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Abstract

This is the final technical report of the ‘Quantifying Weather Influence on RTTA’ (QWIRTTA) project, which was awarded funding through the Engage 2 KTN’s first Call for catalyst funding.

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Engage 2

QWIRTTA

Quantifying Weather Influence on RTTA

Final technical report

Engage 2 catalyst fund project

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Engage 2

THE SESAR 3 KNOWLEDGE TRANSFER NETWORK

Engage 2

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1 Introduction

1.1 Abstract

The project developed a methodology for quantifying the influence of hyperlocal urban weather (including the uncertainty of weather forecasts, associated with longer lookahead times of weather prediction) on strategic deconfliction of U-space flights in metropolitan airspaces. The methods were applied to simulated drone traffic use cases in two European cities: Ljubljana (Slovenia) and Norrköping (Sweden). Several U-space performance metrics (and their probability distributions) were calculated for multiple scenarios with varying weather, drone service demand and other parameters. The results contribute to addressing requirements laid out in EASA's AMC/GM (specifically, GM2) to Article 18(f) of EU U-space Regulation 664 (planning and review phases, in particular – the technical review). It will allow competent authorities to make an important technical step towards compliance with the regulations and performance-based regulations overall.

1.2 Executive summary

Demand and Capacity Balancing (DCB) and strategic Conflict Resolution (CR) are at the heart of unmanned aerial systems' (UAS) traffic management (UTM). A fundamental question in UTM is when to do the strategic deconfliction of U-plans (a U-plan is a UTM counterpart of the flight plan in conventional aviation). The European ConOps for the U-space (CORUS) and its Urban Air Mobility (UAM) extension (CORUS-XUAM) suggest that instead of First Come First Served (FCFS), U-plans may be deconflicted at a certain time before the start of the flight: the length of this time interval between the deconfliction and the flight start was dubbed RTTA (Reasonable Time to Act, sometimes expanded as Required Time to Act).

We investigate how UTM performance depends on RTTA values, taking into account forecast uncertainty, different traffic intensities, mission mix, etc. We evaluate several Key Performance Indicators (KPIs) from the Key Performance Areas (KPAs) of Access and Equity, Capacity, Efficiency, and Safety. Thus, among SESAR's 9 KPAs, we do not explicitly measure Predictability, Flexibility, Environment, and Security KPIs. While the Environment and Security KPAs are outside our scope, the RTTA notion per se is all about Predictability (when the situation at takeoff can be predicted confidently enough to approve the U-plan?) and Flexibility (how long before the operation do drone operators have the flexibility to change their plans?) questions. Hence, overall, our work is related to 7 out of 9 SESAR's KPAs.

The specific KPIs measured are average delay (also per delayed drone) and maximum delay (Efficiency), number of delayed missions and number of drones delayed by more than 15 min (Capacity), Gini index (Equity), and number of potential conflicts (Safety). The KPIs are evaluated under a variety of scenarios: for each of the considered cities (Norrköping in Sweden and Ljubljana in Slovenia), the scenarios differ by the demand level (Low, Medium, High), traffic mix (scheduled vs. on-demand services), presence or absence of priority drones, and type of deconfliction (strategic vs. tactical). In addition to the baseline scenario without weather effects, we also consider 12 weather scenarios that differ in terms of forecast uncertainty (reflecting reduced reliability with earlier predictions) and wind field variability (because we did not have a location-specific realistic urban weather data, the same weather scenarios were used for both cities).

We also look at users' diversity regarding their potential business needs: while all operators prefer to fly without delays and to know about delays early (i.e., having a large RTTA), different missions have different tolerances for the same delay D of the flight. For instance, inspections scheduled at regular intervals (e.g., weekly or monthly) may not care about being delayed for some time if they know about the delay well in advance and have the time to replan (have reasonable time to act); on the contrary, on-demand services, such as hot food delivery, do care about the delay and do not even know about the operation long in advance (thus, having a large RTTA is of no use for such an operation).

We ran extensive simulations which allowed us to obtain not only the mean values of the KPIs, but also their distributions (our probabilistic approach borrows methodology from the SESAR 2020 ER4 FMP-Met project). Parts of our work build up on SESAR's Metropolis 2 project (we use the same method for demand estimation; the project also evaluated UTM KPIs). Some probability distributions related to RTTA were explored also in the recent work by SPATIO project.

2 Overview of catalyst project

2.1 Operational/technical context

Demand and Capacity Balancing (DCB) and strategic Conflict Resolution (CR) are at the heart of managing traffic of unmanned (aka uncrewed) aerial systems (UAS, drones). A fundamental question in UAS traffic management (UTM) is when to do the strategic deconfliction of U-plans (a U-plan is a UTM counterpart of the flight plan in conventional aviation). EASA's acceptable means of compliance and guidance material (GM7 Art 3(4)] to the U-space Regulation 664 allows local authorities to define a time window during which flight activation may be requested, as well as to limit how long before the takeoff the flight authorization may be sought. These measures are envisioned to augment First Come First Served (FCFS) DCB and CR (complying to the U-space regulations), making them more efficient and fair to airspace users. The European ConOps for the U-space, CORUS, and its Urban Air Mobility extension CORUS-XUAM suggest that instead of FCFS, U-plans may be deconflicted at a certain time before the start of the flight: the length of this time interval between the deconfliction and the flight start was dubbed RTTA (Reasonable Time to Act, sometimes expanded as Required Time to Act).

The overall idea with RTTA is that a U-plan that is past RTTA is "frozen," i.e., it will not be changed (unless it will conflict with a priority flight like an emergency medical service or police). That is, at RTTA, the USSP promises that the flight may be executed as planned assuming nominal operating conditions. On the contrary, a flight that has not reached its RTTA may still be rejected by the USSP, e.g., because it conflicts with another flight, and a modification of the U-plan may be suggested. This way, RTTA values balance early airspace reservation versus the flexibility of last-minute adjustments, early deconfliction may lead to inefficient airspace use due to unnecessary reservations (in particular, not taking into account possible U-plan cancellations), while late deconfliction implies reduced predictability for UAS operators (in particular, due to receiving the delay notification from the flight authorization service too close to the desired takeoff time). That is, RTTA is addressing the following two conflicting considerations:

- **Deconflicting early** (e.g., on an FCFS basis, as the U-plans arrive) may be suboptimal because when flight plans that request departure at a later time are scheduled first, it creates gaps between them which may be insufficient for other (later-filed) operations, leading to less efficient use of airspace. This strategy is also sensitive to uncertainty, for example, cancellations: by the time of the flight, the operator may decide to cancel the flight, leaving the reserved airspace unused. (Early airspace reservations are also unfair to operators who do not know their plans well in advance – various kinds of rapid response missions, on-demand services like delivery, etc.)
- **Deconflicting close to the actual flight** discourages early planning, and may disappoint an operator whose plan is rejected by the USSP close to the time when the operation is about to start (thus not giving the operator a reasonable time to act upon the U-plan rejection).

Naturally, it is better for the drone operator to have its U-plan approved sooner rather than later. The approval assures that the operation will happen as planned because the airspace for the flight is reserved. On the contrary, the USSP would want to deconflict the flight as close to the start of the operation as possible because then the USSP has better situational awareness: more information is available regarding the other (potentially conflicting) U-plans, the airspace capacity is better known, the weather forecast uncertainty decreases with the time (we emphasize that the issue regarding weather is particularly salient: for urban use cases, it is very difficult to have accurate urban microweather prediction services; for rural/regional air mobility use cases, we will still need more granular en route weather predictions than what we currently have today), and so on. In particular, the USSP may not want to commit to an early reservation of the airspace for the operator simply because the flight may be canceled or delayed (due to a variety of reasons, e.g., drone not being ready to fly, dynamically changing demands, etc.). This leads to revenue loss, as another U-plan might have been overly-conservatively rejected (or modified to fly around, which increases the operating cost) due to a (no longer relevant) conflict with the to-be canceled flight.

CORUS-XUAM ConOps identifies RTTA with the Pre-Tactical phase; however, in many other places (e.g., in D4.2 Section 2.2.3.2.1 introducing RTTA for the first time) the ConOps gives a more reasonable definition that RTTA is a single moment in time when the USSP checks whether the submitted U-plan can be executed as planned or should be modified (e.g., to avoid conflicts). The question is how far in advance of the flight that moment should be. Additionally, better understanding how RTTA can be used for strategic demand management has the potential to help inform the Cooperative Operating Practices (COPs) currently being developed as a part of the US Federal Aviation Administration (FAA)’s UAM Concept of Operations. Such COPs are expected to take the form of industry-defined (e.g., UAS fleet operators), regulator-approved practices that inform aspects such as airspace usage equity and demand-capacity balance.

Understanding the optimal look-ahead (or look-back) time (or distance) is a fundamental ATM question. For instance, it would be hard to handle traffic in Terminal Maneuvering Areas (TMAs) if the aircraft were appearing unexpectedly on a short notice. Extending the planning-horizon to sequence the aircraft 100-200 nmi before the TMA (e.g., using the SESAR’s solution Extended Arrival Management E-AMAN or the Extended Metering function of US FAA’s Time-Based Flow Management tool) leads to more efficient, smooth, and organized traffic management. In the limit, as the planning horizon goes further and further back from the TMA, one would deal with the full gate-to-gate trajectory (arriving at ideas like Trajectory-Based Operations TBO and Ground Delay Programs keeping the aircraft from flying until the capacity constraints are alleviated). However, with a longer lead time, the uncertainty of the situation increases, which complicates traffic flow management. Striking the correct middle ground by finding the right distance/time to look back, when the uncertainty is sufficiently low (so predictability is good) while there is still time to act/change the course of action without high cost, is an area of active research. Finding the right value for RTTA looks to be an analogous challenge: to address it, one needs to see how multiple KPIs (delays, fairness, safety, etc.) depend on RTTA in various scenarios.

2.2 Project scope and objectives

Despite the interest in RTTA (due to its critical role in UTM) both in the EU and the US, there exist no guidelines on deciding how long the RTTA should be, which motivates further research on the topic. The project developed methodology for evaluating how UTM KPIs depend on RTTA in various operational scenarios, providing not only the average values, but also the probability distributions of the KPIs.

Performance evaluation of air traffic services has been high on the agenda of ATM modernization efforts both within SESAR in Europe and NextGen in the U.S. ("If you can't measure it, you can't improve it"). The same applies to UTM: U-space regulatory framework underlines the need to establish and monitor a set of metrics for performance of U-space services. In particular, Article 18 of U-space Regulation (EU) 2021/664 is a list of "Tasks of the competent authorities" related to the U-space; the Acceptable Means of Compliance and Guidance Material (AMC/GM) [13] to this regulation expand and clarify the tasks. For instance,

- GM2 to Article 18(f) of the regulation (page 132) reads: "The complexity of the U-space airspace should be addressed through its different life cycle phases".
- GM2 to Article 18(f) of the regulation (page 132) further suggests: "establishment of indicators/KPIs or metrics (covering aviation performance, safety metrics, and sustainable urban mobility) on the national, regional and local level of the U-space deployment".

This project shows what can be done to comply with the regulations on a local level; future work may address the same questions on the regional and national levels.

In addition to the above quotations from AMC/GM,

- GM1 to Article 3 "U-space airspace" (page 20) reads: "(g) The regular reassessment of the U-space airspace is expected to be conducted by the Member States to evaluate its effectiveness in supporting the safe, secure, and efficient conduct of UAS operations."
- GM1 to Article 18(g) (page 142) says: "The competent authority may monitor or audit authorisation and rejection data to assure equitable access to airspace" in order to support operational performance.

The project results suggest how RTTA can be used (instead of FCFS) in the flight authorization service to contribute to more efficient and equitable airspace access.

Note that because currently there is no RTTA, the relevance of EU Regulation 2021/664 and the AMC/GM regarding regular maintenance of U-space operating conditions are hypothetical. While RTTA is not yet regulated, the project's work on performance metrics is a possible technical step toward preparing for performance-based regulations and a future U-space where such concepts may be adopted.

2.3 Research carried out

We started from an initial set of simulations, to develop the methodology. We simulated drone traffic over Norrköping municipality in Sweden, using the Cal model (which we developed earlier with UC Berkeley – hence the name Cal). Many features of the model are similar to the ones used by Airbus UTM, e.g., straightline routing and Poisson demand; the spatial scale of our simulations was also similar to the one in the package delivery scenario by Airbus (12km), as was the speed of 25m/s of our drones. We simulated the traffic over 12 hours which was sufficient to obtain statistically meaningful results, as the outputs did not vary much from hour to hour. As with Airbus, we used ground delay for the deconfliction. The main difference of our Cal model from the Airbus' setup is that the latter had point sources (origins of the flights) and sinks (destinations) of two types – point and area sinks (the destinations were drawn from Gaussian distribution); our Cal model assumes a slightly more realistic scenario of the traffic demand proportional to the population density – both the origin and destination types are area sinks. Because both the sources and the sinks are spread over the whole city, we used higher traffic intensities (thousands requests/hr) and larger conflict radius (150m) than those in the Airbus' scenario (25-250 requests/hr and 50m resp.): with low traffic intensity and small conflict radius (i.e., rare conflicts), RTTA did not have a profound effect on the delays.

Here is a detailed comparison of our experimentation simulator, its capabilities and limitations, with the Airbus UTM setup that they used in [5].

- **Routing**. Both we and [5] used straightline U-plans only (however, both our and Airbus' simulators can, in principle, handle arbitrary routes; we used direct routing for computational efficiency).
- **Flight level**. Both our work and [5] used only one flight level (however, both our and Airbus' UTM are capable of routing on several flight levels; see, e.g., our ICRAT'18 paper [4]).
- **Drone speeds**. While Airbus' simulator can vary drones' speeds, in [5] they used a constant speed of 25m/s. In our work, the speed changed depending on the wind.
- **Conflict zone**. While Airbus' simulator can vary the separation threshold, in [5] they used a constant conflict radius. In our work, the conflict zone changed depending on the weather (in [5] weather was not considered).
- **Spatial scale**. The region of interest was a square with the side of about 12km for both us and [5]. Airbus UTM used synthetic scenarios; our square was in the center of a mid-size town.
- **Demand model**. While [5] routed between a fixed set of sources and sinks, we had origins and destinations anywhere within the region of interest; also, our simulator assumes the demand to be proportional to population density.
- **Traffic intensity**. In [5], the number of requests per hour was 25-250 (depending on the scenario); we used thousands of requests (750, 1250, 1750, for the three demand levels) -- because our origins and destinations were distributed over the whole area, larger traffic volumes were needed to obtain meaningful number of conflicts between the drones.
- **Deconfliction**. Both we and [5] used ground delay. This is the main limitation of our simulator. With substantial extra effort we could reroute the drones, but left it for follow-up work. While in future real operations, ground delay will not be the only way to avoid conflicts, for strategic deconfliction, delaying the start time may be the most fundamental and first action before considering route modifications, making it a possible focus in the initial performance analysis.

Because we wanted to explore the full spectrum of possible RTTA values (including the upper bounds), our RTTA range (up to 240 minutes) was very long in comparison with the few minutes considered by CORUS and CORUS-XUAM. While delivery operators may value minutes-long RTTAs, a small RTTA would not encourage scheduled services (e.g., inspections) to submit their U-plans early. At the same time, USSPs may benefit from early planning since it will allow them to predict the resource [re]distribution (the reasonable time to act on a change may be longer for a USSP than for an operator -- we discussed this with a potential USSP during this project). In Airbus' scenarios from [5] even for delivery operations, the file-ahead times of 30min were considered; moreover, without the file-ahead, the average ground delay of the operator could be as high as 1 hour 45 minutes -- we wanted to consider RTTAs also in this ballpark. In our experiments, file-ahead time was distributed uniformly (i.e., the proportion of flights known before RTTA decreased linearly with RTTA). Perhaps a more realistic approach could use real-world proportions of on-demand vs in-advance-known flights; however, business modeling was outside the scope of this project.

To model the uncertainty, we postulate that U-plans may be canceled. Canceling close to the start of the flight is less likely than canceling well before the flight: we modeled the probability of cancellation as a decreasing linear function of the file-ahead time (falling from 10% probability of cancellation at 24 hours before the start – the upper bound on the file-ahead time in our experiments – to 0% at 10 minutes before the start). Following the RTTA principles outlined above, any flights past their RTTAs were frozen: they were flying as scheduled. For example, if flight C-D is delayed because it conflicts with a flight A-B, then even if flight A-B is canceled after C-D has been deconflicted, the flight C-D will nevertheless start delayed (see the figure below) – again, the logic is that after RTTA the operator prefers to have no changes (even if now a change would be favorable) because the operator does not have a reasonable time to act on the change (update the delivery time, reschedule charging, etc.).

Right: At 1000, Operator 1 submits the plan to fly $A \rightarrow B$ at 1200; the RTTA is 1 hour, so the plan is approved at 1100. At 1140, Operator 2 submits a plan to fly $C \rightarrow D$ at 1155; because the plan conflicts with an already approved flight, the flight is delayed. Left: At 1145, Operator 1 cancels its flight. If RTTA were shorter (e.g., 5 minutes vs. 1 hour), the first flight would not need to be approved, and the second flight could go direct from C to D.

The results from the initial set of simulations are presented in the next section.

As suggested by the project mentors, different values for the “delay tolerance factor” c were tried, where c is the coefficient in front of RTTA in the formula for the operator's cost (or price, as defined by Airbus) P(D, RTTA) as a function of the delay D and RTTA: P(D, RTTA) = $[D - c \cdot \mathrm{RTTA}]_+$ where $[x]_+$ is x for x>0 and is 0 otherwise. The constant c determines the relative importance of RTTA (having time to act, after learning about the delay) vs. the price of the delay. Specifically, the term $c \cdot \mathrm{RTTA}$ represents the benefit of knowing about a delay earlier, i.e., the value of having time to act. For fixed c and D, larger RTTA means decrease in the price of the delay D. On the same note, larger c means that it is important to know about the delay early, i.e., larger c emphasizes the importance of RTTA. E.g., c=0 is the delay-only price (no matter what the value of RTTA is, the price is the delay D); c=0.5 represents a moderate value of predictability, etc. The price as a function of RTTA for various c (one graph per value of c) may be found in the next section.

We then considered the weather forecasting. TruWeather Solutions kindly provided API access to their products (Single Point Weather Observation, Area Weather Observation, RouteCAST, MissionCAST, Core Forecast); however, it was beyond the reach of the project to verify how realistic the data is. We therefore used a generic model postulating that for larger lookahead time, the uncertainty of the weather forecast increases, i.e., the forecast becomes more and more precise as it approaches nowcast. One crucial parameter influenced by the lookahead time of the forecast is the minimum separation distance between drones: the longer the lookahead time, the greater the uncertainty, which requires drones to be spaced farther apart to avoid collisions or interference caused by unpredictable weather conditions. Thus, if the drones are deconflicted earlier (longer time before the flight, i.e., with larger RTTA), the radius r of the protected airspace around each drone increases, which leads to the decrease of the airspace capacity (fewer flights can be routed so that the radius-r disks, centered on the drones, do not overlap while the drones fly). This way additional delays are incurred, when the weather uncertainty is taken into account.

We quantify the weather influence by applying the RTTA analysis above: we ran the same simulations as above, but with the radius r dependent on the RTTA: we use a simple dependence of $r = r_0 + c_w \times$ RTTA where r is in meters, RTTA is in minutes (if a flight request was submitted past its RTTA, we use the time request submission and intended departure instead) and $r_0 = 150$m is the radius used above assuming perfect weather forecast (our techniques extend to any other model of how the forecast uncertainty grows with the lookahead time). We fix the value of the "RTTA importance constant" $c = 0.1$ and look at different values of c_w which represents how the safety radius around drones increases with the lookahead time. See the next section for the results.

For drone traffic, one of the most influential weather phenomena is wind. We explored how wind prediction uncertainty may affect the delays at different RTTAs. We ran the same simulations for the RTTA analysis as above to explore how wind speed uncertainty influences the costs. To keep the results as general as possible, our experiments did not assume any specific dependence of the uncertainty on lookahead time (the uncertainty is determined by the weather prediction service and may be supplied along with the prediction), and instead look at different fixed values of the wind speed uncertainty $w \in$ {0 m/s, 5 m/s, 10m/s, 15 m/s, 20 m/s}. We set the value of the "RTTA importance constant" $c = 0.1$ and use the safety zone radius $r_0 = 150$ m. See the next section for the results, quantifying the impact of RTTA on the cost under different weather predictions.

We remark that according to EASA's AMC/GM to Reg664 a U-plan is "a series of one or more 4D volumes expressed in height (base, ceiling), longitudinal and lateral limits, and duration (entry and exit times)" and that "The conflict detection process is simply the identification of overlapping 4D volumes" (item (b) of GM1 Annex IV UAS flight authorisation request referred to in Article 6(4)). Our conflict definition as intersection of the disks around the drones is a special case of EASA's 4D volumes intersection: each of our U-plans is a single 4D volume with constant height (we consider a single flight level), longitudinal and lateral limits defined as the planned trajectory fattened by the conflict zone, and entry and exit times being the planned takeoff and landing times resp. The AMC/GM further suggests that "Each dimension includes the uncertainty of the flight, considering the UAS operational performance, and the assumptions on the operator proficiency and weather conditions." Our modeling gives one specific way to include the weather forecast uncertainty by increasing the radius (i.e., "longitudinal and lateral limits" of the 3D volume); the wind, in particular, affects the speed and hence the duration of the flight (the time dimension of the 4D volume, in EASA's parlance). Thus, our models are equivalent to a special case of EASA guidelines; in particular, our simplified view assumes that the drones remain within the 4D volume 100% of the time (in line with AMC/GM's suggestion that "The UAS operator submits this series of volumes, committing to remain within them") instead of the EASA-recommended 95% of the time.

We then turned to more extensive experiments to evaluate more KPIs and also their probability distributions. We first determine the parameter values for the scenarios (demand levels, percentage of priority missions, etc.) and define the experimental setup (length of each experimental run, the number of runs, etc.) to obtain statistically meaningful results (the KPIs distributions as functions of RTTA).

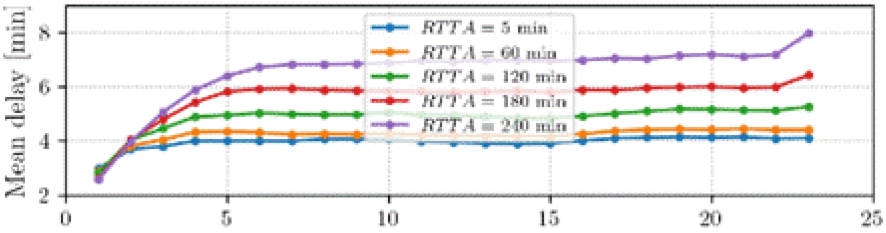
We chose Norrköping in Sweden (the guinea pig city in our earlier work in the project) and Ljubljana in Slovenia (the host of SIDs 2025) as the cities. Since the cities differ in size (1500 sq km vs. 275 sq km, resp.), as our regions of interest we adopted 12×12 sq km squares centered at the respective city centers (58.5885°N, 16.1883°E and 46.0514°N, 14.5061°E), similarly to the earlier work [1, 4-10]. Following the approach in SESAR's Metropolis 2 project [11], we apply the method from [12] to set UTM demand levels. The method estimates drone-based package delivery volumes in European regions based on the annual parcel volume, urban population share, average economic growth rate, population within the area of interest, and a set of predefined scaling factors, which are presented in the table below for our use cases (the table also shows our outputs). Guessing that parcel delivery will constitute approximately three fourths of overall UAV activity, we derive rough estimates of hourly U-space traffic demand to be 600-750 requests for Norrköping and 950-1250 for Ljubljana. For comparability, we adopt a common set of demand levels for both cities, by selecting the maximum estimated value for each city, along with an overconservative upper bound of 1750 requests/hr: the resulting demand levels are 750 (low), 1250 (medium), and 1750 (high). This roughly coincides with the 850 and 1750 requests/hr used by Airbus and our first paper [1] written within this project. The rest of the experiments also followed the methodology from [1]; in particular, larger weather uncertainty led to larger safety radius *r* around each drone, and stronger winds implied decrease in the speed *v*. The new thing, in comparison with the initial paper [1], was that the experiments were much more extensive. (We remark that understanding the demand for drone services is a million-dollar question which we are by no means trying to answer here; our experiments merely demonstrate the difference in KPIs for various demand levels.)

City	Annual parcel volume (country level)	% living in urban areas (country level)	Economic growth rate (%, country level)	% living in the area of interest	Hourly demand (pessimistic)	Hourly demand (realistic)	Hourly demand (optimistic)
Norrköping	202M[a] (2022)	89[c] (2023)	1.1[d] (2025)	1.1[e] (2025)	465 (2035)	492 (2035)	548 (2035)
Ljubljana	40M[b] (2024)	56[c] (2023)	2[d] (2025)	13[e] (2025)	714 (2035)	788 (2035)	957 (2035)

[a] https://www.pitneybowes.com/content/dam/pitneybowes/us/en/shipping-index/23-mktc-03596-2023_global_parcel_shipping_index_ebook-web.pdf
[b] https://www.statista.com/statistics/1219822/courier-express-parcel-market-volume-slovenia/
[c] https://data.worldbank.org/country
[d] https://economy-finance.ec.europa.eu/economic-surveillance-eu-economies_en
[e] https://human-settlement.emergency.copernicus.eu/download.php?ds=pop

Inputs and outputs for parcel delivery demand estimates for 2035, based on the EU ATM Master Plan

To obtain statistically meaningful estimations, we simulated 24hrs of traffic for several RTTAs and discarded the initial and final hours when the system exhibits the warm-up and cut-off effects (noticed also in prior work -- see our second paper written within this project [2] for details). The initial simulation results, presented in the figure below, show that it suffices to simulate 9hrs of traffic and take the results from the 8th hour.

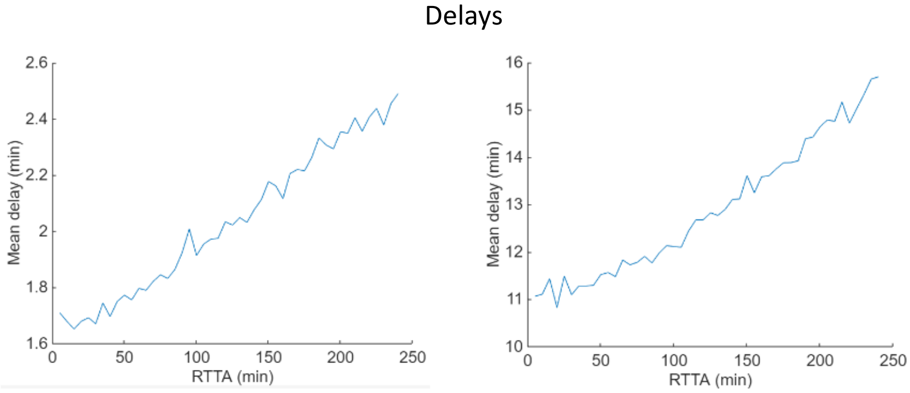


Mean delay at different hours; see Figure 1 in [2] for details

The next section presents a selection of results of the extensive simulation runs.

2.4 Results

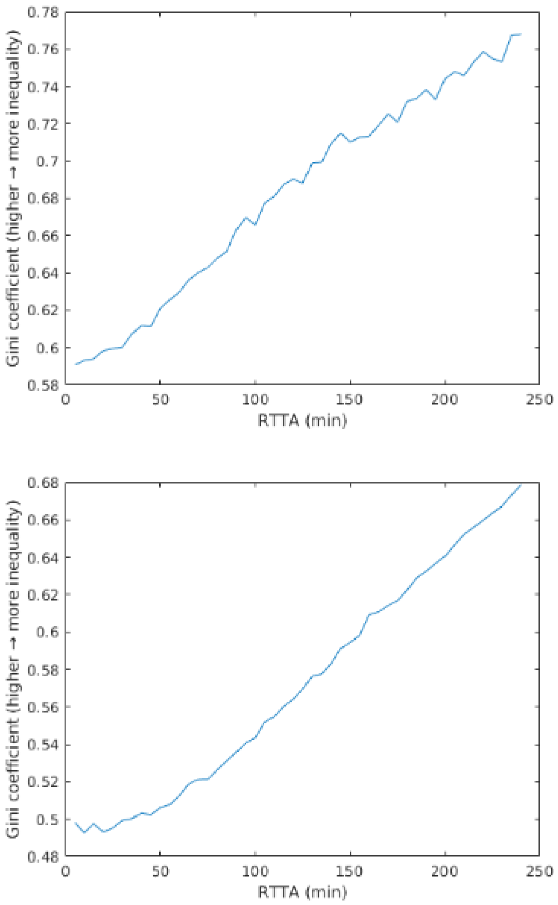
The figures below show the Delays and Fairness KPIs obtained for 2 traffic intensities from the initial, small set of simulations.



Average delay per flight. Left: 850 requests/hr. Right: 1700 requests/hr.

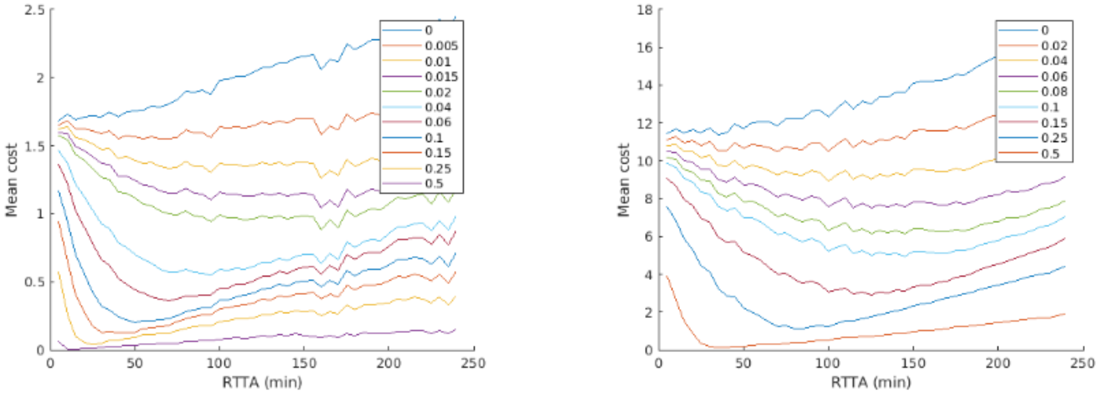
With small RTTAs there are fewer flights for which the airspace is reserved, and they mostly fly with small delays. With larger RTTAs, the airspace is reserved for more flights, and the delays are larger on average. This illustrates the tradeoff between the delays (longer delays are bad) and RTTA (the larger RTTA is, i.e., the earlier you know about your delay the better—even if the delay itself is slightly larger—as this gives you more time to act on the delays, signifying the name Reasonable Time to Act).

Fairness



Gini inequality coefficient of the delays where 0 represents complete equality and 1 is complete inequality. Top: 850 requests/hr. Bottom: 1700 requests/hr

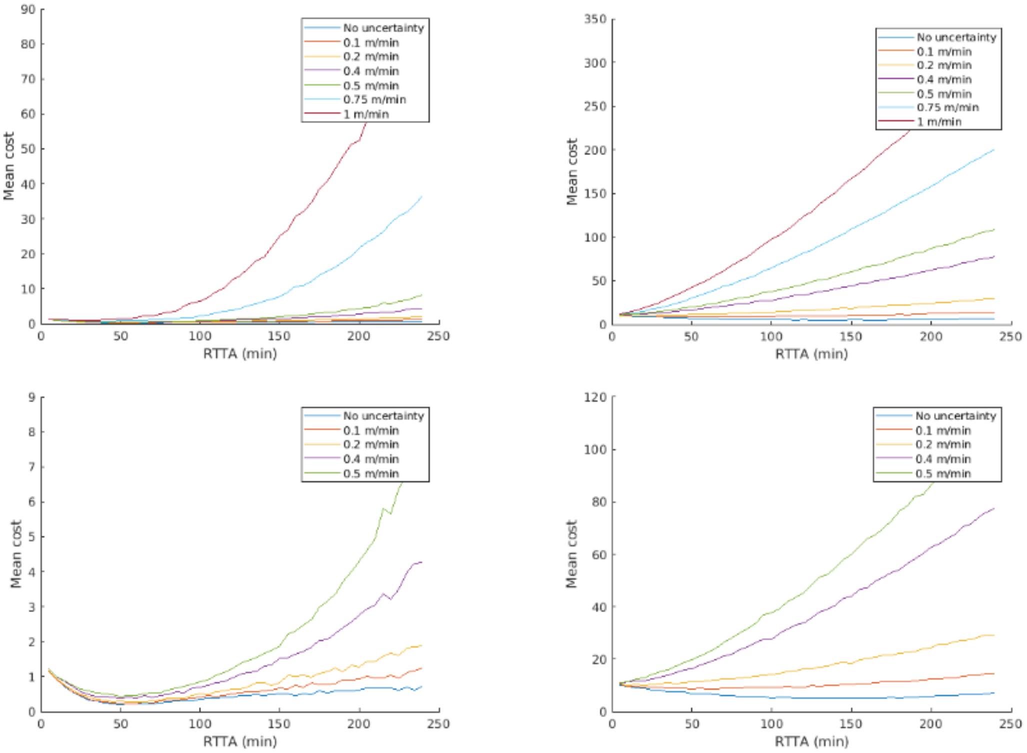
The price as function of RTTA for various values of the “RTTA importance constant” c is below.



Left: 850 requests/hr. Right: 1700 requests/hr.

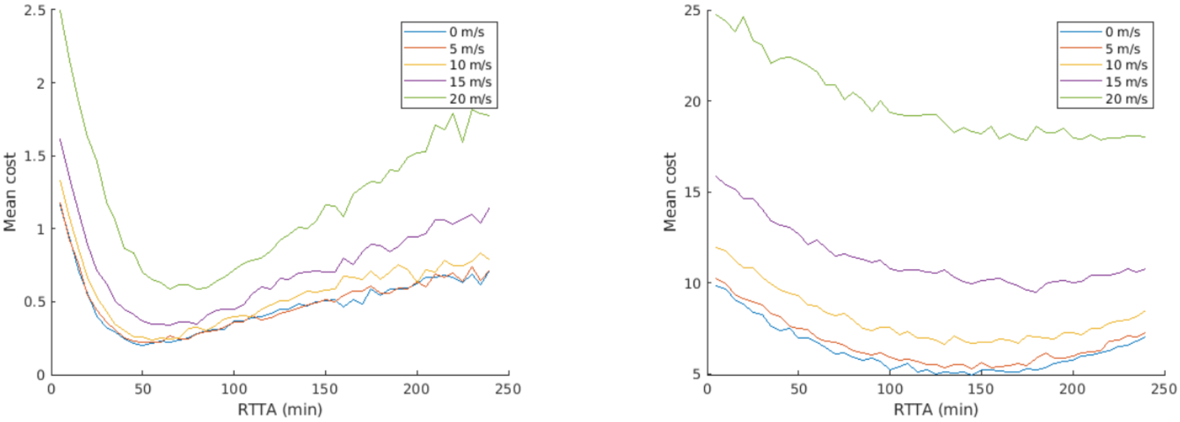
For c = 0 the price is just the delay (the top line on the plots are the same lines as in delays figure), so the minimum price is at RTTA = 0. As c increases, the importance of RTTA (knowing about the delays earlier) grows, and hence the minimum price is attained at larger and larger RTTA. However, when c is large, $c \cdot RTTA$ becomes larger than the delay, and the price drops to 0 for many flights (recall from the price formula that we do not allow negative prices) – such operations do not benefit from higher RTTA, and hence the optimal RTTA (minimizing the total, or average price) decreases. Overall this implies that there is no need to increase the RTTA past a certain value (the value itself may depend on the demand: when the traffic intensity is higher, the operators may want to know about their delays earlier than in a low-traffic scenario).

The figure below shows the price as a function of RTTA with the weather uncertainty taken into account. It can be seen that for larger c_w (i.e, with the larger weather influence), the optimal RTTA is smaller (i.e., the U-plans should be deconflicted closer to their departures) – our results quantify this intuition.



The price as a function of RTTA for various coefficients of weather uncertainty c_w (one graph per value of c_w). Left: 850 requests/hr. Right: 1700 requests/hr. The bottom row is the same as the top row but zoomed in on the lower values of c_w .

The figure below shows how the cost changes with RTTA under different values of w. Again, our results indicate that RTTA should be chosen not based on the expected ("mean") weather, but rather should depend on the weather uncertainty.



The price as a function of RTTA for various coefficients of wind uncertainty w (one graph per value of w). Left: 850 requests/hr. Right: 1700 requests/hr.

Below are selected results of extensive simulations for the 2 chosen cities in various scenarios, modeling weather impact (different safety margin *r* and speed *v*), under the 3 demand levels, and for different percentage of priority missions (the figure numbers are from [2]).

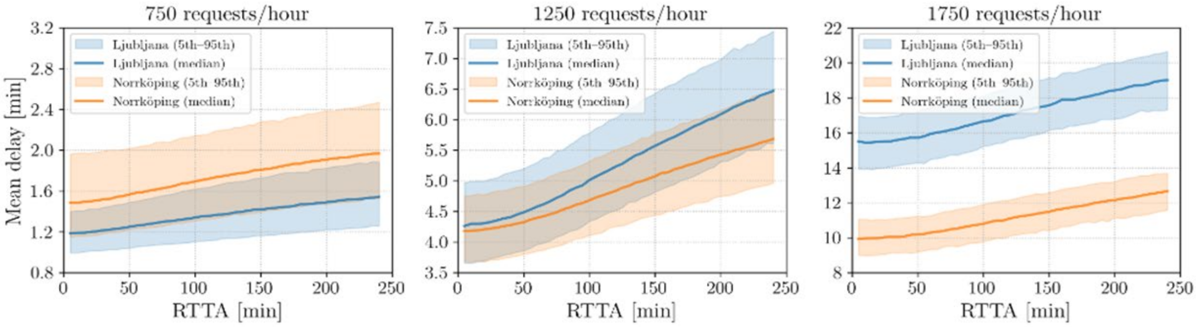


Fig. 2. Mean delays as a function of RTTA for Ljubljana and Norrköping at 3 demand levels, with $r = 150$m and $v = 25$m/s.

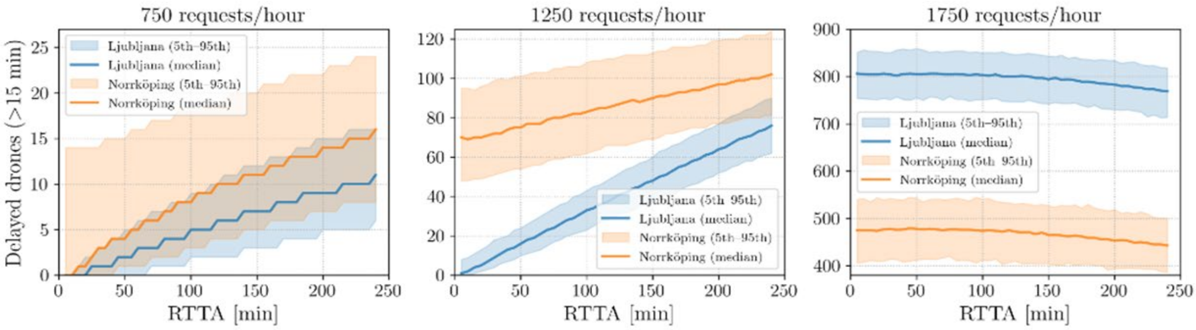


Fig. 3. Number of drones delayed by > 15min as a function of RTTA for Ljubljana and Norrköping at 3 demand levels, with $r = 150$m and $v = 25$m/s.

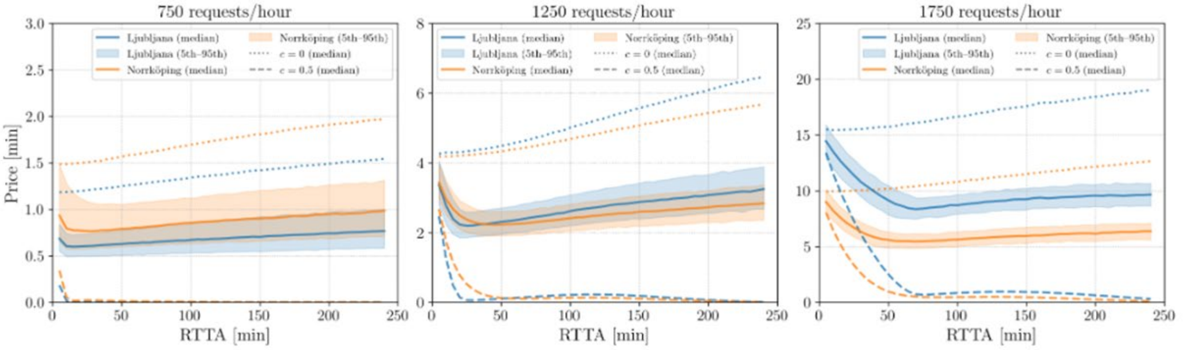


Fig. 4. Mean price as a function of RTTA for Ljubljana and Norrköping at 3 demand levels, with $r = 150$m and $v = 25$m/s. Drones are have $c = 0$ or $c = 1/2$ with probability $1/2$. Median results for $c = 0$ and $c = 0.5$ are also shown.

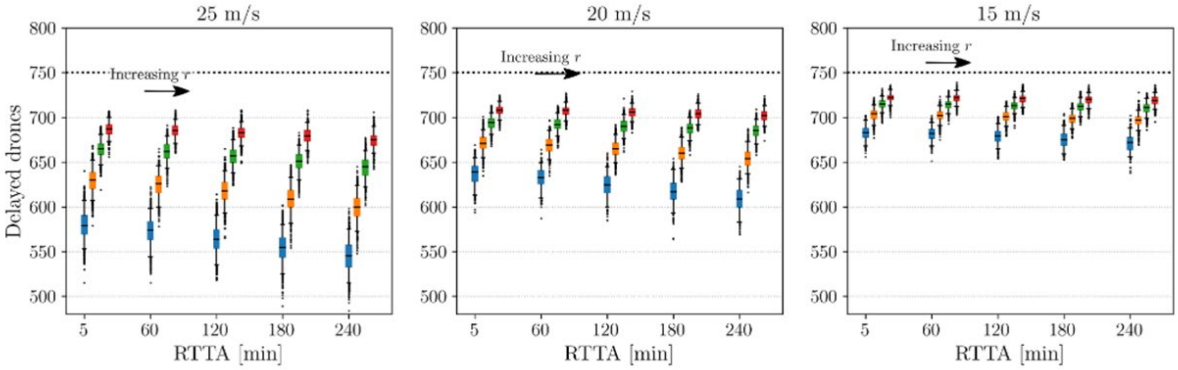


Fig. 5. Number of delayed drones as a function of RTTA for Ljubljana at 750requests/hr, evaluated across 3 groundspeeds. For each combination of groundspeed and RTTA, results are shown for $r \in \{150, 175, 200, 225\}$m.

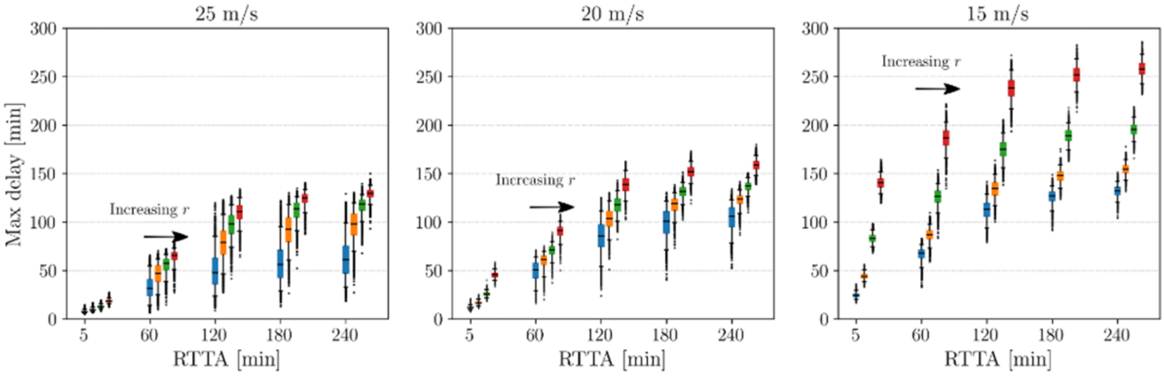


Fig. 6. Maximum delay as a function of RTTA for Ljubljana at 750requests/hr, evaluated across 3 groundspeeds. For each combination of groundspeed and RTTA, results are shown for $r \in \{150, 175, 200, 225\}$m.

The overall system performance, as indicated by the mean delay (Fig. 2), deteriorates with increasing RTTA, regardless of city or demand level; the deterioration becomes more significant at higher demands, and remains mostly similar between the cities, with the most noticeable divergence at 1250requests/hr. The KPI distributions are symmetric (this finding is valid for all scenarios considered in this study), and their dispersion (i.e., difference between 95th and 5th percentiles) slightly grows for 750 and 1250requests/hr, but remains constant at the high demand. As an example application of the distribution, if RTTA = 120min at 1250requests/hr, then the average delay is < 5min with probability 30% for Ljubljana and 69% for Norrköping. Interestingly, at 750requests/hr, Norrköping is more affected by the delays than Ljubljana, while at 1750requests/hr, Ljubljana is more impacted. The number of drones delayed by more than 15 minutes (Fig. 3) increases more rapidly for Ljubljana as demand rises; at 1750requests/hr, this number is around 60% higher in Ljubljana compared to Norrköping.

For the traffic mix, we assigned the values of $c = 0$ or $c = 0.5$ to the drones uniformly at random. The resulting trends are presented in Fig. 4. It can be seen that in the extreme cases, where all drones are assigned either $c = 0$ (dotted curve) or $c = 0.5$ (dashed curve), the mean price increases or decreases with RTTA, respectively. When both cases appear in the traffic mix, the resulting price evolution exhibits a minimum at low RTTA values; the position of this minimum shifts rightward as the demand increases.

We computed the distribution of each KPI as a function of RTTA for Ljubljana at 750 requests/hr for $v = 25$m/s (baseline), 20m/s, and 15m/s. For each v and RTTA, safety radii $r \in \{150, 175, 200, 225\}$m, accounting for weather forecast uncertainty, were considered. As illustrative examples, we present the results for the number of delayed drones (Fig. 5) and maximum delays (Fig. 6). As can be seen from Fig. 5, the number of delayed drones is already high under the baseline scenario ($v = 25$m/s and $r = 150$m). For instance, if RTTA = 5min, at least 75% of post-RTTA U-plans will need to be modified with probability 86%. However, most of these delays are relatively small, which suggests using flexible departure windows rather than rigid departure times, as proposed in [3]. While the number of delayed drones decreases with RTTA, the severity of their delays rises (Fig. 6). Moreover, the dispersion in the maximum delays gets wider with increasing RTTA, ranging from 4min at RTTA = 5min to 66min at RTTA = 240min.

As far as the different combinations of forecast uncertainty and wind variability are concerned, several findings can be highlighted:

- As the uncertainty increases, both the number of delayed drones and maximum delays increase.
- As the wind variability decreases, the number of delayed drones becomes nearly independent of RTTA, while its influence on maximum delays grows.
- As the forecast uncertainty increases or as the wind variability decreases, the dispersion of the maximum delays does not vary monotonically, but instead exhibits a peak as a function of RTTA.
- As the wind variability decreases, the maximum dispersion shifts toward higher values of the forecast uncertainty.

- For any fixed wind variability, the increase in forecast uncertainty leads to the decrease in the dispersion of the number of delayed missions.

Please see [2] for further discussion of the results.

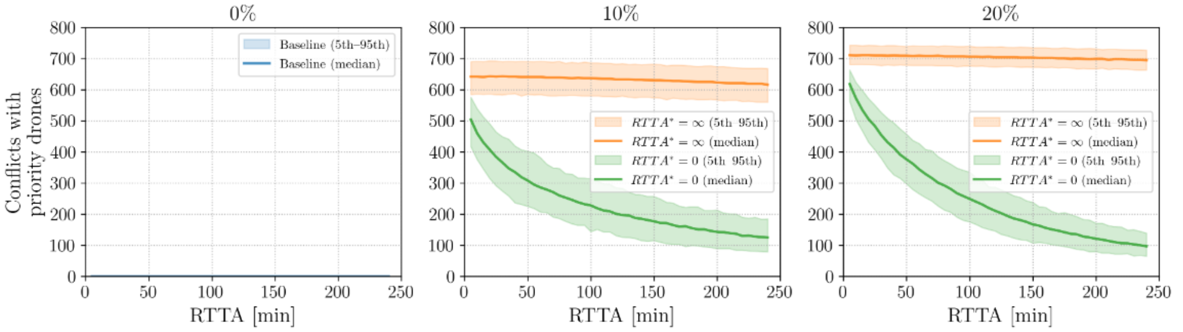


Fig. 7. Number of conflicts with priority drones as function of RTTA for Ljubljana at 1250requests/hr, evaluated across 3 scenarios with 0%, 10%, and 20% of drones designated as priority. Results are shown for both $RTTA^* = 0$ and $RTTA^* = \infty$.

For the priority missions, we consider 2 scenarios:

- Strategic deconfliction with priority missions. The regular drones must be delayed if they conflict with priority operations. In our framework, this is easily modeled by assigning an infinite RTTA to all priority drones (we denote their RTTA by RTTA∗). This ensures that by the time any non-priority U-plan is being deconflicted, all priority drones have already been assigned their requested 4D volumes. In effect, priority missions reduce the available airspace capacity for the other operations.

- Tactical deconfliction with priority missions. The priority missions are on-demand operations, i.e., they are not known in advance: they just pop up and fly. In our framework, this is easily modeled by assigning a zero RTTA to all priority drones (RTTA∗ = 0): it is too late to strategically deconflict any non-priority U-plan with any priority flight.

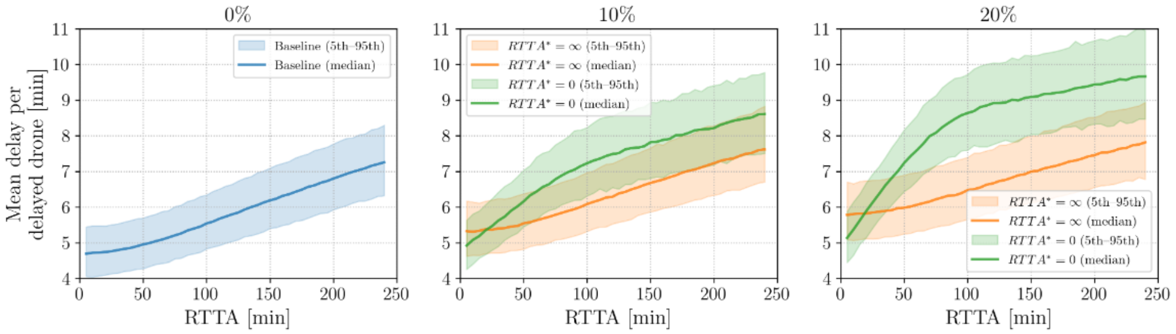


Fig. 8. Mean delay per delayed drone as function of RTTA for Ljubljana at 1250requests/hr, evaluated across 3 scenarios with 0%, 10%, and 20% of drones designated as priority. Results are shown for both $RTTA^* = 0$ and $RTTA^* = \infty$.

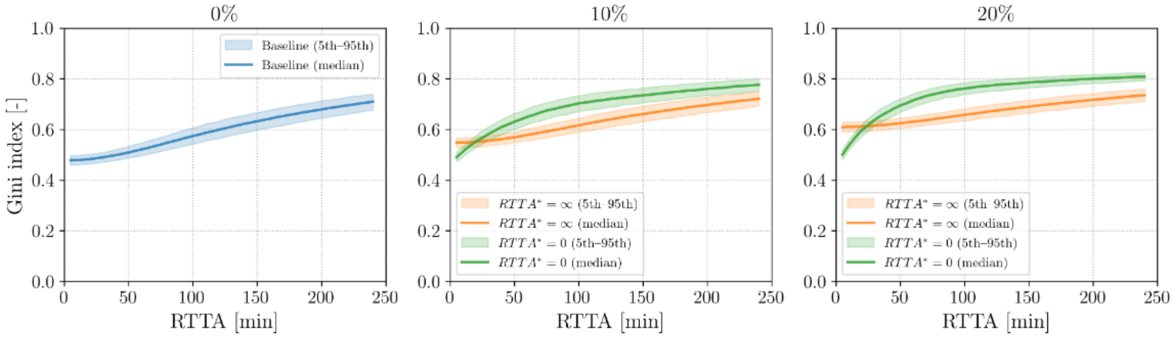


Fig. 9. Gini index as function of RTTA for Ljubljana at 1250requests/hr, evaluated across 3 scenarios with 0%, 10%, and 20% of drones designated as priority. Results are shown for both $RTTA^* = 0$ and $RTTA^* = \infty$.

Note that we do not deconflict priority vs. priority, assuming that this is done outside the "normal" UTM, similar to how civil air traffic controllers only guide commercial aircraft around military operations, while separation between military flights is delegated to military ATCOs.

We computed the distribution of each KPIs as a function of RTTA for Ljubljana at 1250requests/hr, across 3 scenarios: 0% (baseline), 10%, and 20% of drones designated as priority, with RTTA∗ = 0 or RTTA∗ = ∞. As illustrative examples, we present the results for the number of conflicts with priority drones (Fig. 7), mean delay per delay drone (Fig. 8), and Gini index (Fig. 9). For a given proportion of priority drones, the number of conflicts between regular and priority drones (Fig. 7) is generally lower when RTTA∗ = 0 than when RTTA = ∞ inf. This is expected: when RTTA∗ = ∞, conflicts can occur with all regular drones, whereas when RTTA∗ = 0, they can only occur with regular drones still on the ground. Please see [2] for further discussion of the results.

3 Conclusions, next steps and lessons learned

3.1 Conclusions

We evaluated a set of UTM KPIs, for multiple RTTA values, on a variety of simulated scenarios for drone operations in European cities. The evaluation produced not only the mean values, but also the distributions of the KPIs. Studies like ours (KPIs and the U-space assessment in general) will contribute to addressing the requirements laid out in EASA's AMC/GM to Article 18(f) "Tasks of the competent authorities" of EU U-space Regulation 664 (planning and review phases, in particular -- the technical review). It will allow competent authorities to make an important technical step towards compliance with the regulations and performance-based (instead of prescription-based) regulations overall.

ChatGPT https://chatgpt.com/share/68e2c88c-ecdc-8002-ac35-48e0072386f6 said that "developing a methodology and applying it on simulated scenarios" (as done in this project) is TRL 3-4 which sounds reasonable.

3.2 Next steps

Future work may consider other costs/profits associated with the delays and RTTAs, look at more KPIs, and do simulations in more cities, using various other scenarios and demand generation methods.

The second paper written by the project was submitted to the 15th SESAR Innovation Days (SIDs 2025) and will be presented at a future ATM conference.

For the next steps within SESAR, we should be invited to a consortium (preferably led by EUROCONTROL) including drone operators and USSPs.

3.3 Lessons learned

The management worked extremely smooth; in particular, we acknowledge the interaction with the mentors (as well as with a weather provider and a USSP), which was very helpful with the project work. The funding amount felt a bit small for producing 2 papers, but the hope is that the gained knowledge and experience will be useful for participation in a larger consortium targeting a SESAR Call.

4 Dissemination

The project had the honor to be presented at Engage 2 Thematic Workshop at Airspace World 2025.

5 References

5.1 Project outputs

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[2] J. Nunez-Portillo, J. Lundberg, V. Polishchuk, L. Sedov. A Comprehensive Evaluation of U-space KPIs https://www.itn.liu.se/~valpo40/pages/UTM_KPI.pdf. Submitted to SIDs'25.

5.2 Other

[3] Z. Liu, Y. Wang, X. Li, and X. J. Ban, "Characterization of strategic deconflicting service impact on very low-level airspace capacity," Drones, vol. 8, no. 9, p. 426, 2024.

[4] L. Sedov, V. Polishchuk. Centralized and Distributed UTM in Layered Airspace *ICRAT'18* Slides

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[9] V. Duchamp, L. Sedov, and V. Polishchuk, "Density-adapting layers towards PBN for UTM," in 13th USA/Europe ATM R&D Seminar, 2019.

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[13] EASA, "Acceptable Means of Compliance and Guidance Material to Regulation (EU) 2021/664 on a regulatory framework for the U-space," Issue 1, 16 December 2022. https://www.easa.europa.eu/en/document-library/acceptable-means-of-compliance-and-guidance-materials/amc-and-gm-implementing

6 List of acronyms

Acronym	Description
AMC	Acceptable Means of Compliance
ATM	Air Traffic Management
COP	Cooperative Operating Practice
CR	Conflict Resolution
DCB	Demand and Capacity Balancing
E-AMAN	Extended Arrival Management
FCFS	First Come First Served
GM	Guidance Material
KPA	Key Performance Area
KPI	Key Performance Indicator
RTTA	Reasonable Time to Act
TBO	Trajectory Based Operations
TMA	Terminal Maneuvering Area
UAM	Urban Air Mobility
UAS	Unmanned Aerial Systems
USSP	U-space Service Provider
UTM	Unmanned Traffic Management