ensuring a maximum performance (number of missions accepted), before notifying their acceptance or rejection.

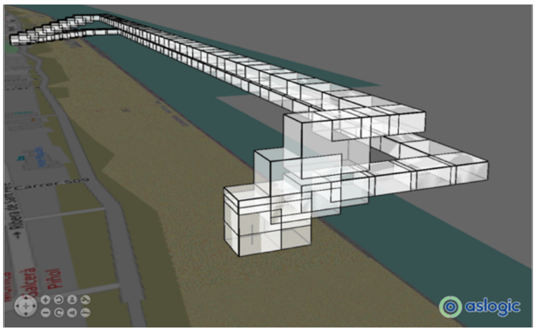


*Figure 6. Illustration of the airspace digitalization performed by the DronAs U-space services to handle 4DT trajectories*

High performance USSPs, i.e., those who implement a batch planning strategy instead of just FCFS, who can process 4DT flight plans, and who have the capability to optimize the time parameters, will benefit all users operating in a shared U-space volume. However, those high performance USSP operators, and the airspace efficiency at the end, will be penalized by other service providers who have lower capabilities in terms of planning strategies, trajectory representation and less flexibility in the planning milestones (e.g., how far in advance the planned missions need to be reported? Are they going to be accepted/cancelled or modified at that exact time? or they will be confirmed after a certain time).

# 4 Simulation Study

The DronAs USSP platform will be used for the experimentation purposes. In addition to the provision of U-space services, the platform has a suite of tools for designing the airspace architecture, including different simulation capabilities. For this work goals, its demand-capacity balance (DCB) analysis tool has been used.

This tool emulates the strategic planning process to assess how a particular operation's demand will be accommodated considering the different variables related to the safety target level (focused on separation criteria), trajectory representation (as described in section 3.1), planning timeline (as described in section 3.2), and planning policies (as described in section 3.3).

## *4.1 Impact assessment of trajectory representation*

For this section experimentation goals, the planning strategy will be set to FCFS, and the planning milestone values (see section 3.2) will be fixed and shared by all three USSPs in order to focus the discussion on the flight trajectory representation concerns. For the sake of a fair comparative analysis, the operation demand for each USSP will be the same in all cases (i.e., same traffic set), and just the representation of the trajectory submitted to the strategic deconflicting service will be different (see Figure 4): 4DT for USSP A, Polyline for USSP B and Volume for USSP C.

The traffic is randomly generated by the simulation platform for a given simulation time (one hour of operation in this case). The traffic generator uses the airspace corridor-based structure shown in Figure 1 to define 4DT closed trajectories departing from one of the vertiports, delivering the parcel at one of the established delivery points and returning to the launching point. All these points, as well as the requested takeoff time, are randomly selected. A traffic set of 3.000 4DT trajectories is generated for the later stochastic simulation. To emulate the USSP that does not have capabilities to deal with 4DT trajectories, the DronAs mission design tool is used to transform this traffic set into the polyline and volume versions of the 4DT trajectories. The three images in Figure 4 show the 3D representation of this wrapping transformation process. All three traffic sets, with 3.000 trajectories each, are loaded into the DCB Analyzer. As mentioned before, the simulation study will focus just on the different trajectory representation capabilities of the three USSP, leaving separation criteria and planning milestones the same for each USSP.

The traffic density is one of the parameters to be set for the DCB analysis. It defines the number of missions to be randomly selected from the traffic set. For instance, a density of 100 operations during one hour of simulation will randomly select 100 of missions out of the 3.000 in the traffic set. For the sake of experiment repeatability and fair comparison, the random generator seed is controlled to ensure that the same missions are selected as the demand for each USSP. The missions are the same but the trajectory representation changes, with the polyline and volume versions being mere spatial transformations of the 4DT trajectories. This is illustrated in Figure 4, where the polyline version (center) and volume version (right) are spatial transformations of the 4DT representation (left).

In order to improve the statistical significance of the results, each DCB analysis is composed by a set of traffic scenarios. In this analysis, 25 scenarios are defined and there are no changes on the scenario parameters, just the selected flights are randomly different from one scenario to the other, emulating this way 25 hours of operation. As it will be discussed later in this section, only the used traffic set must be changed from one DCB analysis to the other.

For better understanding the difference to be observed in the results, it is important to pay a look into the influence of the trajectory representation on the strategic deconflicting algorithms. This process is based on the detection of the spatiotemporal interactions between two or more trajectories (potential loss of separation or conflict). In a nutshell, a spatiotemporal interaction appears when one volume representing the location of an aircraft overlaps one or more volumes for other aircrafts during a given time interval. Two or more flights showing spatiotemporal interactions are considered as interdependent flights. The deconflict algorithms must determine if there exists a time shift for each interdependent flight that removes the spatiotemporal interactions.

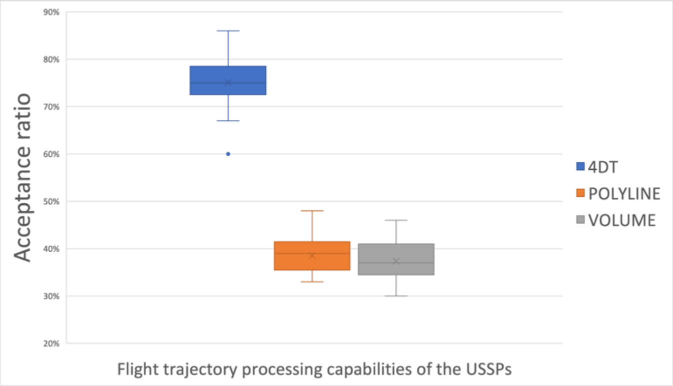


*Figure 7. Average acceptance differences depending on the flight trajectory representation*

The 4DT trajectories are digitalized into arrays of voxels, elements of volume that constitute a three-dimensional space (see Figure 6). The dimensions of the voxels are mainly determined by the vertical and horizontal separation criteria, as well as by the navigation performance. Each voxel is occupied during the time interval set as Authorized Launch Window (ALW). Hence, a spatiotemporal interaction exists when there exists a non-empty intersection, both spatial and temporal, amongst two or more voxels of different trajectories. In this case, the mitigation algorithm searches for a time shifting of the ALW of the interdependent flights subject to the rules described in section 3.2. As this set of experiments limits the analysis to a FCFS policy, the strategic deconflicting is executed every time a new flight authorization is requested to the USSP. If no conflict exists, or the conflicts generated with already authorized flights can be mitigated by calculating the appropriate ALW, the new request is authorized.

For the airspace capacity impact assessment of the flight trajectory representation, USSP A will be able to process the 4DT trajectories as described, USSP B will be able to process high resolution polylines (see Figure 3), and USSP C will process volumes. The mitigation mechanism will be the same in all three cases: the strategic deconflicting as described in section 3.2.

The first set of simulations aim to assess the differences in the average acceptance ratio (accepted vs requested missions) in the case that the airspace is not shared (one USSP at each simulated scenario). The traffic set is the same for each USSP and just the flight trajectory representation changes according to the USSP capabilities. Figure 7 shows the statistical results.

As it could be expected, the USSP A acceptance ratio (75%) is much higher than others. However, there is no big difference between USSP B (39%) and C (37%). This is because of the corridor-based structure (see Figure 1). The time that a polyline representation will occupy the longer corridors on the way to the delivery point and the way back to the vertiport is similar to the time that the volume representation occupies the same segments of the corridor. This can be easily observed in the polyline and volume representations of the same flight shown in Figure 4. Therefore, the probability of having conflicts with other planned missions is also quite similar for both representations and, consequently, similar acceptance ratios can be expected.

The second set of simulations aims to assess scenarios where the three USSP operate in shared airspace. In this analysis case, flights are randomly selected from the three traffic sets and the approval request is sent to the proper USSP according to the representation version (4DT, polyline or volume).

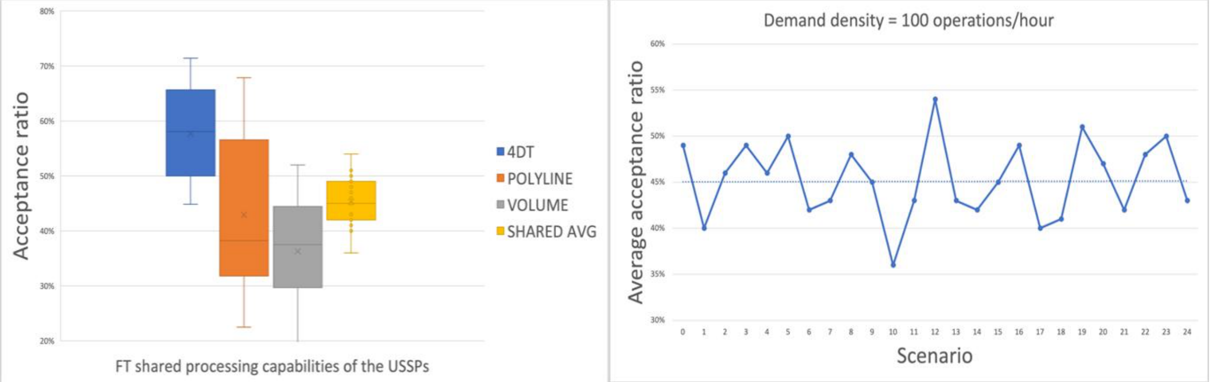


*Figure 8. Comparative acceptance ratio when the three USSPs are sharing the airspace (left). Evolution of the acceptance ratio in the simulated scenarios (right)*

Figure 8 shows the statistics of approved flight trajectories when all three USSPs operate on the shared airspace. In the left plot, the degradation of the quality of service provided by USSP A (4DT) to its DOs can be observed, dropping from an acceptance ratio of 75% when standalone down to 58% when co-existing in the shared airspace with the others lower performance USSPs. In the case of USSP B and C, the average acceptance ratio remains approximately the same value ranges. The SHARED AVG box plot shows that average acceptance ratio (45%) is higher compared with ratios from the polyline and volume representation standalone scenarios, but still far away from the acceptance ratios that can be obtained with the 4DT trajectory representation. Worth to mention is the high dispersion (right plot at Figure 8), which is a consequence of the FCFS policy during the random selection of the different trajectory representations.

## 4.2 *Impact assessment of planning timeline*

In strategic planning and deconflicting services, the different time windows (see section 3.2) may have varying impacts on airspace capacity. However, it's uncertain whether these impacts are positive or negative for all the stakeholders, and to what extent. The Table 1 summarizes the hypothesis regarding the stakeholder's preferences by assuming the AM is mostly interested in maximizing the use of the airspace in terms of number of accommodated operations, and the DO is mostly interested in flying as much as possible with the maximum flexibility.

**Table 1. Assumptions about stakeholder preferences in relation to the planning timeline**

| Time Window | Airspace Manager (AM) | Drone Operator (DO) |
|---|---|---|
| Submission Window (SW) | Earlier | Later |
| Confirmation Window (CW) | Longer | Shorter |
| Requested Launch Window (RLW) | Longer | Shorter |
| Authorized Launch Window (ALW) | Shorter | Longer |

The rationale behind these assumptions relates to the trade-off between the predictability and efficiency of airspace required by the AM and the flexibility sought by the DO. AM asks for earlier SW to know well in advance the operation requests to have longer time for organizing the demand, whereas the DO prefers later SW to have a quicker response to their operational needs. AM asks for longer CW because during this window still can move up and down the ALW to accommodate new requests arriving before fixing it, whereas the DO prefers shorter CW to have a longer reaction time once the ALW has been fixed. AM asks for a longer RLW because this is the window where the ALW can be moved up and down during the CW having higher chances to find better optimal solutions when new operation requests arrive, whereas the DO prefers shorter RLW to reduce the uncertainty related to the final location of the ALW, which is assumed something positive concerning the DO own logistics for preparing and executing a mission. Finally, the AM asks for a shorter ALW as it stablishes the protection time buffer for the UAS position during the flight execution, so the shorter the ALW the lower the spatial-temporal occupation of the airspace. The DO prefers longer ALW to have a bigger interval to start the flight, but also to respect the time dimension of the trajectory during the flight.

Given these competing interests in the planning timeline, it is worthwhile to assess the impact of the different parameters on airspace occupancy in order find a tradeoff between the AM airspace predictability and efficiency objectives and the DO flexibility objective. To analyze these questions, the following experimentation will be based on just flight plans described as 4DT trajectories to avoid any cross influence related to the trajectory representation. Thus, a single high performance USSP is operating in this simulation analysis. The FCFS policy will used in all cases. The simulation scenarios define different settings for the timeline parameters in order to compute the airspace occupancy rate. Each scenario simulates one hour of traffic with a demand of 100 missions/hour. Monte Carlo simulation method is used to randomly generate the traffic sets, including departure, delivery, and landing points. To ensure statistical significance of the mean values obtained in the simulation of each scenario, each instance was run 3000 times. Separation minima have been fixed to 30 m both horizontally and vertically (this is the separation criteria that was used during flight campaigns in CORUS-XUAM (Sesar, 2023)).

The first set of experiments aims to assess the impact of submission and confirmation windows on the occupancy ratios for the demand described above. For this purpose, the size of the RLW and ALW is kept at the same value in all simulated scenarios. The Table 2 shows the parameter setting. For instance, in scenarios A.1 the operation approval request must be sent at least 5 minutes prior to the RLW start (see submission due time in Figure 5). Then one scenario is created for different values of the CW, 1 to 4 minutes in this case (see confirmation window in Figure 5).

The simulation results are presented in the graph shown at Figure 9. Results indicate that the average acceptance ratio does not show significant variation with changes in the submission window and confirmation window. With a span from 39.73% to 41.37%, this range is not sufficient to conclude that these two-time windows have a significant impact on airspace capacity. This result could be expected from a FCFS policy, where the time available to make the approval/rejection decision is less relevant than the order in which the authorization requests arrive. This assertion will be further elaborated in the next section.

The second set of experiments aims to assess the impact of the requested and authorized launch window size on the occupancy ratios for the same demand used in the previous simulations. For this purpose, the size of the SW and CW is kept at the same value in all simulated scenarios.

**Table 2. Planning timeline parameter settings**

| Scenario Configuration | Flight Authorization Interval (minutes prior to RLW) | | RLW (min) | ALW (min) |
|---|---|---|---|---|
| | SW (min) | CW (min) | | |
| Scenarios A.1 | 5 | 1, 2, 3, 4 | 10 | 1 |
| Scenarios A.2 | 15 | 5, 10, 14 | | |
| Scenarios A.3 | 30 | 5, 10, 15, …, 29 | | |
| Scenarios A.4 | 60 | 5, 10, 15, …, 59 | | |
| Scenarios A.5 | 120 | 5, 10, 15, …, 119 | | |
| Scenarios B.1 | 30 | 5 | 10, 12, 14, 16, …, 60 | 1 |
| Scenarios B.2 | | | | 2 |

The Table 2 shows the parameter setting. For instance, in scenarios B.1 the operation approval request must be sent at least 30 minutes prior to the RLW start (see requested launch window in Figure 5) and the CW is 5 minutes. Then one scenario is created for each of the RLW values (10, 12, 14, 16, …, 60) and the ALW is set to one minute in this case (see requested and authorized launch windows in Figure 5). The simulation results are presented in the plot shown at Figure 10. The results indicate here a clear correlation between the size of the RLW and ALW and the average acceptance ratio, which grows almost linearly with the size of the RLW, ranging from 40% up to 80% when the ALW is one minute. Regarding the ALW size, the acceptance ratio approximately doubles as the ALW halves. These are the acceptance rate trends that might be expected under the assumptions used to build the simulations. Enlarging the RLW implies a bigger solution space for the optimization algorithm to allocate the ALW, so bigger chances to find feasible solutions. As already discussed in Section 4.1, the ALW determines the time buffer that each trajectory voxel is occupied by the UAS (see Figure 6). Therefore, it could be expected that the ALW has also a strong impact on the of the airspace capacity.

The planning timeline impact assessment shows that both the RLW and ALW size have a strong influence on the effective airspace capacity. However, the influence of the SW and CW is almost negligible. The experimentation in next section will provide an explanation for this to happen.

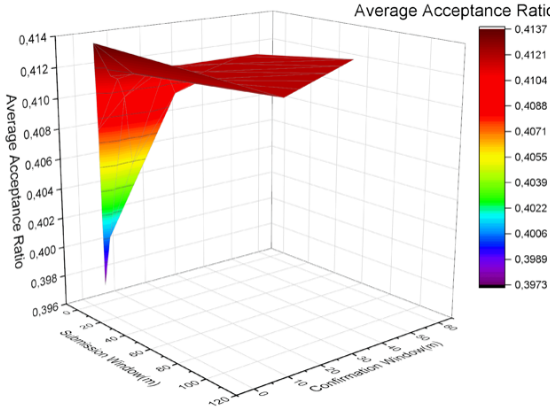


*Figure 10. Average acceptance ratio with respect to submission and confirmation window variation*

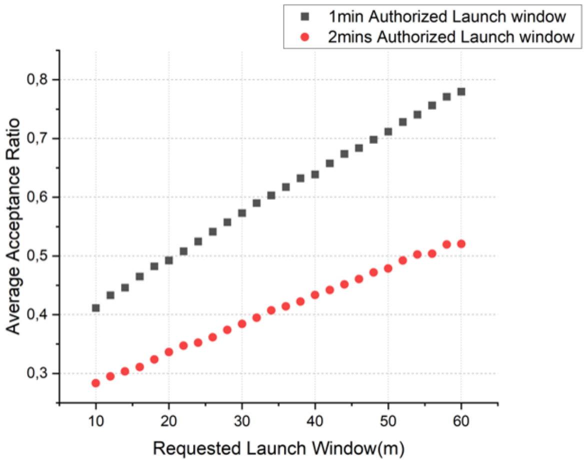


*Figure 10. Average acceptance ratio with respect to requested and authorized launch window variation*

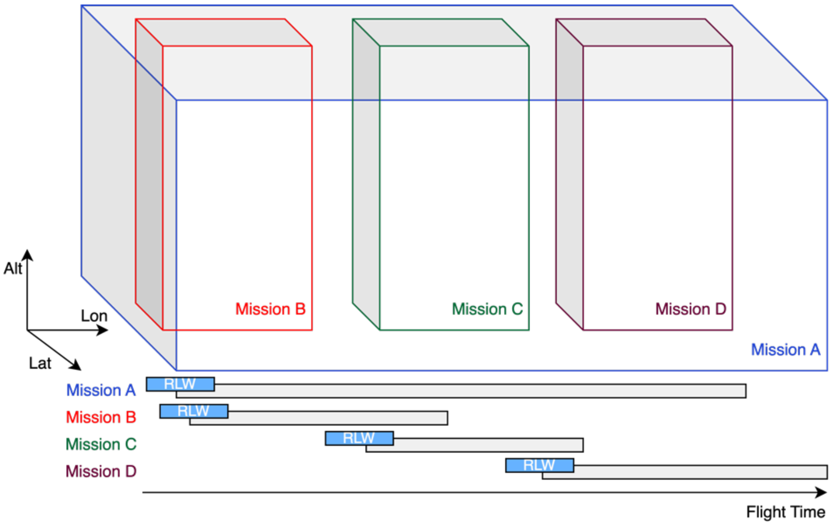


*Figure 11. Spatiotemporal interactions between four missions represented as volumes*

## 4.3 *Impact assessment of planning policies*

To explain the low impact of the Submission and Confirmation windows on the acceptance ratio when a FCFS planning policy is in place, it is necessary to analyze how the deconflicting algorithm tries to remove the spatiotemporal interactions introduced in Section 4.1. A spatiotemporal interaction exists when the intersection between the geometries of two or more trajectories is non-empty and there is a time interval overlap in the use of such non-empty intersection. Figure 11 illustrates this concept: there are non-empty intersections between mission A and B, C and D, and a time interval overlapping according to the declared flight duration (note that all flight trajectories are represented as volumes and therefore they block the whole volume during the flight time). The execution of missions B, C and D has time interval overlaps, but their geometry has no intersections, so no spatiotemporal interactions exist amongst them.

Considering the traffic set in Figure 11, Mission A will be approved if the authorization request arrives first. Then, the other three missions will be rejected by the deconflicting algorithm regardless of their order of arrival since there is no possible ALW shift within Mission A RLW that avoids the spatiotemporal interactions with the remaining missions. In this sequence of approval requests the acceptance ratio would be 25%. It doesn't matter how far in advance the mission A has arrived (SW), nor for how long its ALW can be adjusted (CW). Once Mission A is approved, none of the remaining missions can be approved. If, on the other hand, any of the requests for authorization from missions B, C or D arrive first, all other missions except A will be approved regardless of their order of arrival. In this sequence of approval requests the acceptance ratio would be 75%. This simple example illustrates why the order of arrival of the authorization requests has a much stronger impact on the airspace efficiency when compared to the Submission and Confirmation windows.

Alternatively to FCFS, a batch planning policy will be analyzed. In this case, approval requests are grouped to form a batch before deciding which of them will be authorized. Using this batch planning policy, the acceptance ratio in this simple example will also be 75%, provided the optimization objective is set to maximize the number of approved batched missions.

In the case of the used USSP platform, a batch planning policy can be put in place. The last set of experiments in this work aims to assess the impact of the planning policy on the acceptance ratios. To analyse what improvement could be achieved by replacing the FCFS policy with the Batch planning policy, the selected traffic demand is composed by the mix of trajectories represented by volumes, polygons and 4DT already used in the experiments at Section 4.1.

In order to obtain comparable results, one single USSP is considered to deploy the Batch policy. All the missions at each simulated scenario form a batch regardless of the trajectory representation format. This batch of authorization requests is submitted to the deconflicting service. The optimization algorithm has as objective the maximization of the number of approved missions. The simulation results are presented in the box plot shown at Figure 12. The acceptance rate achieves an average of 61%, an increase of 35% compared to the FCFS policy (as it was presented previously, the average acceptance ratio of the FCFS policy is 45% for this mixed traffic demand).

Batch policy clearly outperforms the FCFS policy in terms of airspace efficiency. However, this policy poses a series of concerns for its deployment in a multi-USSP operational context. These concerns will be discussed in the next section.

*Figure 12. Comparison of Batch versus FCFS planning policies*

# 5 Discussion

The calculation of the effective airspace capacity, in particular in U-space, remains as an open question. Up to the authors' knowledge, no analytical method exists and only simulation-based methods have been approached in the literature and in the ongoing research projects. It is clear that the actual capacity is affected by many factors such as UTM system performance, UAS navigation performance, CNS performance, weather conditions, societal and environmental constraints, or airspace location amongst others.

Whilst some of these factors will set limits on the maximum acceptable traffic density (e.g. societal and environmental concerns), many of the other factors (e.g. UAS navigation and CNS performance or wind conditions) will determine the separation criteria (horizontal, vertical and along-track or time separation) to achieve a given Target of Safety Level.

It is also clear that the separation criteria has a strong impact on the effective use of the airspace capacity, and maintaining this separation at the planning phase is the task of the strategic deconflicting service. Therefore, it can be concluded that the performance of the strategic deconflicting services will have a strong impact on the airspace use efficiency.

This paper has presented a simulation-based quantitative approach to assess the impact of the strategic deconflicting service by considering three different factors that determine the performance of the provided service: trajectory representation, the planning timeline set to process equally and transparently the flight authorization requests and the implemented planning policy.

The first simulation setup aimed to evaluate the impact of different flight trajectory representations on the effective airspace capacity. Three USSPs operating on a shared airspace have been emulated using the Demand-Capacity analysis tools provided by the DronAs U-space suite. Each emulated USSP has different capabilities for handling the flight trajectory representation: 4DT, Polyline and Volume. For the sake of a fair comparative analysis, the rules and policy for planning, as well as the strategic conflict resolution measures, are the same for all USSPs. The airspace usage efficiency is measured in terms of the acceptance ratio for highly dense scenarios (demand of 100 operations/hour). Under the same conditions, i.e., the same flight operations but with three different trajectory representations, the USSP capable of dealing with 4DT clearly outperforms the other USSPs (acceptance ratio almost doubles the others). However, there is no big difference between polyline and volume representations from airspace efficiency perspective, although one would expect the former to be larger than the latter. This behaviour is likely to be a consequence of the corridor-based structure used int simulation scenarios, and most likely larger differences could be observed in less constrained airspace structures (e.g. free flight).

The second simulation case in this setup puts in place the three USSPs operating simultaneously in a shared airspace. Interoperation uses the CISP model to share the relevant information between the three USSPs, basically the set of already approved missions when a new authorization request arrives. Simulation results show that the achieved acceptance ratio is a bit higher compared with the polyline and volume representations under the single USSP scenario, but still far away of the airspace usage efficiency that can be achieved when all flight trajectories can be handled as a 4DT representation.

Although these results may seem obvious, the simulations performed in this simulation setup provide a quantitative assessment about how the flight trajectory representation impacts on the airspace usage efficiency. It is worthy to note that all the U-space services and systems provided by the USSP platform that have been used for the stochastic simulations are the same services and systems that are used in real flight operations.

The second simulation setup aims to evaluate the impact of the planning timeline from flight authorization request to the final approval of the launch window, so-called Authorized Launch Window (ALW) in our proposal. The milestones proposed in this work pose some questions on the possible competing interests between the Airspace Manager (AM) and Drone Operator (DO) preferences. The simulation results show that only two of the four milestones have a significant impact on airspace efficiency: the size of the Request Launch Window (RLW) and of the ALW. The AM would rather prefer longer RLW to maximize the use of the airspace whereas the DO would prefer shorter RLW to reduce the uncertainty of the final ALW allocation. The tradeoff between these competing interests could be handled by considering a sort of demand forecasting, setting longer RLW in peak periods and shorter in low demand periods. In the case of the ALW, the AM would prefer it to be as short as possible for capacity reasons, while the DO would prefer it to be as long as possible for flexibility reasons (ideally as long as the RLW). The ALW minimum size is limited by safety reasons since it determines the time buffer that can compensate different sources of uncertainty in the UAS position, such as the navigation performance or wind conditions. The simulation results clearly show how the acceptance ratio is penalized when the ALW is increased. The tradeoff between these competing interests could also be handled using the demand forecasting, setting shorter ALW in peak periods and longer in low demand periods. The simulation results in this setup also showed that the other two milestones, the Submission Window (SW) and the Confirmation Window (CW), have a low impact on the maximization of the airspace use. In these cases, the DO preferences with respect to these parameters could be favoured with the limits set by the AM for different reasons such as, for instance, have a sufficient predictability of the airspace usage, or having time enough for manual authorizations, or deploy DCB measures.

The third simulation setup sought to explain why the SW and CW have a little impact on airspace efficiency, whereas the planning policy has a strong impact instead. The simulation results have shown why the order of arrival of the authorization requests is much more relevant than how far before the operation the request is submitted or how much time pass before the ALW is finally allocated. This is a common issue of the FCFS policy in any stochastic planning application domain. Alternatively, a Batch planning policy has been tested. The authorization requests are processed in batches, yielding an acceptance rate improvement of 35% with respect to the FCFS under the same operational conditions. However, several questions remain open for deploying the Batch policy. It is not clear how to deal with batches in a multi-USSP operational context according to existing U-space regulations, since the authorization process is delegated to the participating USSPs and a centralized authorization service is not contemplated. Moreover, it is also unclear what rules should be defined to form the batches while maintaining equity and transparency among airspace users. These rules should be incorporated into the optimization algorithms in order to avoid the starvation of flight plans that penalize the airspace occupancy (e.g. a surveillance operation in a big volume compared to several 4DT delivery operations in the same area).

The observed results in these three simulation setups can also contribute to answer the set of questions that were formulated at the beginning of the paper:

*Could a mission be accepted or rejected due to a non-optimal performance of a different USSP capabilities in a shared airspace?*

Yes, provided that the FCFS policy without any kind of prioritization mechanism is in place. As illustrated by the simulations, the airspace time occupancy of the polyline and volume representations of the same type of operation is much higher compared to the 4DT representation. Thus, when lower-performing USSPs accept a mission, the airspace is blocked for a longer period of time, preventing new requests for authorization from being approved for a longer period of time.

*Can a USSP jeopardize the level of service of another USSP offering their services in a shared volume?*

Clearly yes, the highest performance achieved with 4DT representation (75%) drops down to 45% when less accurate trajectory representations are in place simultaneously. Therefore, 30% of the operations in average are not approved because of the co-existence with USSPs performing worse. The DO contracting the USSP A (with 4DT trajectory representation capabilities) will notice that the rate of acceptance of its operations requests will drastically drop when co-existing USSP B and C are also providing services to other DO in the shared airspace. However, the DO will hardly understand the reason for receiving a clearly lower level of service.

*Should a minimum performance level be required from USSPs and their services according to the complexity of the airspace where the service is provided?*

In author's opinion, the answer is clearly yes. As the DCB analysis shows, lowest performance USSPs (e.g., those who can only handle flight trajectories represented as volumes) jeopardizes the overall airspace capacity, which penalizes higher performance USSPs and the airspace users. However, some DO still might choose to contract lower performance USSP because of different reasons, for instance lower service fares. In this case, the fair USSP competition may not be enough to discriminate which USSP will survive, and which ones will disappear, and the overall performance will be negatively impacted.

The obtained simulation result figures are certainly conditioned by the corridor-based structure, and these figures might be different in another airspace architecture (e.g. free flight). However, a different airspace architecture should not show a different trend in the comparative analysis of the impact of USSP performance on airspace efficiency, as the time occupancy dimension of the flight representation has proven to be a key factor in managing strategic planning.

It is worth to mention that one single platform has been used for emulating the co-existence of three USSPs. Therefore, it has not been possible to reproduce a problem that is common to decentralized decision-making systems: concurrent allocation requests of shared resources. This issue must be addressed in the future, probably by the CISP, since it can easily happen in dense scenarios where two or more USSPs are processing concurrently an authorization request without knowing the resulting picture after their decision, which eventually can result in the authorization of two or more missions that have conflicts.

Finally, the experimentation framework defined in this paper opens a set of questions to be explored in the future. Whatever trajectory representation, planning timeline and policy are put in place, they define the common rules for users to access the airspace for the sake of equity and transparency. Although having available airspace capacity (note the statistical dispersion in the simulation results), there will be rejected missions according to these rules. Therefore, it can be assumed that there exists a latent capacity in the airspace. The open question is how to take advantage of this latent capacity: which type of mechanisms can mitigate the performance loss due to trajectory representation or planning inflexibility? The proposed approach here is to 'relax' the rules for the rejected mission, but in an organized and transparent manner. For instance, the ALW lies within the RLW but would the DO accept a larger RLW or an alternate RLW to accommodate a rejected mission? Authors' research is currently addressing this type of negotiation mechanisms by means of a Multi Agent framework that makes use of machine learning techniques, in particular Reinforcement Learning and Deep Reinforcement Learning. It is expected that this multilateral negotiation framework will empower DO with new services to increase their chance to perform the required operations, as well as the AM with new features that contributes to the maximization of the airspace use.

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## *Contributor Statement*

Ramos has participated in the paper conceptualization, writing, developing the applied methods, and obtaining the fundings supporting the research. Liu and Muñoz have participated in the investigation process, performing the experiments and reviewing and editing the paper. Pastor and Barrado have participated in the experimental cases design, and in reviewing the paper.

## *Conflict Of Interest (COI)*

There is no conflict of interest.

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