EXPLORATORY RESEARCH

D3.2 Concept Trade-off Report

Deliverable ID:	**D3.2**
Dissemination Level:	**PU**
Project Acronym:	**METROPOLIS 2**
Grant:	**892928**
Call:	**H2020-SESAR-2019-2**
Topic:	**SESAR-ER4-31-2019 U-space**
Consortium Coordinator:	**TUD**
Edition date:	**12 June 2022**
Edition:	**02.00.00**
Template Edition:	**02.00.02**

Founding Members

EUROPEAN UNION EUROCONTROL

SESAR JOINT UNDERTAKING

Authoring & Approval

Authors of the document

Name/Beneficiary	Position/Title	Date
BADEA Andrei (TUD)	Researcher	30/05/2022
MORFIN Andres (TUD)	Researcher	30/05/2022
VIDOSAVLJEVIC Andrija (ENAC)	WP3 leader	20/05/2022
Niki Patrinopoulou (UoP) **Giannis Daramouskas (UoP)**	Researcher Researcher	25/05/2022
Leonid Sedov (LiU)	Researcher	30/05/2022

Reviewers internal to the project

Name/Beneficiary	Position/Title	Date
ELLERBROEK Joost (TUD)	Project leader	30/05/2022, 12/07/2022
Valentin Polishchuk (LiU)	Team leader	03/06/2022

Approved for submission to the SJU By - Representatives of beneficiaries involved in the project

Name/Beneficiary	Position/Title	Date

Rejected By - Representatives of beneficiaries involved in the project

Name/Beneficiary	Position/Title	Date

Document History

Edition	Date	Status	Author	Justification
0.1	10/05/2022	First draft	ENAC, TUD	Document Template
1.0	27/05/2022	Final draft	All	Contribution of all partners in the report production
2.0		Final		Final edits after review

Copyright Statement

Metropolis 2

A UNIFIED APPROACH TO AIRSPACE DESIGN AND SEPARATION MANAGEMENT FOR U-SPACE

This Project Management Plan is part of a project that has received funding from the SESAR Joint Undertaking under grant agreement No 892928 under European Union's Horizon 2020 research and innovation programme.

Abstract

Metropolis 2 will provide the fundamentals for concrete solutions for U-space U3/U4 services that are needed to enable high-density urban aerial operations, with a unified approach to the following U-space services: strategic deconfliction, tactical deconfliction, and dynamic capacity management. Thus far, U-space efforts have focused on developing a set of baseline services (i.e., U1 and U2 capabilities enabling services such as identification, flight planning, and tracking). When deployed, these services will enable low traffic density applications such as agricultural surveillance and infrastructure inspection. Urban, high-density operations, however, will require a different approach, and a degree of autonomy that does not yet exist in current-day air traffic management. First, in order to sustain high traffic demands, the urban airspace must be able to allow a shared use of airspace, rather than the approach used today of exclusively assigning parts of the airspace to individual flights. Secondly, at the expected extremely high traffic densities, airspace design, flight planning, and separation management become increasingly interdependent. With the traffic densities that are considered for urban applications these interdependencies necessitate a unified approach to all aspects of traffic management that determine how vehicles interact with each other. This project will develop a unified approach to airspace rules on the one hand, and flight planning and separation management approaches on the other hand. It will build upon the results of the current U-space projects, the first Metropolis project, and established separation algorithms. Several concepts, differing in how separation is performed (strategic/tactical, ground/air) will be compared using simulations, and the most promising concept will be validated in a real-world demonstration. The results of Metropolis 2 will contribute towards enabling safe and efficient U-space operations in urban environments.

Table of Contents

List of Tables

List of Figures

1 Introduction

The Metropolis 2 project seeks concrete solutions for UTM that are needed to enable high-density urban aerial operations, with a unified approach to the following U-space services: strategic deconfliction, tactical deconfliction, and dynamic capacity management.

Figure 1: Metropolis 2 air traffic control concepts.

Several concepts (Figure 1), differing in how separation is performed (strategic/tactical, ground/air) are proposed in WP4 and will be compared using simulations in WP3, and the most promising concept will be validated in a real-world demonstration trial (WP6). The results of Metropolis 2 will contribute towards enabling safe and efficient U-space operations in urban environments. Figure 2 shows project structure and interrelation between work packages.

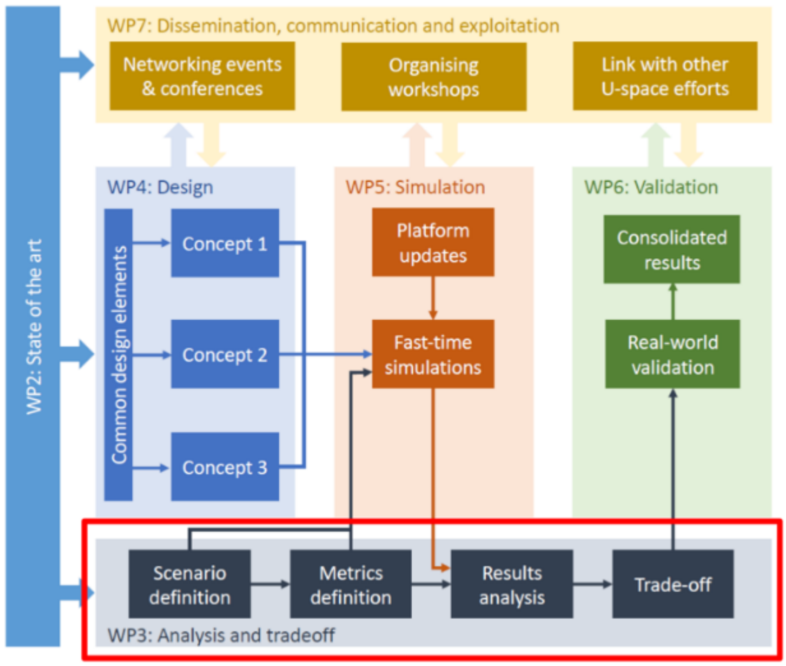

Figure 2: Work package 3 position and inter-relation with other work packages.

The project, hence, seeks to respond to the following research questions: What is the effect of the deployed separation and flight management strategy (centralised, hybrid and decentralised) on the urban airspace performance? What is the effect of each individual component of the deployed separation and flight management strategy (strategic and tactical)?

To provide answers, the ultimate objective of WP3 is to perform comparison and trade-off analyses of the different U-space design concepts developed in this project, and to select the most promising of these concepts for the validation phase. To achieve this, the work in WP3 is organized in 4 tasks:

- Task 3.1 – Scenario definition
- Task 3.2 – Metrics definition
- Task 3.3 – Results analysis
- Task 3.4 – Trade-off

The results of the development of scenarios, that were used in the simulation trials, and definition of metrics, that would be used in the analysis, (Task 3.1 and 3.2) are reported in the deliverable D3.1.

This deliverable D3.2 reports the results of tasks T3.3 and T3.4. It is organized in the following way. The introduction explains objectives of the project and position of WP3 in achieving these objectives, aim of this report and potential usage. Chapter 2 gives a short explanation on the data analysis platform and explains several updates to the metrics presented in D3.1 [1]. Chapter 3 goes through the relevant metrics and presents the main results of the simulation. The effects of density, traffic mix, and uncertainties are presented. Moreover, an analysis on the conflict and intrusion probabilities is presented. This is followed by a comparison of the nominal hybrid concept to a modified hybrid concept. The end of Chapter 3 presents a high-level relative comparison of the concepts in each metric.

Chapter 4 shows the correlation between a selection of metrics to investigate and illustrate two aspects of the simulation results. The first relates to concept implementation differences. The second presents correlations related to the degree of centralisation. Chapter 5 gives a detailed trade-off discussion between concepts for each metric group and uncertainty parameter. Finally, Chapter 6 presents the overall conclusion of the results and the trade-off analysis.

This document is intended to be used by SJU programme manager and by Metropolis 2 members. Metropolis 2 WP6 members, responsible for the developments of the real time trials are first concerned since the most promising U-space design concept in the simulation would be selected for validation phase.

Finally, international research community members interested in the UTM system may find interesting conclusions about the effects of the degree of centralisation on the performance of a separation management system, that is great starting point for the further developments in the research for the best U-space separation and flight management strategy.

2 Data analysis platform

2.1 Scope

A data analysis platform was designed and developed as part of WP3 of the project to support the concepts' evaluation and trade off. The platform's main scope is to read all the data generated from the Metropolis2 simulations, reorganise them, process them, compute the metric values for all scenarios and finally create graphs to represent the calculated metrics.

The analysis platform was developed to create an automated procedure for processing the large amount of data created from the simulations. The Metropolis 2 project simulated three U-space concepts on five traffic densities, three traffic mixes (mission type ratios) and nine repetitions. In addition, simulations included uncertainty scenarios with three different wind levels, and three levels of rogue aircraft, resulting in over 1,000 scenarios with 6 million flights. The output logging files from the simulations are of 12GB in size. The utilisation of such a platform speeds-up the data analysis process significantly and decreases the probability of human error during the process.

2.2 Inputs/Outputs

The platform inputs are the log files produced from the Metropolis2 simulations and the flight intention files, describing the simulated scenarios. There are five types of log files: REGLOG, FLSTLOG, CONFLOG, LOSLOG and GEOLOG.

The platform loads the inputs files and saves the information of interest in data-frames. There are two types of outputs produced; pandas data frames saved as dill files and diagrams presenting the computed metrics.

The data-frames that the platform creates can be distinguished into two categories; log data frames and metrics data-frames. Log data frames contain information mainly derived from the input files and have a low processed level, while the metrics data frames contain the final metric values and for most of them are produced by processing the log data frames. The data frames all listed below:

- Log data-frames:
  - Flst_log_dataframe: is aggregated per flight and per scenario and contains data describing each flight from the FLSTLOG and the flight intention files. Each row of the data-frame describes a different flight and the data-frame contains all the flights from all the scenarios and concepts. The data describing each flight are a combination of raw data extracted from the FLSTLOG and the flight intention files, baseline data computed based on the aircraft's flight intention and computed aircraft-specific metrics produced from the raw data.
  - Loitering_nfz_datframe: is aggregated per loitering aircraft and per scenario and contains data describing the geofence created from the loitering aircraft. The included data are generated based on data contained in the FLSTLOG and the flight intention files. Each row of the data frame describes a different loitering flight and contains information only regarding the created geofence (geofence area, application time, name). The data frame is necessary to compute some of the safety metrics.

- Los_log_dataframe: is aggregated per loss of separation event and per scenario and contains data describing each loss of separation event. The included data are extracted from the LOSLOG. Each row of the data frame describes one separate loss of separation event.
- Conf_log_dataframe: is aggregated per conflict detection and per scenario and contains data describing each conflict detection event. The included data are extracted from the CONFLOG. Each row of the data frame describes one separate conflict detection.
- Geo_log_dataframe: is aggregated per geofence breach and per scenario and contains data describing that geofence breach event. The included data are generated by reading the GEOLOs and with the use of the Loitering_nfz_datframe and the Flst_log_dataframe. Each row of the data frame describes one separate geofence breach.

- Metrics data frames:
  - Env_metrics_dataframe: is aggregated per scenario and it includes the computed values for the ENV2 and ENV4 metrics for every scenario. The two metrics are calculated based on the data in the REGLOGs.
  - Env3_1_metric_dataframe: is aggregated per scenario and per sound exposure point and it includes the computed values for the ENV3_1 metric for every scenario. The metric is calculated based on the data in the REGLOGs.
  - Env3_2_metric_dataframe: is aggregated per scenario and it includes the computed values for the ENV3_2 metric for every scenario. The metric is calculated based on the data in the REGLOGs.
  - Dens_dataframe: is aggregated per timestamp (one every 30 seconds of simulation time) and per scenario and includes the density (number of aircraft flying) in each time step. The density values are computed based on the REGLOG data.
  - Dens_constrained_dataframe: is aggregated per timestamp (one every 30 seconds of simulation time) and per scenario and includes the constrained density (number of aircraft flying in constrained airspace) in each time step. The constrained density values are computed based on the REGLOG data.
  - Metrics_dataframe: is aggregated per scenario and it includes the computed values for all the metrics aggregated in a scenario level for every scenario. The metrics' computations use all the following data frames: Flst_log_dataframe, Los_log_dataframe, Conf_log_dataframe, Geo_log_dataframe, Env_metrics_dataframe, Env3_2_metric_dataframe.
  - Prio_metrics_dataframes: is aggregated per priority level and per scenario and it includes values for the PRI3, PRI4, PRI5 metrics. The metrics' computations use the flst_log_dataframe.

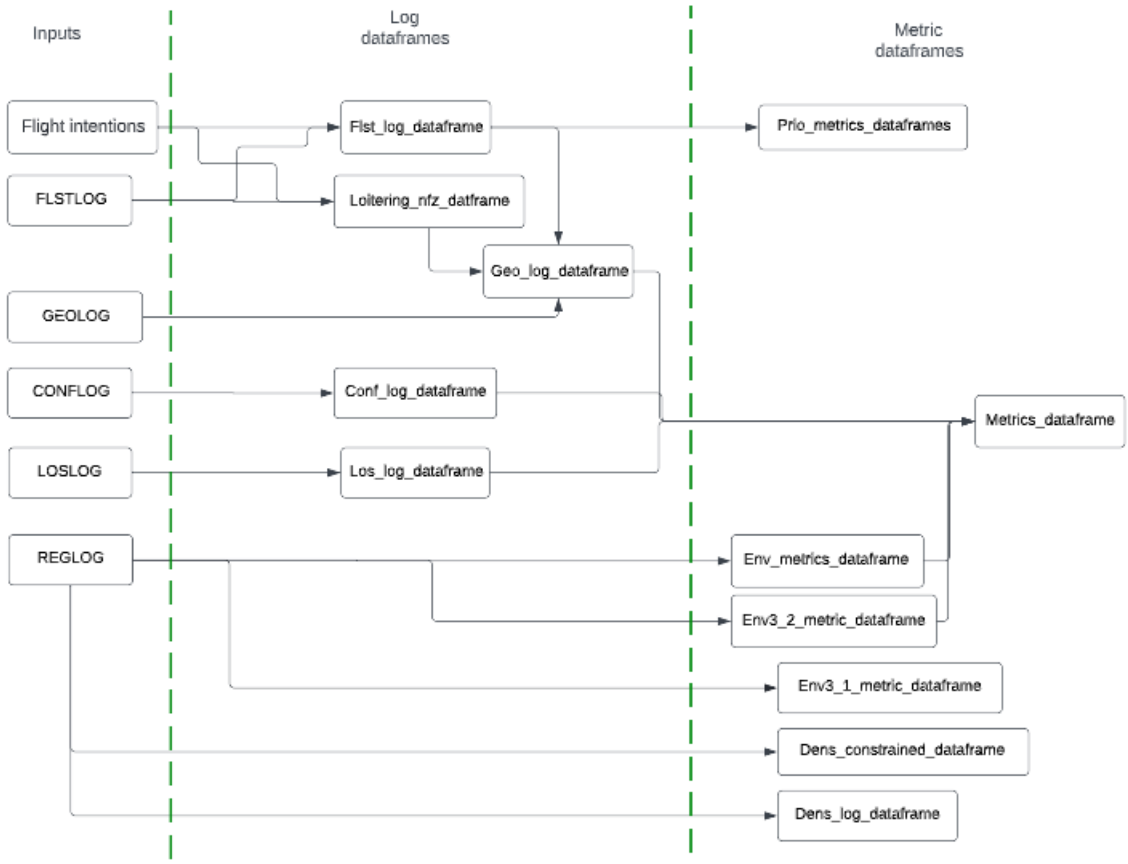

Figure 3: Data frame creation sequence and relations

Figure 3 shows the relations between the input data and the generated data frames and the creation order of the data frames. The specific attributes of all the data frames are listed in Appendix B.

2.3 Architecture

The platform includes two main processes; the data analysis and the graph creation. The data analysis process breaks down into the following steps:

1. Load the raw data
2. Produce processed data
3. Compute metric values
4. Save all the useful data into data frames

While the graph creation process loads the data frames to generate all the graphs.

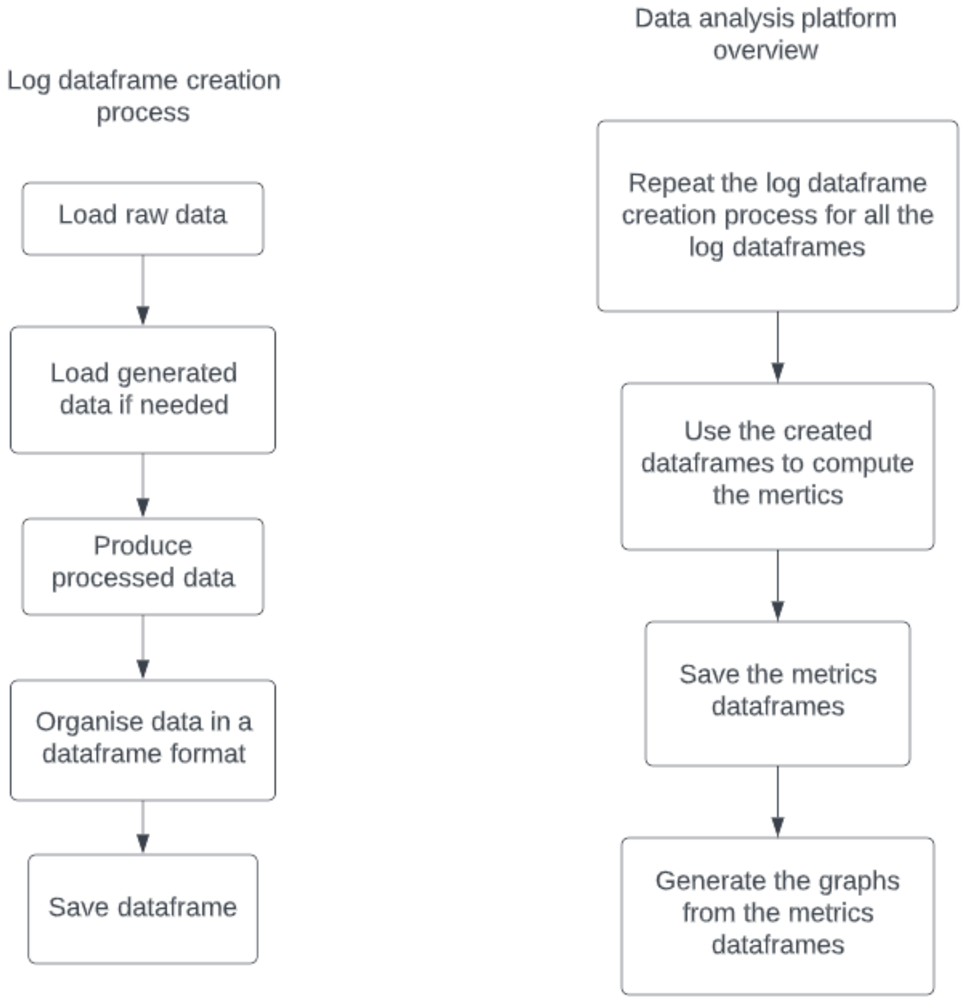

Figure 4: Flow charts for the log data frame creation process and the overall platform system

Figure 4 presents the processes for creation of every log data frame and the overview system of the data analysis platform.

2.4 Development

The platform was developed in python, using pandas data frames to organise the data. The platform code is open source and available at GitHub (https://github.com/Metropolis-2/M2_data_analysis_platform) with guidelines on how to use the platform.

The hardware requirements to run the platform are a minimum of 16 GB of RAM memory with an extra 1.5 GB for every thread.

2.5 Metric update

As explained, the platform intended to implement all metrics defined in the T3.2 and reported in D3.1. However, some of the metrics could not be computed due to missing data, some others **became** irrelevant for the M2 study (although they are still relevant for future studies), due to choices in U-space concept definition, and hence were not computed either. Finally, some additional metrics were proposed as replacement for those not possible to be computed.

This section reports these differences between metric definition report D3.1 and the ones used in the analysis. In addition, it explains how thresholds, needed for the computation of some metrics, were established. The final list of all metrics implemented in the platform is reported in Appendix A.

Two of the metrics described in D3.1 were not computed as part of the platform analysis: EFF7 and EFF8 (take-off and landing procedure delays). These metrics turned out not to be targeted at differences between concepts, and are therefore not relevant to the M2 research scope. One environmental metric (ENV3) was modified and separated into two metrics (ENV3_1 and ENV3_2). ENV3_1 and ENV3_2 are both indicators of the sound exposure in 4481 node points in constrained airspace, with ENV3_1 representing the aggregated sound exposure over the simulation time at every point and ENV3_2 representing the number of points over all time steps with sound exposure over the threshold of 55 dB, based on the outdoor noise limits identified by the United States Environmental Protection Agency (EPA) [2]. The reference noise of one drone flying at 30 feet was set to 73.19 dB, based on the sound level tests of [3]. For the computation of the noise metrics ENV3_1 and ENV3_2 aircraft with flight altitude lower than 30 feet (aircraft at the take-off and land stages) were filtered out and the noise was computed based only on the cruising aircraft. All the flights of the simulations were assigned a mission completed flag, indicating if the concerning aircraft successfully completed its mission. A mission is defined as successfully completed when the aircraft was spawned, it was deleted (landed) before the simulation ended and its deletion point was had a distance less than 8 km from its destination. The 8 km threshold was selected to filter out a small percentage of flights that were presented with a problem during the landing stage and after not landing successfully escaped the airspace, the landing procedure is out of the scope of the M2 research and the number of such cases is so small that did not affect the metrics values. For any metrics concerning arrival delay, route length, flight duration and work done only successfully completed flights were considered.

Finally, 14 safety metrics were added in order to provide a better description of the conflict, loss of separation and geofence violation events. The new metrics are listed here:

- SAF1_2: Number of conflicts per flight.
- SAF1_3: Number of conflicts in constrained airspace.
- SAF1_4: Number of conflicts in open airspace.
- SAF2_1: Number of severe intrusions; An intrusion is defined as sever if it would lead to a collision between two aircraft. To mark an intrusion as sever the minimum horizontal distance and altitude distance of the aircraft is compared to the aircraft's size. The aircraft including landing equipment is 1.7m long and 0.7 meters tall [4].
- SAF2_2: Number of intrusions in constrained airspace.
- SAF2_3: Number of intrusions in open airspace.
- SAF5_1: Average time spent in LOS.
- SAF6_1: Number of severe geofence violations; A geofence violation sis defined as sever in the aircraft intruded more than 1 meter into the geofenced area.
- SAF6_2: Number of severe loitering NFZ violations.
- SAF6_3: Number of severe buildings/static geofences violations.
- SAF6_4: Number of severe open airspace geofences violations.
- SAF6_5: Number of severe building violations.

- SAF6_6: Number of severe loitering NFZ violations with origin/destination in NFZ; The metric counts the severe loitering NFZ violations, in which the violating aircraft's origin or destination point were contained in the NFZ area.
- SAF6_7: Number of severe loitering NFZ violations within 3 minutes of the NFZ activation; The metric counts the severe loitering NFZ violations, in which the violating aircraft was in the NFZ area already when the geofence was applied.

3 Individual key performance area analysis

The following chapter presents the results obtained from the simulation of the traffic scenarios. The results are given individually for each of the Key Performance Areas (KPA) and metrics initially reported in D3.1 and amended during development of the result analysis platform as explained in section 2.5. A Pareto and trade-off analysis is given in Chapter 4. Note that in situations where several metrics have comparable trends, for sake of brevity, not all individual metrics are presented in this report. The full set of simulation results and graphs can be found in the project data repository [5].

3.1 General considerations

In the Metropolis 2 project, traffic density and traffic mix (ratio between different mission types) were chosen as “independent variables” since their change is assumed to influence the performance of the concept. Five levels of traffic density have been considered: very low, low, medium, high, and very high. The average and maximum instantaneous traffic densities can be seen in Table 1. For a motivation and reference for these choices see [1]. Traffic mix was chosen to include four different traffic patterns, representative of the following mission types: parcel (hub-spoke) and food delivery (point to point), loitering (geofenced) and emergency mission. Loitering and emergency missions were kept at a fixed level. For parcel and food delivery, three levels of Traffic mix were simulated: 40% traffic mix with 40% of food and 60% of parcel delivery, 50% traffic mix with equal ratio of food and parcel delivery, and 60% traffic mix with 60% of food and 40% of parcel delivery.

Table 1. Average and Maximum instantaneous traffic densities for different traffic scenarios

Traffic scenarios	Average instantaneous traffic density (aircraft per square kilometre)	Maximum instantaneous traffic density (aircraft per square kilometre)
Very Low	14,68	54,75
Low	20,45	76,26
Medium	26,21	97,77
High	31,98	119,28
Very High	37,75	140,79

Furthermore, to evaluate the effect of unpredictable events, two sets of uncertainty scenarios have been developed, considering various levels of wind and the presence of rogue aircraft (vehicles not complying to concept rules).

The result analysis section is therefore organized in four principal sections where the effect of independent and uncertain parameters will be analysed. Unless indicated otherwise, results are presented using box plots, indicating the median with a horizontal line, four quartiles (box and whiskers), and potential outliers (diamonds). By default, the data used for each graph is based on the 40% traffic mix case, as traffic mix was shown not to affect the trends of any of the considered metrics. Conclusions are taken with regard of our specific scenarios and situations.

3.2 Effect of traffic density on metrics

In this section, the performance of centralised, hybrid, and decentralised concepts is analysed as a function of traffic density.

3.2.1 Access and equity

Access and equity metrics are intended to measure whether all users have equal right of access to the UTM service (accessibility) and whether the "total cost of the solution" is shared among those users in an equitable manner.

3.2.1.1 AEQ1: Number of cancelled demands

The AEQ1 metric is calculated as the number of flight intentions that would be cancelled before operations, since the offered service/solution doesn't satisfy user requirements. As user flight plan acceptance is not modelled in M2, the cancellation is post-computed based on the total delay at destination compared to ideal trajectory (that represents user expectation). If total arrival delay is greater than given threshold (see chapter 2), flight intention is considered as likely to be cancelled.

Figure 5 shows the number of cancelled demands as a function of traffic density for the 40% traffic mix. The graph shows that for the centralized and decentralized concept, the AEQ1 metric increases almost linearly with traffic density at a small positive slope. Values range between 20-70 for centralized and between 10-170 for the decentralized concept, but remain below 2% of the total demand.

The results for the hybrid concept show a different trend, with an exponential relation between the AEQ1 metric and traffic density (R-squared equal to 0.98). This can be explained by the fact that the hybrid concept chose to limit the density of traffic in the constrained airspace (favouring longer flights through unconstrained airspace) in order to avoid safety issues. As a result, flights make more detours and arrive late at their destination (compared to their idealized trajectory). However, this result should be interpreted with caution since the choice of ideal trajectory is made to enable comparison of concepts that had different airspace structure and rules. In real operations, the notion of user-acceptable trajectories would be dependent on the chosen UTM system.

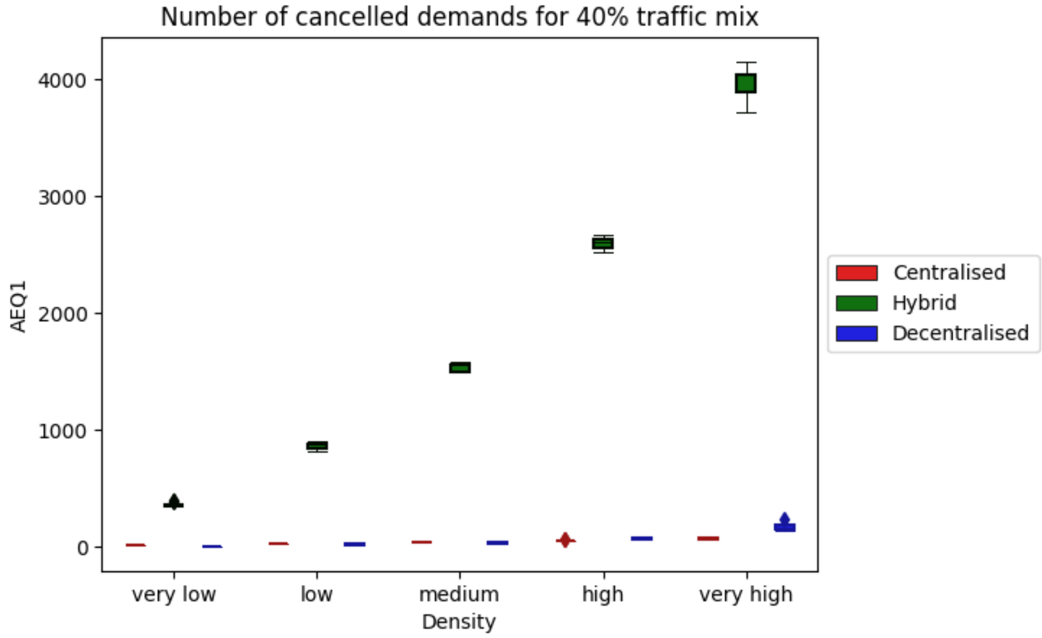

Figure 5: Number of cancelled demands for 40% traffic mix as function of traffic density.

3.2.1.2 AEQ2_1: Number of inoperative trajectories

Metric AEQ2 observes the number of inoperative trajectories, and complements the previous AEQ1 metric in the sense that although we don't know user specific requirements for the mission's duration there will be ultimate mission duration limits that have to be respected at all cost, such as drone autonomy linked with battery capacity. Hence for every concept it is possible to estimate the number of inoperable flights a-posteriori as the number of flights whose total duration, considering both strategic and tactical separation management, was greater than the drone's autonomy. This number is a good indicator of UTM system accessibility.

Figure 6 shows the percentages of inoperative trajectories (as a ratio of total number of flights) for 40% traffic mix as function of traffic density. The first thing to notice is that the percentage of inoperative trajectories is stable for different traffic densities for all concepts. This can be explained as follows. For every concept there exists a "threshold" above which origin-destination pairs result in inoperative trajectories. This "threshold" is dependent on the structure of each concept, and its separation management strategy. In M2, traffic distribution[1] over municipalities of Vienna city remains the same relative to traffic density (it is only scaled). This explains the results for AEQ2_1, since the relative number of origin-destination pairs above the threshold remain stable.

[1] In M2 traffic distribution over municipalities is based on trip production and attraction models that were calibrated using regression analysis with socio-economic indicators (see D3.1), hence, in relative values distribution remains the same for all traffic densities (almost same since traffic generation models are stochastic). It is only scaled for different traffic densities/volumes.

Hence, the hybrid concept structure and separation management strategy (detours of the constrained airspace as previously discussed) results in a lower threshold, leading to 18% inoperative trajectories. The centralised and decentralised concept, which have a more direct structure and do not apply a strategy that avoids constrained airspace, result in far fewer inoperative trajectories: 1.5% and 2% respectively. Note that although technological improvements (battery capacity, drone efficiency, etc.) will possibly increase drone autonomy, technical limitations on mission length will still remain relevant.

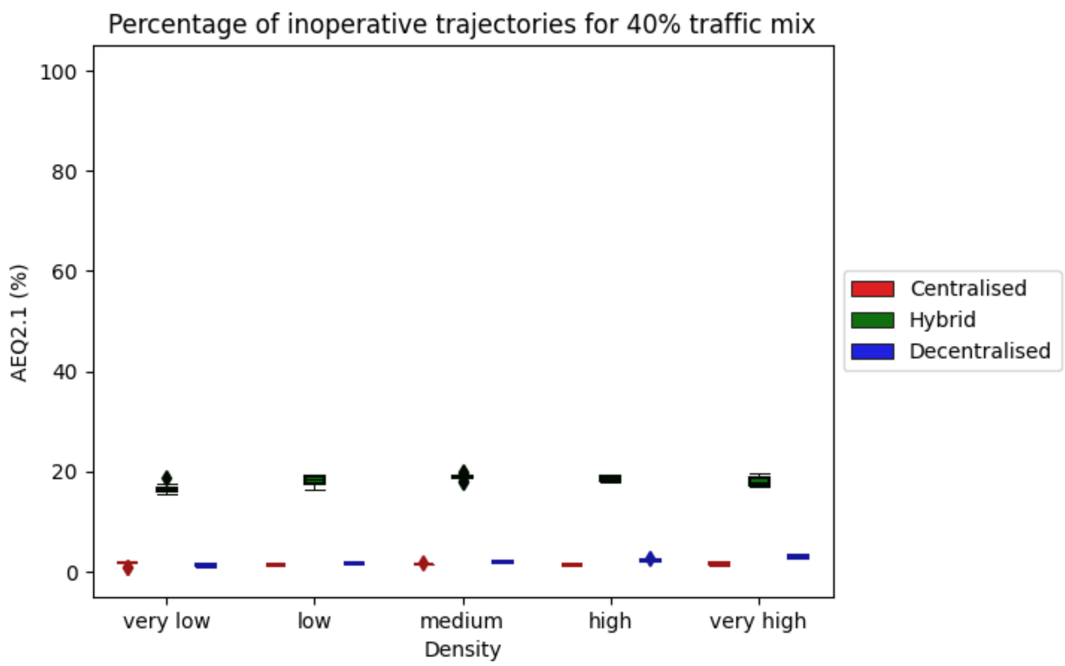

Figure 6: Percentage of inoperative trajectories for 40% traffic mix as function of traffic density.

3.2.1.3 AEQ3: Demand delay dispersion

The AEQ3 metric represents the demand delay dispersion, and is computed as the standard deviation of arrival delay of all flight intentions. Here, arrival delay is calculated as the difference between realized and ideal expected arrival time (as for AEQ1 metric). It is used as a measure of UTM service equity, where low delay dispersion is an indication of equitable delay distribution among the users.

Figure 7 shows a box plot of the demand delay dispersion for 40% traffic mix as function of traffic density. Please remark that plotted values are computed standard deviations (measure of dispersion) for nine repetitions[2], hence, we are interested in their absolute values, and not in distribution over

[2] The box plots shows distribution (IQR)of computed values of standard deviation for nine repetitions, hence simply indicating the range of the values standard deviation took for different repetitions, i.e. some repetitions had small and other greater value of standard deviation.

nine repetitions. Lower standard deviation of delay indicates that individual delays are squeezed around average delay making a more equitable distribution.

From the figure we may see that decentralised concept offers the most equitable service with the values of the AEQ3 metric around 200 seconds. This can be explained by the lack of centralized regulation in the decentralized concept, which allows drones to depart on their planned times (or as soon as local situation allows without concern what happen later during the flight), and because drones are flying almost “direct routes”, resolving potential conflict tactically at a local level. It can also be observed that the delay dispersion only modestly increases with traffic density remaining almost constant. This can be explained as follows. Although conflict probability increases with traffic density it equally affects all individual flights (since traffic distribution is simply scaled, as explained). Hence, individual flight delays increase (and average together with them), due to increased number of conflicts. But since all flights are almost equally affected, the distribution of the delay remains the same i.e., it doesn’t increase with traffic density.

The centralised concept shows similar behaviour, the delay dispersion being almost constant for all traffic densities. This is, however, the result of a completely different phenomenon. The centralised concept relies on a pre-tactical centralised algorithm that assigns departure delay, flight level and alternative route for each flight, such that conflicts are avoided. Since maximum departure delay is bounded (it equals 10 minutes), as well as maximum flight level (limit of UTM airspace), in addition with bounded route extension (only close alternative routes are considered by the algorithm), the arrival delay is also bounded, making its dispersion almost constant for different traffic densities. Nevertheless, like the decentralised concept, the total delay is increasing with traffic density. The variation of the delay dispersion for scenario repetitions, that are more prominent (see bow plots for same traffic density), are simply the result of stochasticity in scenario repetition that affect hazardously global traffic situation making it easier or harder to solve.

Finally, in terms of the AEQ3 metric, the performance of hybrid concept changes with traffic density, making it less and less equitable with increasing traffic density. This is caused by the First-Come-First-Served policies applied, causing later flights to be delayed more, in order to compensate for the lack of capacity in the constrained airspace which the hybrid concept is protecting.

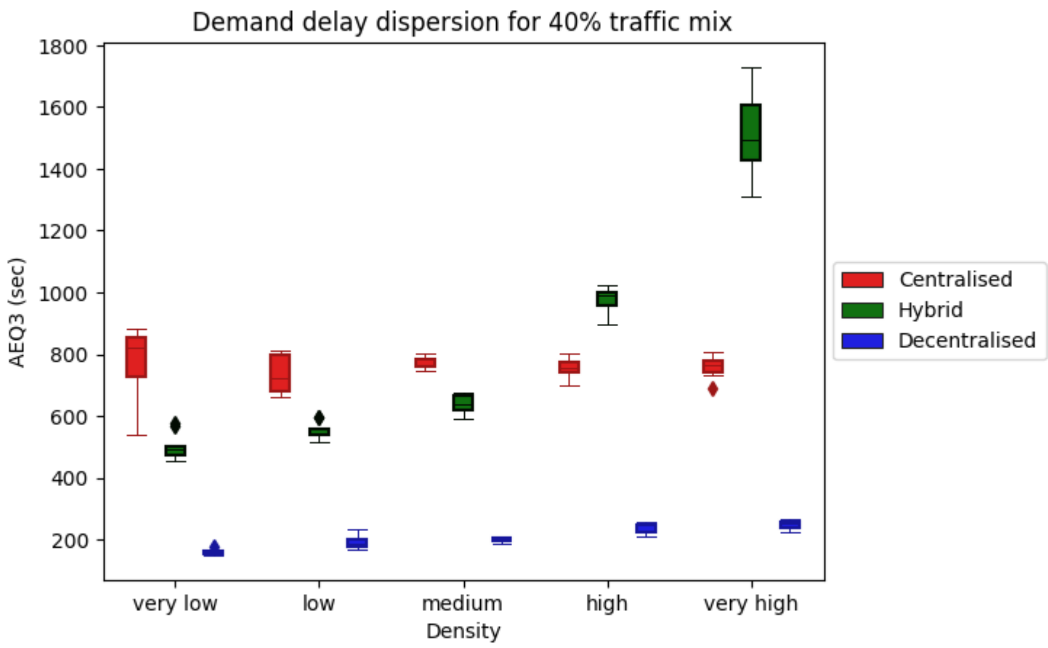

Figure 7: Demand delay dispersion for 40% traffic mix as function of traffic density.

3.2.1.4 AEQ final remarks

The results discussed above show a comparatively better performance of the centralised and decentralised concept with respect to service accessibility, keeping in mind that user expectations (reflected with chosen ideal trajectory in metric computation) depend on the chosen UTM system, hence would affect the results. From an equity point of view, the centralised concept has a lower performance compared to two other concepts.

From these results it can be concluded that the tactical component of the separation management strategy has a positive effect on UTM equity, as it inherently distributes regulation over the users. Although a strategic component with its global view on the system is capable to achieve such performance, it is more difficult to manage different confronted objectives, such as total system cost, priorities, equity, etc. at the same time, hence resulting in the trade-off.

3.2.2 Capacity

In the M2 project a service-centric view of capacity is adopted, as currently used in evaluation of the European ATM system performance [6], measuring whether system capacity is in accordance with current needs i.e., if the current demand may be served without imposing restrictions.

3.2.2.1 CAP1: Average demand delay

The CAP1 metric is computed as the arithmetic mean of the (arrival) delays of all flight intentions (see AEQ1 for delay definition). It represents a proxy for the system capacity, since a lack of system capacity results in degradation of system efficiency (here expressed with average delay).

Figure 8 shows the average demand delay for 40% traffic mix as function of traffic density. It can be seen that the system performance of the centralised and decentralised concepts remains stable with increase of traffic density (with a linear dependency). The hybrid concept, however, shows an exponential degradation of the performance with traffic density. This is a direct result of the hybrid concept separation management strategy to limit the density of traffic in constrained airspace in order to avoid safety issues, which is literally what metric is based on. Further we may notice that the decentralised concept has a higher slope of increase with traffic density compared to the centralised concept.

It should be noted that the CAP1 results are influenced by airspace structure and regulation policies of strategic and tactical separation management chosen for each concept. Hence, these results should be interpreted with respect to those choices.

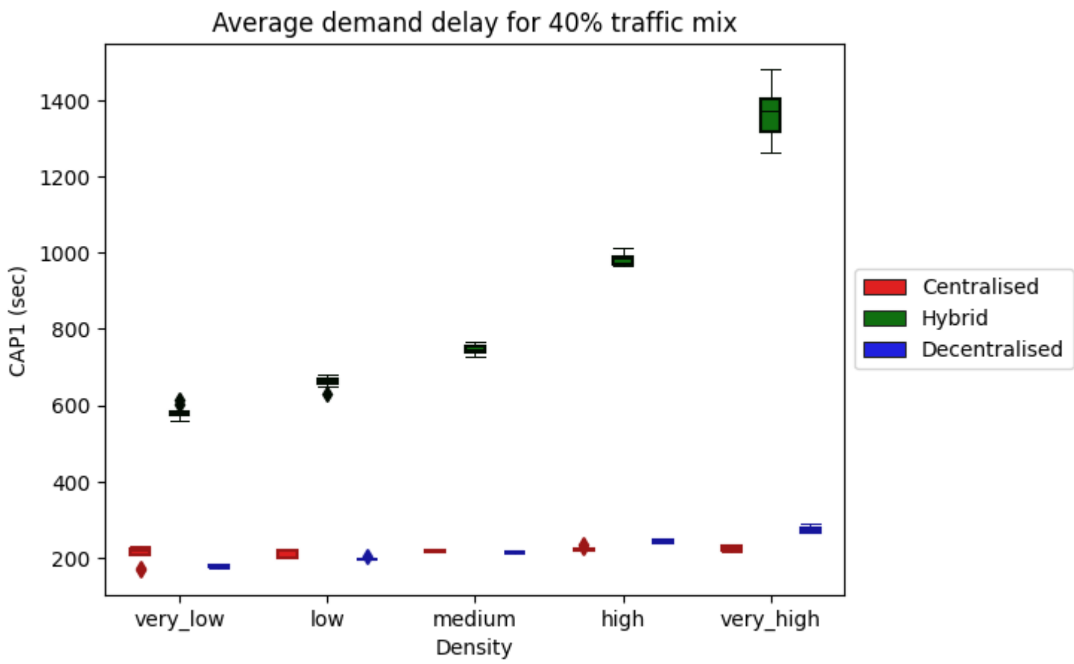

Figure 8: The average demand delay for 40% traffic mix as function of traffic density.

3.2.2.2 CAP2: Average number of intrusions

Similar to CAP-1, the number of intrusions, as a safety indicator, can be used as a proxy for system capacity for relative comparison of different concepts. Here, the average number of intrusions is computed as the ratio between the total number of intrusions (see SAF2) and the number of flight intentions.

Figure 9 shows the average number of intrusions for 40% traffic mix as a function of traffic density. Contrary to the CAP1 metric, the CAP2 metric for the centralised and decentralised concepts deteriorates significantly with increasing traffic density. For all three concepts CAP2 increases linearly with traffic density, where the hybrid concept has a far smaller slope. The slope of CAP2 for the decentralised concept once again has a higher slope compared to the centralised concept, which reveals the limitations of tactical separation management at very high traffic densities.

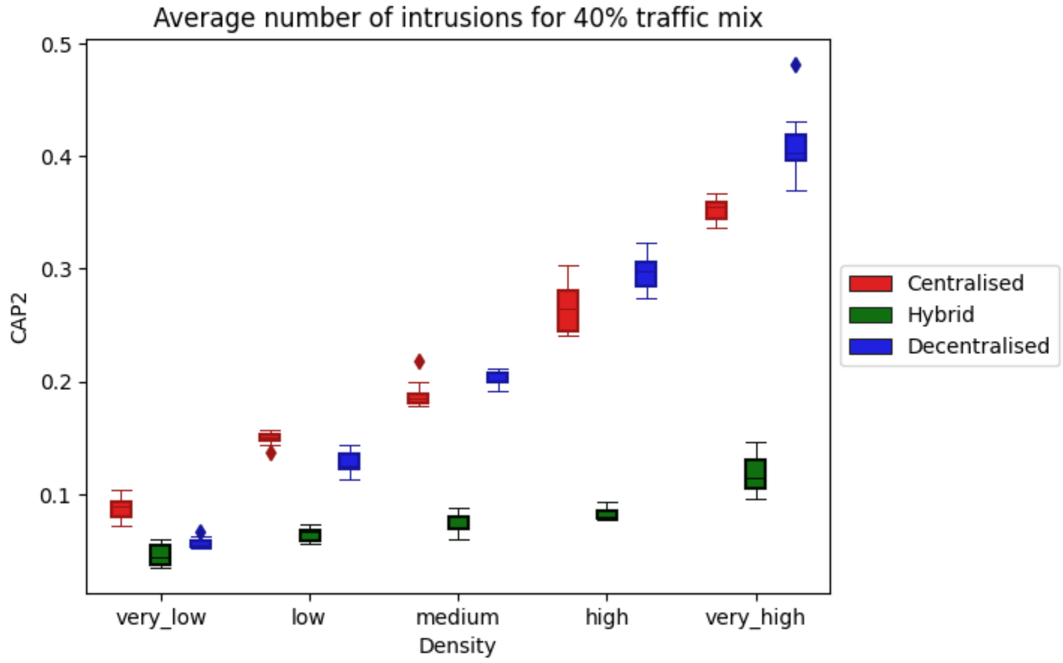

Figure 9: The average number of intrusions per aircraft for 40% traffic mix as function of traffic density.

3.2.2.3 Density graphs

Figure 10 and Figure 11 show the number of concurrent aircraft as a function of time, for the three concepts, for the entire airspace, and for only the constrained airspace, respectively. Figure 10 shows that, over the entire period, the centralised and decentralised concepts have a similar number of concurrently flying aircraft. The hybrid concept data reflects the longer trajectories and flight times that aircraft experienced during their missions, which leads to a higher number of concurrent aircraft, and a slower-paced landing rate at the end of the scenario.

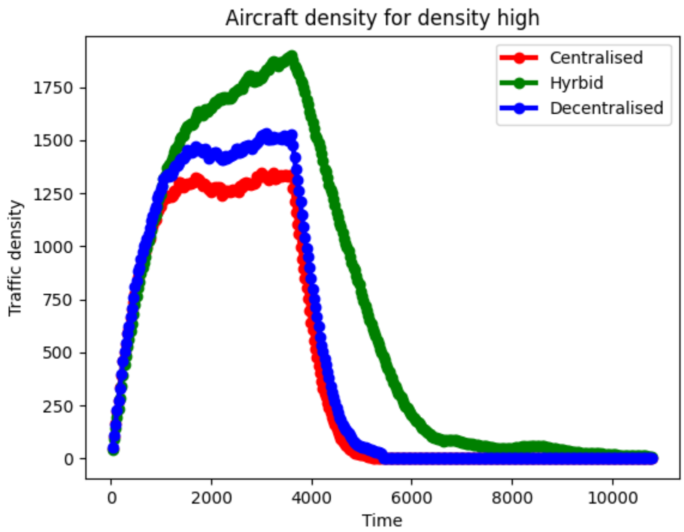

Figure 10: Aircraft density in the whole airspace in function of time for a high-density scenario at 30 second time intervals.

The graph for density in constrained airspace (Figure 11) also reflects the design choices of the hybrid concept, with a much lower number of aircraft present at one time in this area when compared to the other two concepts. However, this implies that the number of aircraft in open airspace was higher for the hybrid concept as a result of the same design choices. Figure 12 makes this difference visually apparent. It presents a heat map of cumulative density throughout the experiment area, for the three concepts. It can be seen that while the centralised and decentralised concepts show a relatively high density in constrained airspace, the hybrid concept is seen to actively avoid this part of the airspace.

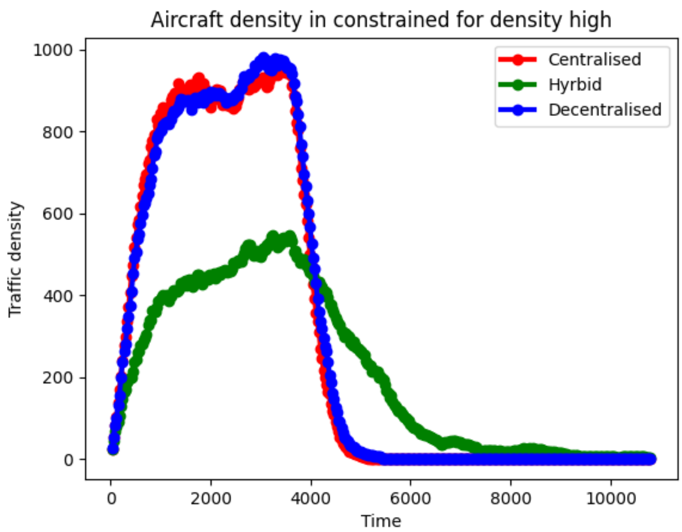

Figure 11: Aircraft density in constrained airspace in function of time for a high-density scenario.

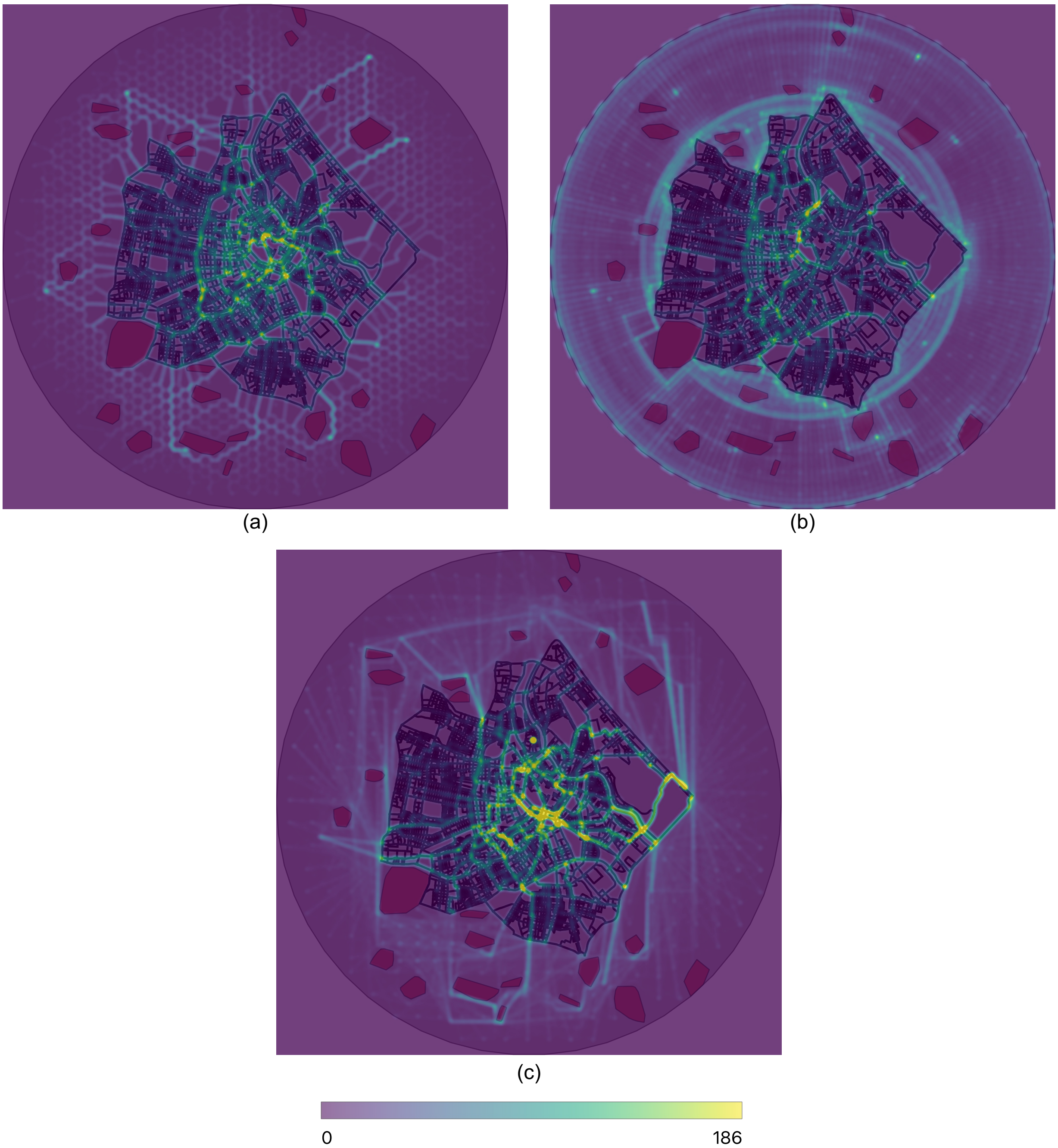

Figure 12: Cumulative density heat maps for high density scenarios for a 40% traffic mix. It shows the number of drones within a radius of 150 metres. (a) Centralised, (b) Hybrid, (c) Decentralised.

3.2.3 Efficiency

The following section presents results for efficiency metrics computed in function of traffic density for the 40% traffic mix case. As most of the proposed metrics were similar in the conclusions that could be drawn, only EFF1 and EFF2 are presented.

3.2.3.1 EFF1: Horizontal route efficiency

The EFF1 metric considers horizontal route efficiency as the ratio between flown routes and the corresponding shortest possible route (for a given origin-destination pair). Figure 13 shows this metric for the three concepts, as a function of traffic density. The results show that the horizontal distance route efficiency varies among the concepts in an expected manner. The decentralised concept attempted to minimise the number of turns in a trajectory while striking a balance with the route duration. The centralised concept attempted to minimise the impact in terms of total route duration and strike a compromise between the efficiency of the route and the alternative routing used for deconfliction. The hybrid concept prioritised safety over efficiency, resulting in a low efficiency, as most aircraft are routed around instead of through the constrained airspace. The routing efficiency did not significantly change as a function of density.

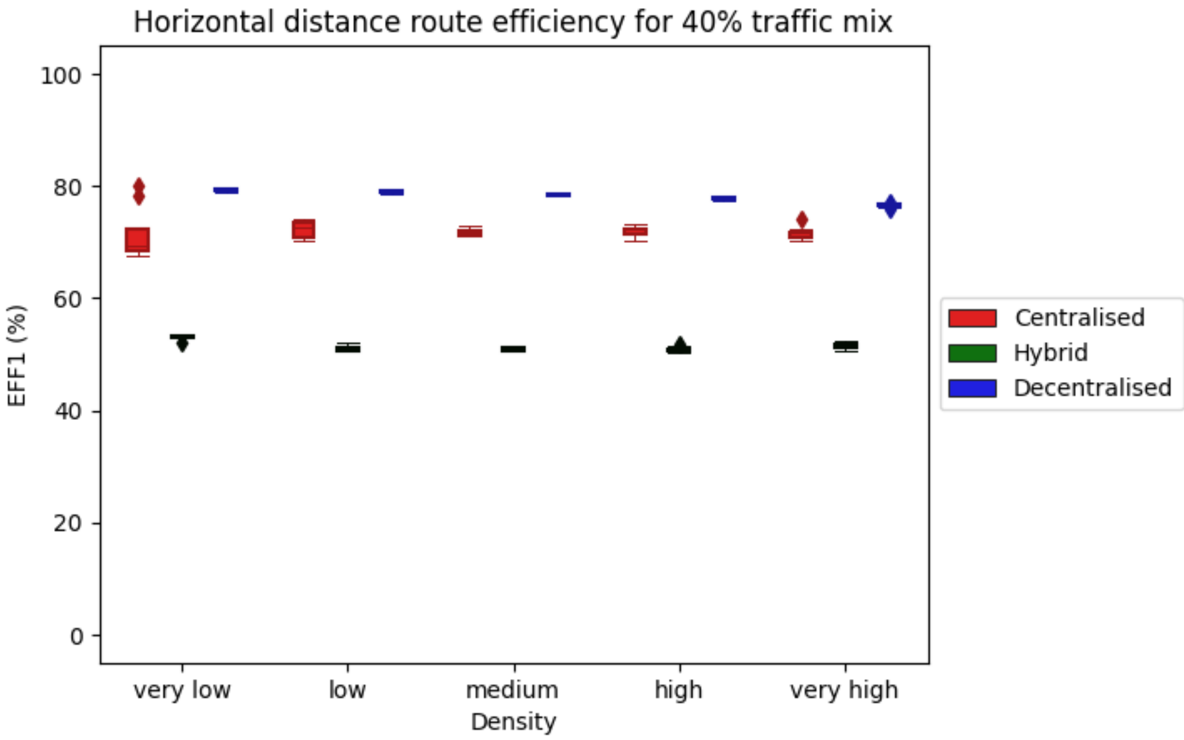

Figure 13: Horizontal distance route efficiency for the 40% traffic mix case.

3.2.3.2 EFF2: Vertical route efficiency

The EFF2 metric represents the ratio between the ideal and the actual vertical travelled distance. Figure 14 shows the vertical route efficiency for the three concepts, as a function of traffic density. The vertical route efficiency mostly depends on the altitude-choosing policy that the concepts have implemented. In the hybrid and centralised concepts, the altitude level was mostly chosen in advance, whereas in the decentralised concept, aircraft choose their altitude depending on the traffic situation around them. Overall, the vertical efficiency of all concepts is relatively low, as the altitude dimension was preferred to solve conflicting situations. However, the centralised concept achieved the best efficient, as the concept did not include altitude-based tactical conflict resolution. The decentralised concept heavily relied on the altitude dimension for conflict resolution, and thus achieved the lowest efficiency. It should also be mentioned that the efficiency criterion was relatively strict, as the ideal route would have only contained altitude changes at take-off and landing.

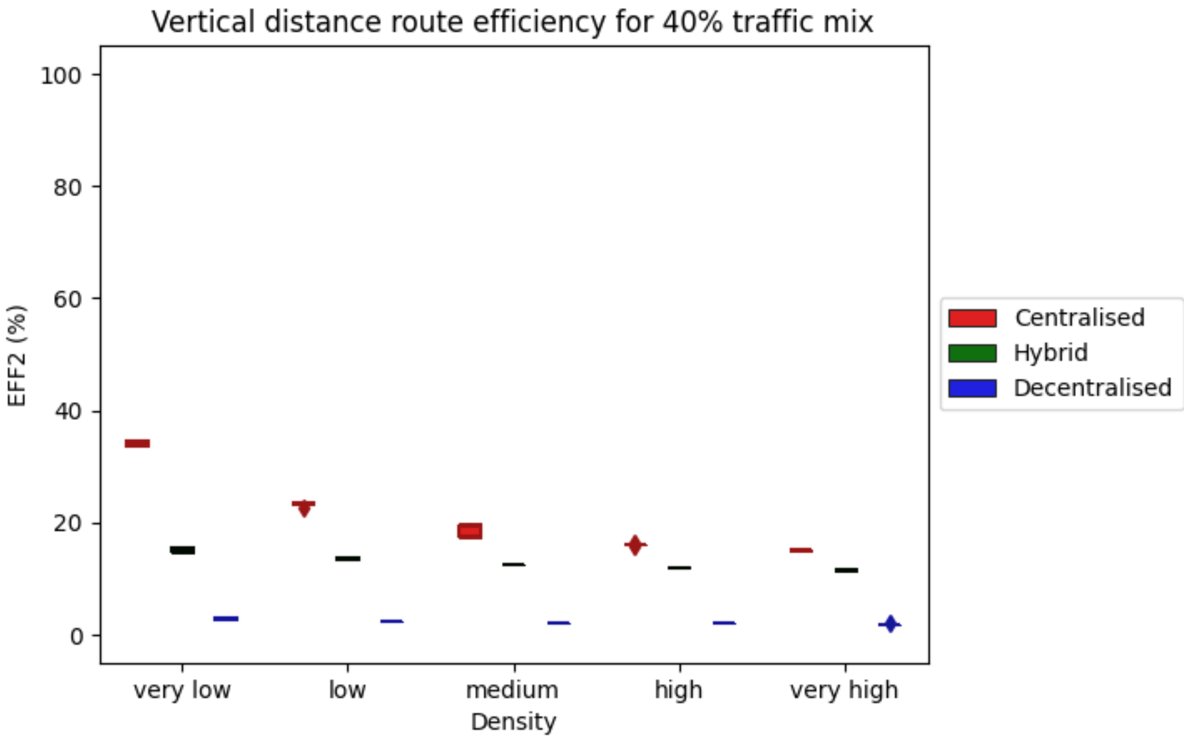

Figure 14: Vertical distance route efficiency for the 40% traffic mix case.

3.2.3.3 ENV5: Route duration efficiency

The route duration efficiency metric represents the ratio between the computed ideal and the actual route duration for missions. Figure 15 shows that the hybrid concept, consistent with the design philosophy, achieves the lowest performance, while the decentralised and centralised concepts perform similarly. Notably, the efficiency of the centralised concept paths remains constant, while the one of the decentralised concepts lowers with increasing density. This is due to the increasing number of tactical conflict resolution manoeuvres that occur with the decentralised concept, forcing aircraft to slow down and thus spend more time fulfilling missions.

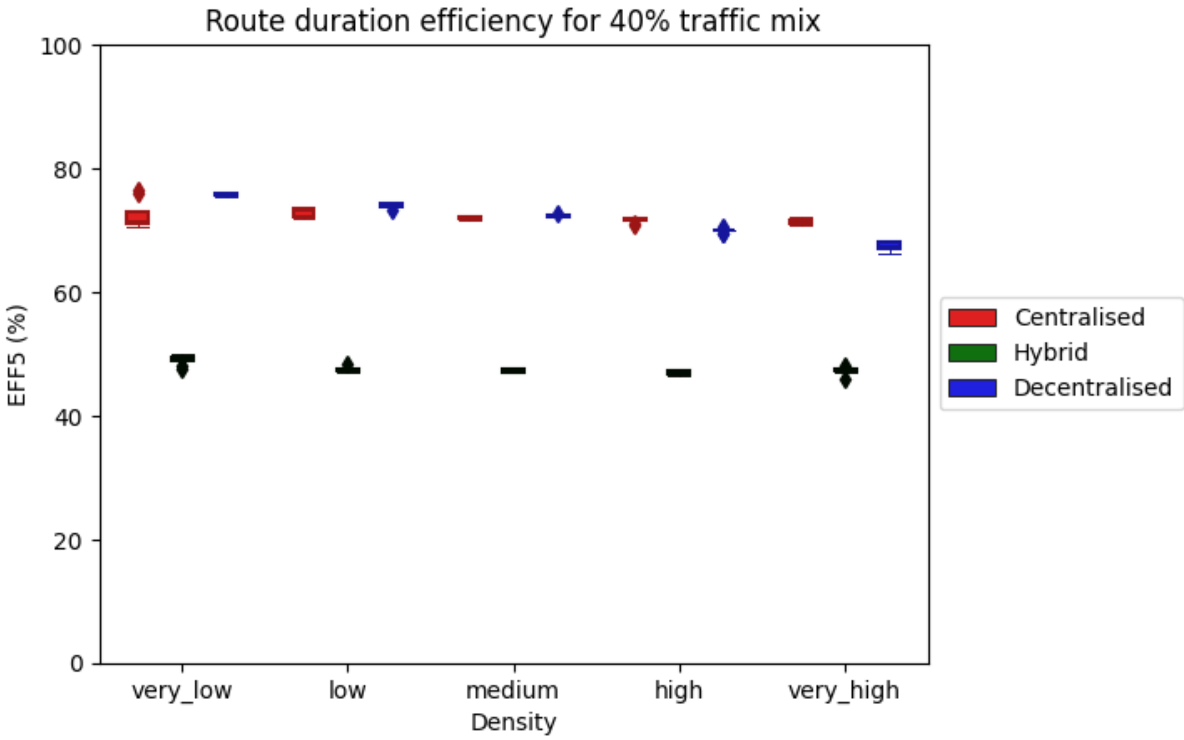

Figure 15: Route duration efficiency for the 40% traffic mix in function of traffic density.

3.2.3.4 Efficiency final remarks

Overall, the hybrid concept had the lowest performance in terms of safety to do the design decision to prioritise safety. The centralised concept had the overall best performance due to the strategic algorithm balancing safety and efficiency. The decentralised concept performed best in terms of route length, as strategic deconfliction was not performed, but overall similarly to the centralised concept.

3.2.4 Environmental impact metrics

From the numerous environmental concerns, in M2 we are mainly interested in the energy efficiency and noise pollution.

3.2.4.1 ENV1: Work done

The ENV1 metric is used as an indicator of total energy used, and in the lack of data on energy use-related aspects such as motor and battery efficiency, it is computed as total weighted flight duration where weights are flight level flown.

Figure 16 shows the work done metric for the 40% traffic mix as a function of traffic density. All three concepts show a linear increase of the ENV1 metric with increasing traffic density. The centralised concept yields the smallest gradient due to a combination of the relatively better horizontal and vertical route efficiency compared to other concepts (see EFF1 and EFF2), with the gap reaching almost 40% between centralised and hybrid concept at very hight traffic scenario.

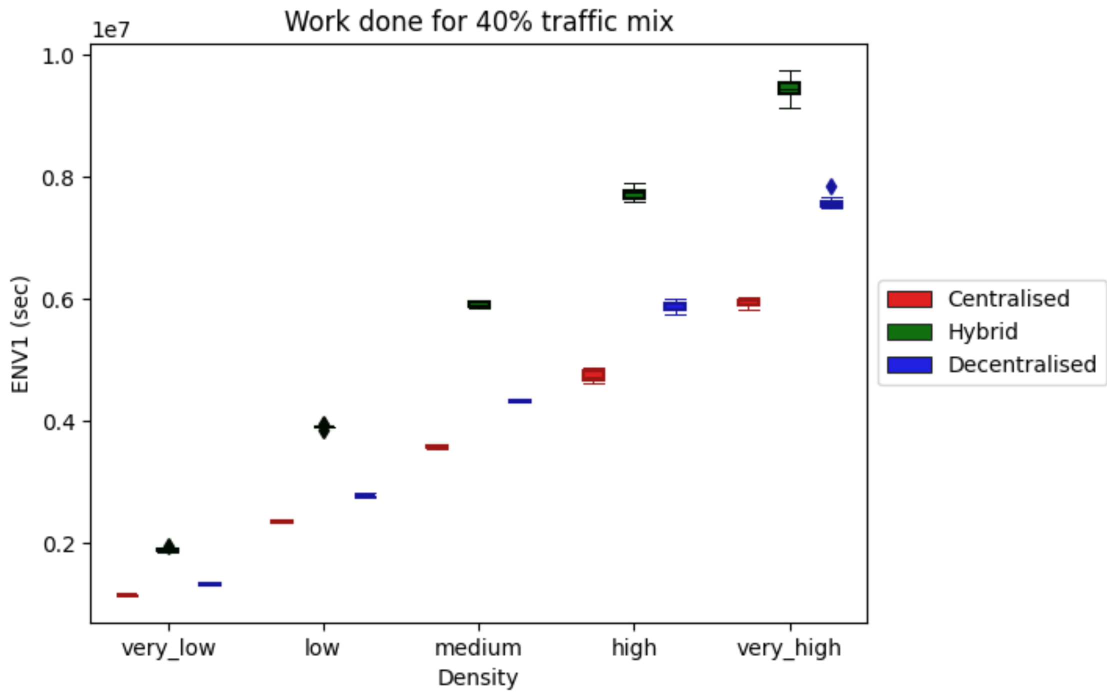

Figure 16: The work done for 40% traffic mix as function of traffic density.

3.2.4.2 ENV2: Weighted average altitude

The ENV2 metric measures the noise footprint experienced by people on the ground, assuming that this effect is higher if drones fly lower and for a long period of time. ENV2 is computed by integrating the flight altitude over the route displacement. Higher ENV2 is, better from the noise point of view.

Figure 17 shows the weighted average altitude for 40% traffic mix as a function of traffic density. It can be seen that the centralised concept has the smallest ENV2 value for the very low traffic density, leading to the highest noise impact compared to other concepts. However, as vertical efficiency decreases with increasing traffic density, ENV2 values increase for all concepts, and it asymptotically reaches a value of 65 meters for the centralised and hybrid concepts, which is the average flight level in the UTM airspace (I.e. meaning that all flight level gets equally used with the increase of traffic density). From a medium traffic density and higher, the decentralised concept has the lowest ENV2 measure leading to relatively higher noise pollution.

Although the ENV2 metric could be used as macroscopic measure for relative comparison of the concepts for a given traffic density, looking at the trends with traffic density could be misleading. For example, it would be wrong to interpret the mentioned increase of the ENV2 value with increase of traffic density as an improvement in terms of noise pollution, since with increasing traffic, noise pollution would increase as well.

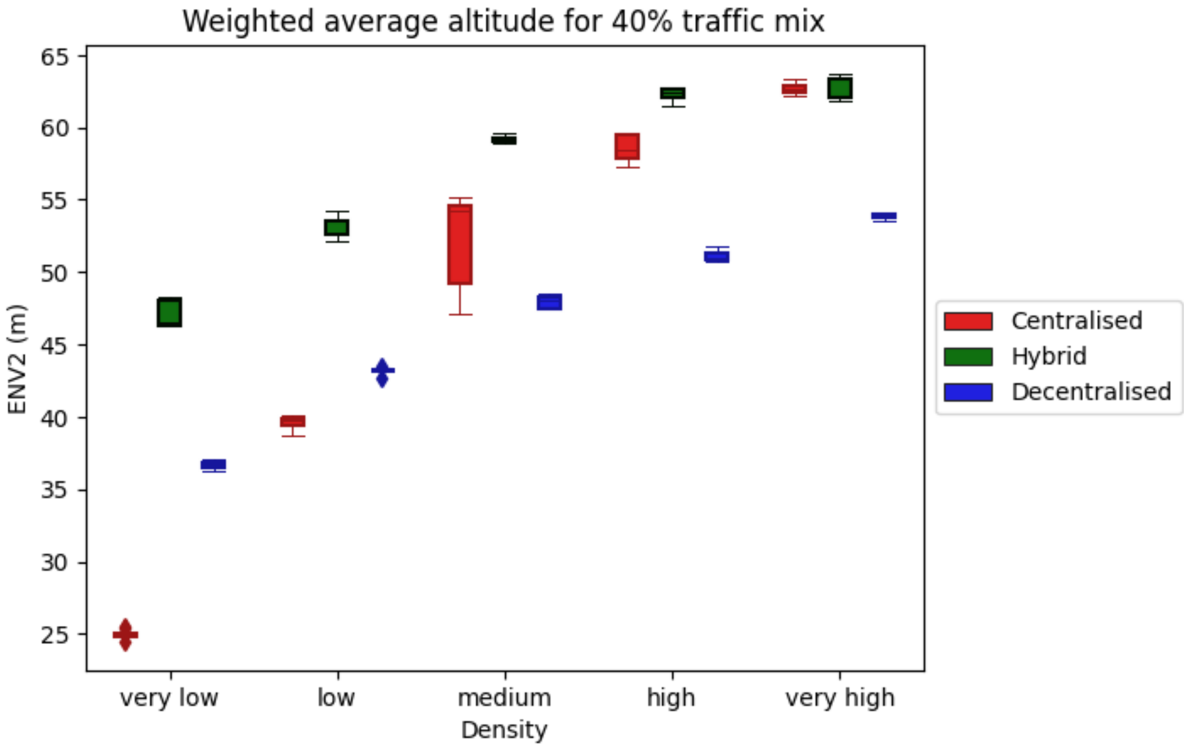

Figure 17: The weighted average altitude for 40% traffic mix as function of traffic density.

3.2.4.3 ENV3_1: Aggregated sound exposure

The ENV3_1 metric represents an indicator of sound exposure and is computed independently for around 4.5k reference points in the constrained airspace. It uses the inverse square law to calculate an equivalent noise level for every individual source of noise and every instance of time, which are further aggregated over the whole simulation period.

Figure 18 shows the aggregated sound exposure for 40% traffic mix as a function of traffic density. All reference points and all scenario repetitions are used as samples (40k samples) for the box plots. Looking at the total range of samples no decisive conclusion can be made on the performance of the different concepts, since the aggregated sound exposure varies a lot from one to another reference point. However, the spread of the middle half of samples (IQR - interquartile range) reveals differences between the performance of the concepts.

First it can be seen that as expected, the ENV3_1 metric value increases with increasing traffic density for all three concepts. The median values for all concept show a linear increase with traffic density, with a low gradient for all three concepts. Keep in mind, however, that every increase of 3 dB represents a doubling of sound intensity or acoustic power (since dB is a logarithmic scale), which is the case for all concepts comparing very low and very high-density scenarios.

A second and more important observation is that the decentralised concept produces a higher sound exposure compared to the centralised and hybrid concepts (5dB more on average). This is a direct result of its separation management strategy that does not anticipate the traffic situation ahead of time, but rather resolves conflicts tactically (using speed reduction beside others). Hence, drones spend more time in the air and contribute more to the noise. On the other hand, both centralised and hybrid concepts have strategic separation management (although with very different strategies), which is partially responsible for the conflict resolution and more fluid evolution of the flights. Furthermore, the centralised concept strategy of choosing fastest rather than shortest routes helps reducing the time drones spend in the air, thus, positively affecting the noise level

[3].

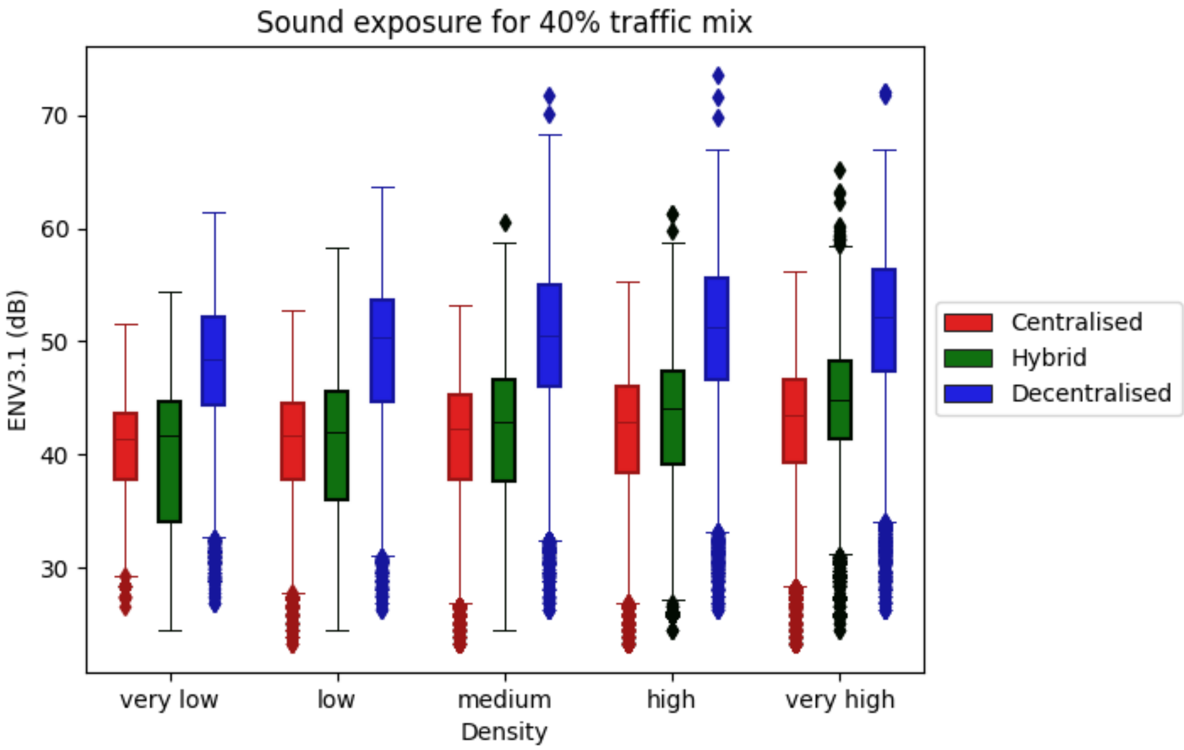

Figure 18: The aggregated sound exposure for 40% traffic mix as function of traffic density.

3.2.4.4 ENV3_2: The number of points with significant instantaneous sound exposure

The ENV3_2 metric is an indicator of instantaneous sound exposure. It is computed in the same way as the ENV3_1 metric, except the final aggregation over the simulation period. Based on 4,5k instantaneous measurements of sound level for each instant of time, a macroscopic metric is computed by counting the number of instantaneous noise exposures exceeding a threshold of 55 dB (EPA noise limit) [2] [3].Figure 19 shows the number of points with significant instantaneous sound exposure for 40% traffic mix as function of traffic density. Similar to ENV3_1, we notice that the ENV3_2 value increases with increasing traffic density. However, differences in concept performance are not so distinct, this time, since slower drone speed has no effect on instantaneous noise exposure (that was predominant effect in ENV3_1).

At lower traffic densities, the centralised concept has the greatest number of points with significant instantaneous noise exposure, while the decentralised concept has the most at higher densities. The centralised concept seeks to minimize total duration of all flights, hence yields higher flight levels only when strictly required. For the lower densities, where conflict probability is still low, this strategy results in a concentration of flights at lower altitudes (see ENV2) hence producing relatively higher noise compare to other concepts. The flights get more equally spread over all available flight levels with increasing traffic densities, diminishing this effect.

The hybrid concept has relatively the best performance compared to other concepts due to its strategic separation management strategy that keeps density in the constrained airspace lower compared to the other concepts.

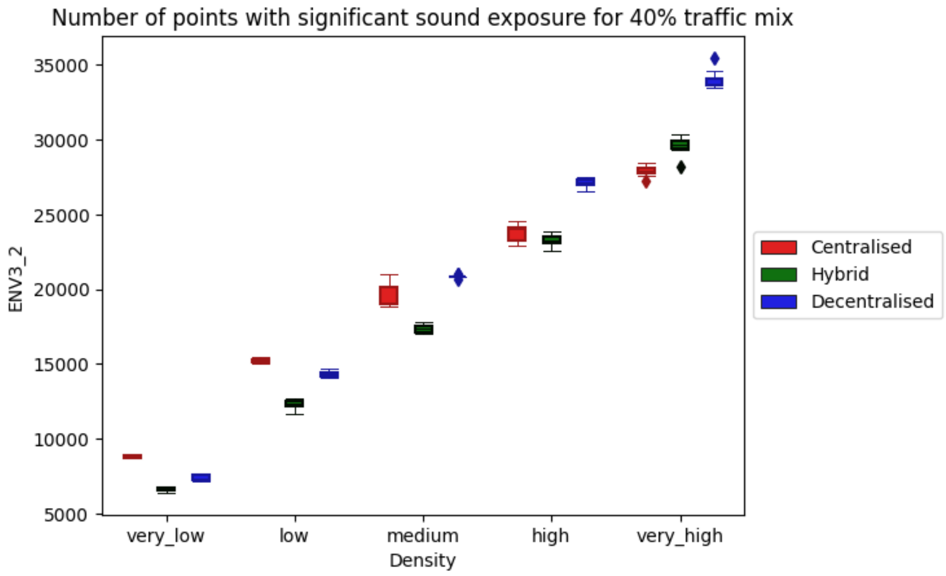

Figure 19: The number of points with significant sound exposure for 40% traffic mix as function of traffic density.

3.2.4.5 ENV final remarks

Based on the results of the simulated scenarios, in can be observed that the constrained airspace protection strategy implemented by the hybrid concept deteriorates concept performance from an energy efficiency point of view due to flight rerouting. This has, however, a positive effect on the noise pollution in highly populated areas, thus achieving good performance in this metric, together with the centralised concept.

The general conclusion is that having a strategic component of the separation management, with the ability to anticipate to a traffic situation and hence partially avoid conflict situations, could be beneficial also for the reduction of noise exposure.

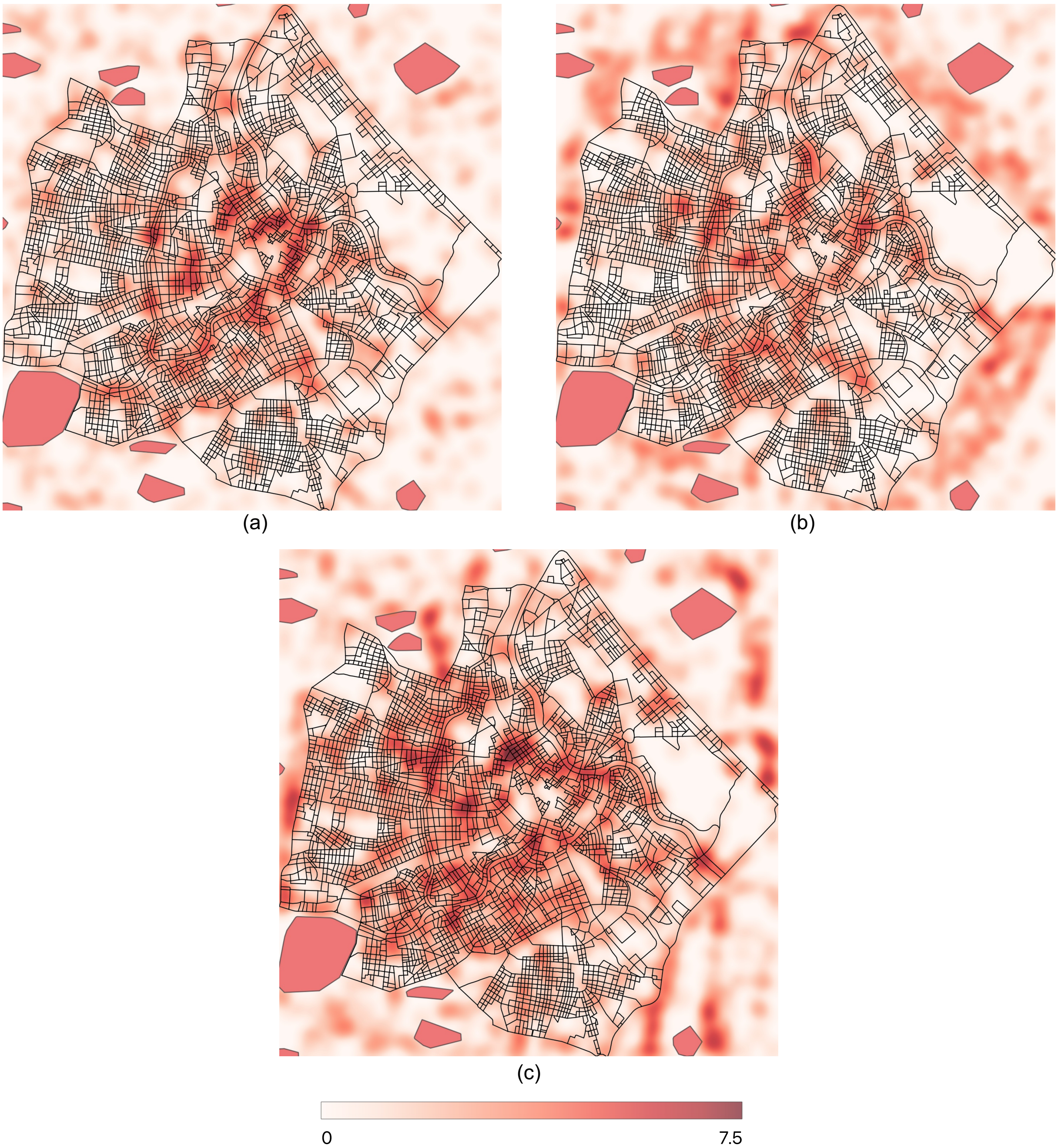

Figure 20 shows a noise heat map for each of the concepts for one high density scenario with a 40 percent traffic mix. The noise was calculated for each point in a 100-metre uniform grid. The higher intensity colour means that more of the measurement points within a radius of 400 metres have 40 decibels or higher noise level. It is seen in the map that hybrid concept has the lowest intensity in constrained airspace because the routing avoids this area if possible. However, in open airspace the hybrid concept has noisier areas than the centralised concept. Finally, the decentralised concept contains more hotspots because traffic is not strategically planned and aircraft tend to fly lower in the high density scenarios (Figure 25).

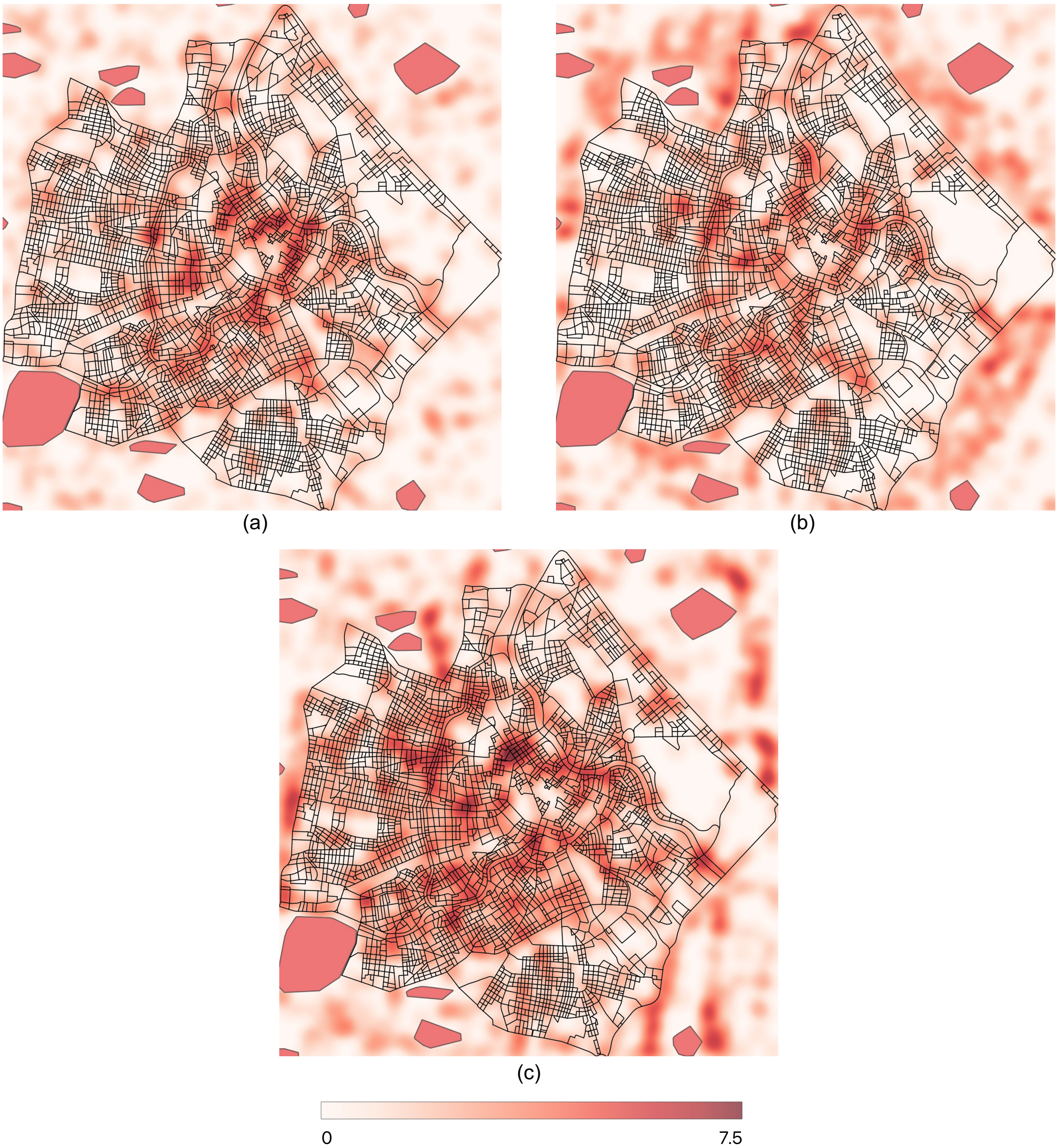

Figure 20: Noise heat map showing areas where the sound level is 40 decibels or larger in a high-density scenario with 40 percent traffic mix. The sound level is calculated for all points in a 100-metre uniform grid and then a 400 metre radius is used in the kernel density estimation algorithm. The gradient shows the number of points in the grid with a 40 decibel or higher intensity. (a) Centralised, (b) Hybrid, (c) Decentralised.

3.2.5 Safety

This section will show several safety metrics for scenarios where 40 percent of traffic originated from distribution centres. It will show the number of conflicts for total (SAF1), constrained (SAF1.3), and open airspace (SAF1.4), the number of conflicts per flight (SAF 1.2), the number of intrusions (SAF 2), the number of severe intrusions (SAF 2_1), the intrusion prevention rate (SAF 3), and the number of severe loitering geofence violations. It also shows the number of conflicts and intrusions in constrained and open airspace.

A conflict is defined as a predicted loss of separation within a specified look-ahead time. To calculate this metric, a state-based conflict detection algorithm is used. This means that the current state of the drones is linearly extrapolated with the look-ahead time, and it is checked whether the minimal separation distances will be violated by other drones during the look-ahead time. Severe intrusions are those in which the minimum separation leads to a crash. The dimensions are a vertical distance of 1.7m and horizontal distance of 0.7m. These are based on the DJI Matrice 600 (reference). The intrusion prevention rate is a measure of how many conflicts did not lead to a loss of separation. Finally, a severe loitering geofence violation happens whenever an aircraft violates a geofence by more than one meter.

3.2.5.1 SAF 1: Total number of conflicts

A conflict is counted a loss of separation is predicted to occur within a certain lookahead time. The prediction is made by linearly extrapolating the current state of the aircraft with the lookahead time. Figure 21, Figure 22, and Figure 23 show the number of conflicts for scenarios with 40% traffic mix for the total airspace, constrained airspace, and open airspace, respectively. The horizontal axis shows the density level, and the vertical axis shows the number of conflicts per scenario.

The number of conflicts for the total airspace increases with the density for all three concepts. Moreover, the hybrid and centralised concepts are both comparable throughout all densities with the hybrid concept having slightly more conflicts in all densities. However, as density increases the difference between the decentralised concept and the other two concepts increases. At very high densities, the difference is an order of magnitude. This can be explained by the fact that decentralised does not perform strategic conflict resolution at the level of individual flights, so aircraft mostly rely on tactical conflict resolution. Similarly, the reason that the number of conflicts for the hybrid is slightly higher than the centralised is because they also perform tactical resolution when a conflict could not be solved strategically. These manoeuvres can then create knock-on conflicts. The centralised conflict does not perform any tactical resolution so there are no knock-on conflicts.

Figure 22 shows that the hybrid concept has the lowest number of conflicts in constrained airspace in most densities because the constrained airspace density is lower than the centralised and decentralised concepts. However, Figure 23 shows that the hybrid concept with the most conflicts in open airspace for the very low and low densities. In the high and very high densities the hybrid concept is in between the centralised and decentralised concepts.

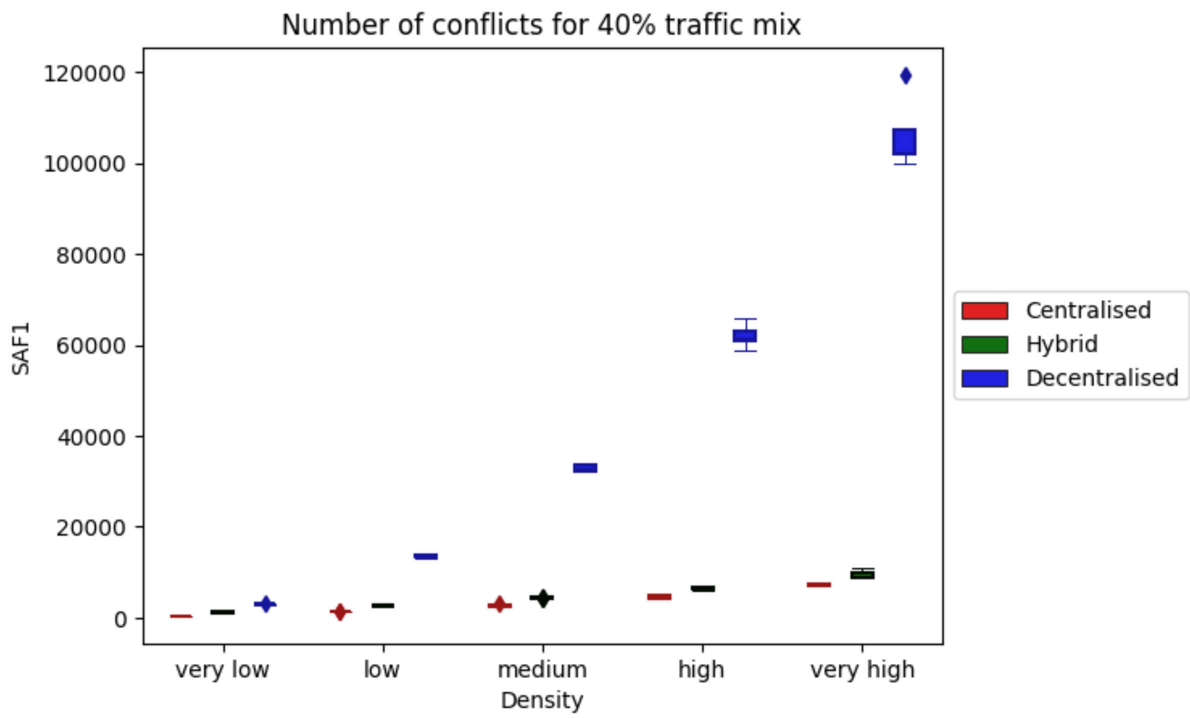

Figure 21: Number of conflicts for the 40% traffic mix.

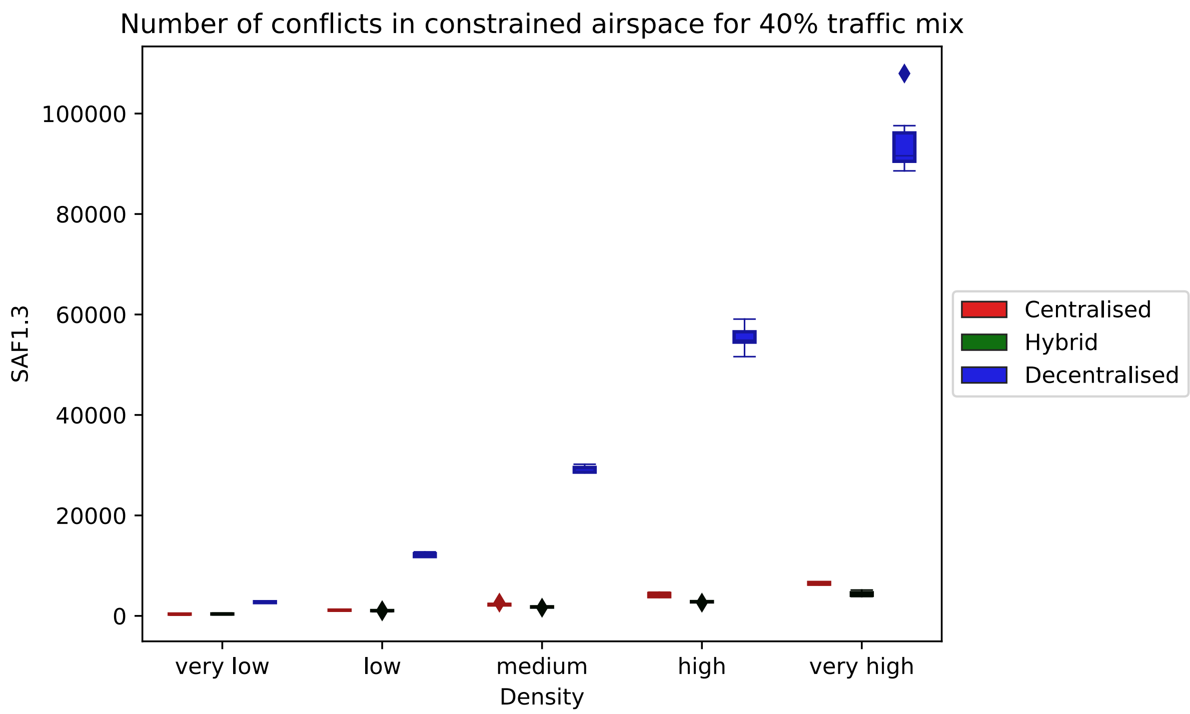

Figure 22: Number of conflicts in constrained airspace for 40% traffic mix.

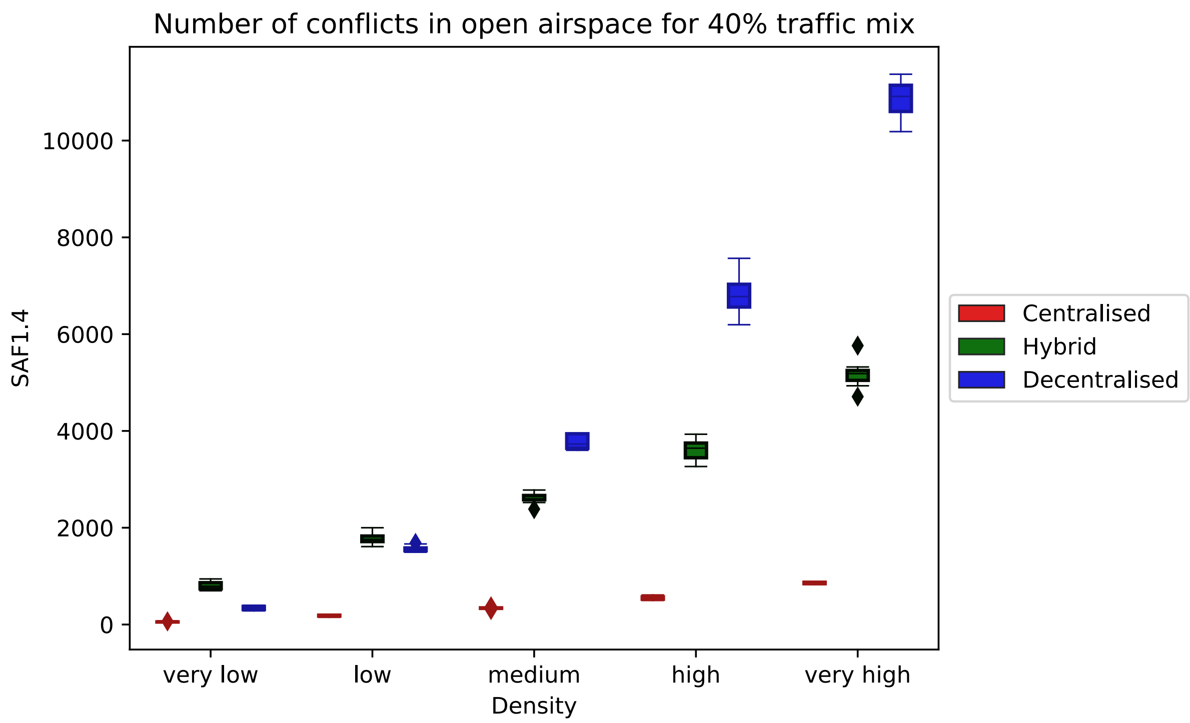

Figure 23: Number of conflicts in open airspace for 40% traffic mix.

3.2.5.2 SAF 1.2: Number of conflicts per flight

The number of conflicts per flight as calculated as the total number of conflicts per scenario divided by the number of spawned aircraft in that scenario. Figure 24 shows the number of conflicts per flight for the 40% traffic mix. The horizontal axis shows the densities, and the vertical axis shows the number of conflicts per flight. The trends are quite similar as the total number of conflicts. The hybrid has slightly more conflicts per flight than the centralised concept. For both concepts, the number of conflicts per flight remains under two conflicts per flight for all densities. The decentralised concept only manages to remain near 2 conflicts per flight for the very low densities. At the very high density the difference between the decentralised concept and the rest is an order of magnitude. This is also explained in the same way as Figure 21. Decentralised relies mostly on tactical conflict resolution for preventing losses of separation. The hybrid concept has slightly more conflicts because they use tactical conflict resolution when strategic conflicts failed.

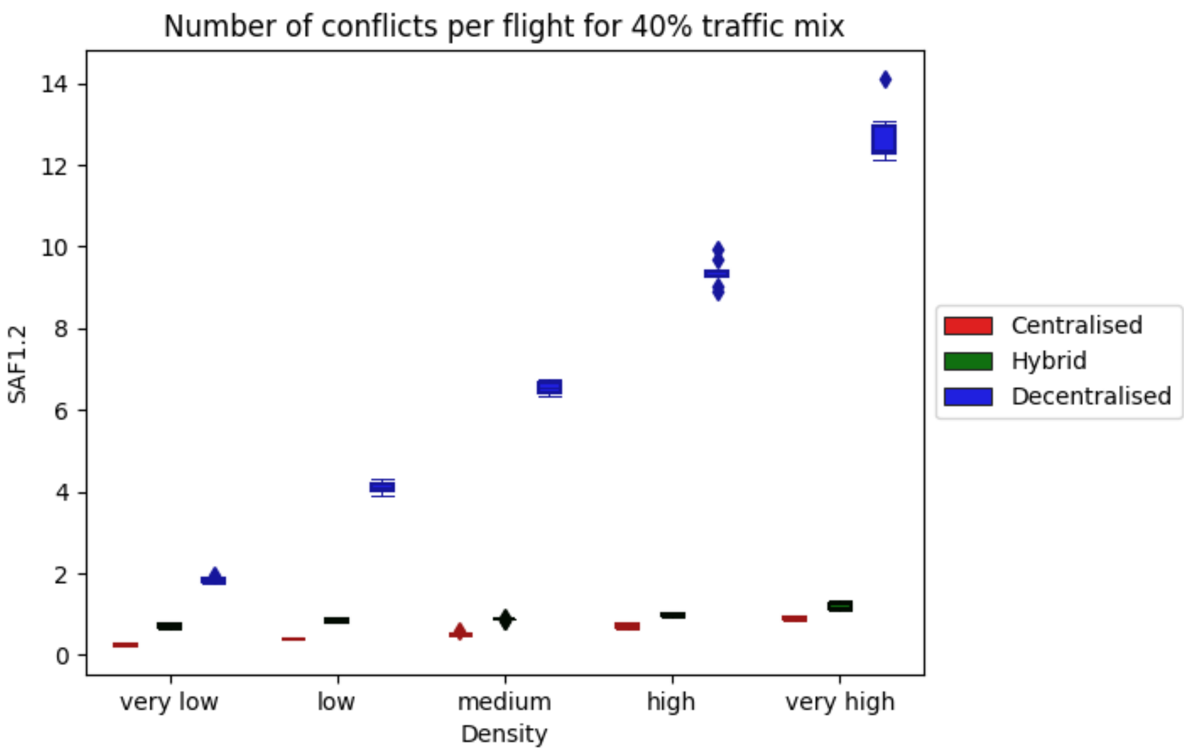

Figure 24: Number of conflicts per flight for 40% traffic mix.

3.2.5.3 SAF 2: Total number of intrusions

The total number of intrusions are calculated by summing all the losses of separation per scenario. A loss of separation occurs when an aircraft enters the protected zone of another aircraft. The protected zone is 32 meters horizontal and 25 feet vertical from the aircraft. Figure 25, Figure 26, and Figure 27 show the number of intrusions for the 40% traffic mix in the total, constrained, and open airspace, respectively. The horizontal axis shoes the density, and the vertical axis shows the number of intrusions per scenario. Figure 28 shows the cumulative average number of intrusions with a heat map for the same scenario. It can be described as the average number of intrusions in a certain location.

For all concepts the number of intrusions increase with the density. The hybrid concept contains the lowest number of intrusions at all densities for the total airspace. This is also true for the intrusions in constrained airspace (Figure 26). In open airspace the hybrid concept is comparable in terms of number of conflicts with the decentralised concept. Since there is more space for tactical conflict resolution in open airspace, both the decentralised and hybrid concepts maintain a lower number of intrusions than the centralised concept in the medium, high and very high densities.

The number of intrusions for the centralised and decentralised concepts are comparable at most densities. In open airspace the decentralised concept manages to stay below the centralised concept. However, in constrained airspace the trend is opposite with the decentralised concept having more intrusions in the higher densities. Although there is a large difference in the number of conflicts, the decentralised concept manages to solve most of them to have comparable intrusion values with the centralised concept.

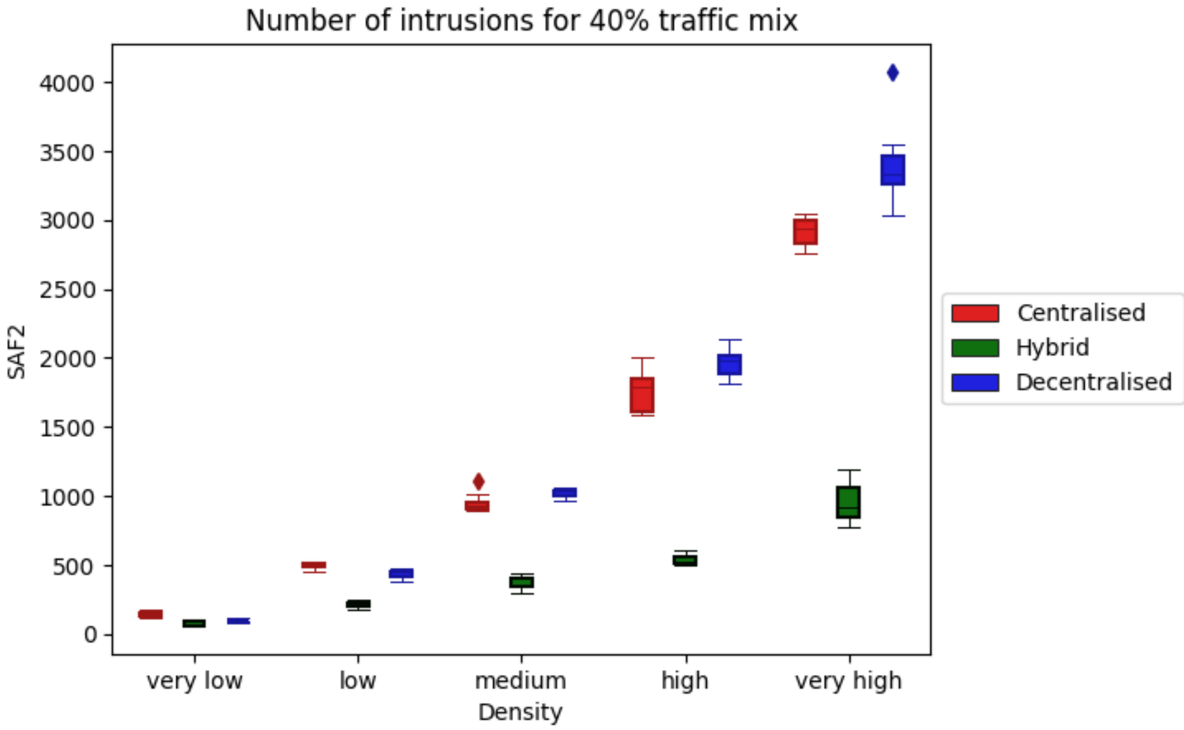

Figure 25: Number of intrusions for 40% traffic mix.

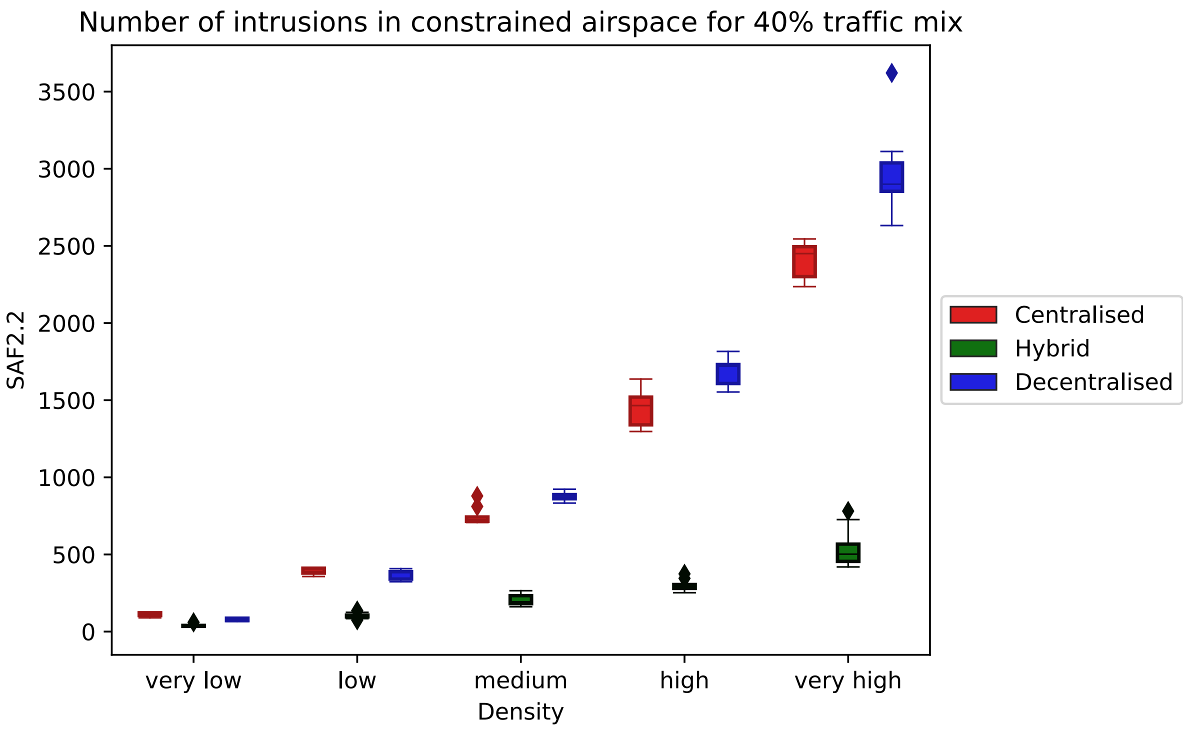

Figure 26: Number of intrusions in constrained airspace for 40% traffic mix.

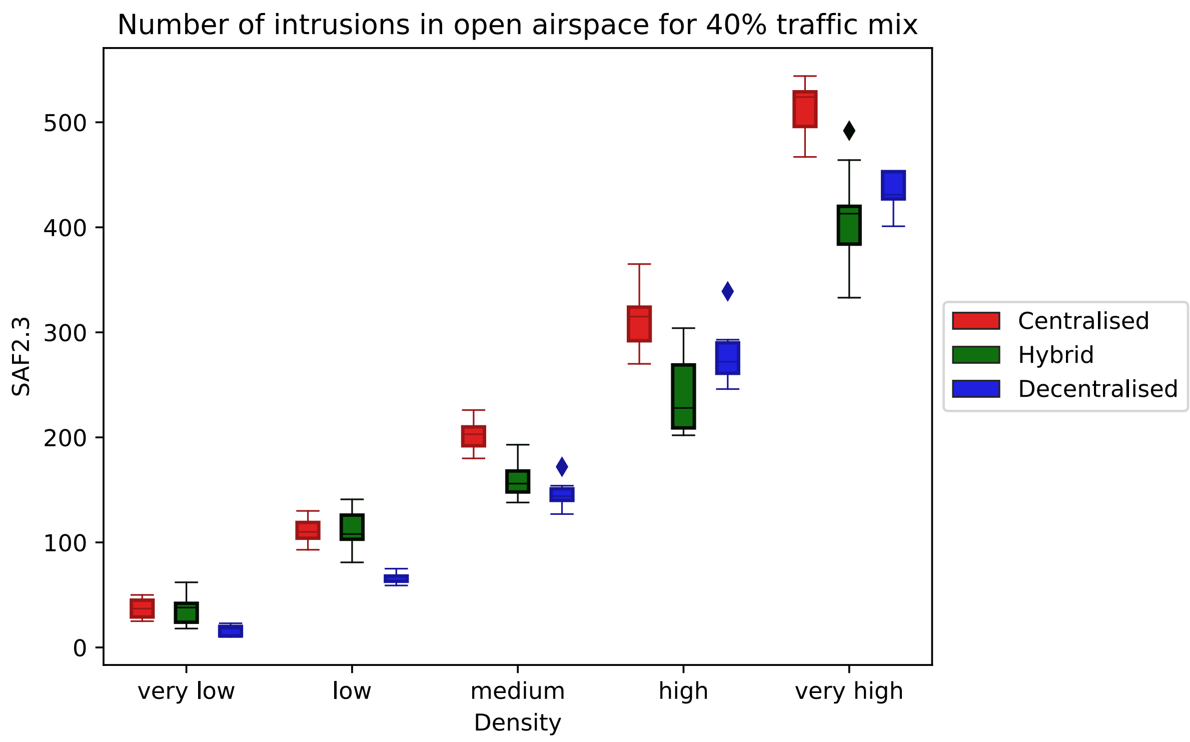

Figure 27: Number of intrusions in open airspace for 40% traffic mix.

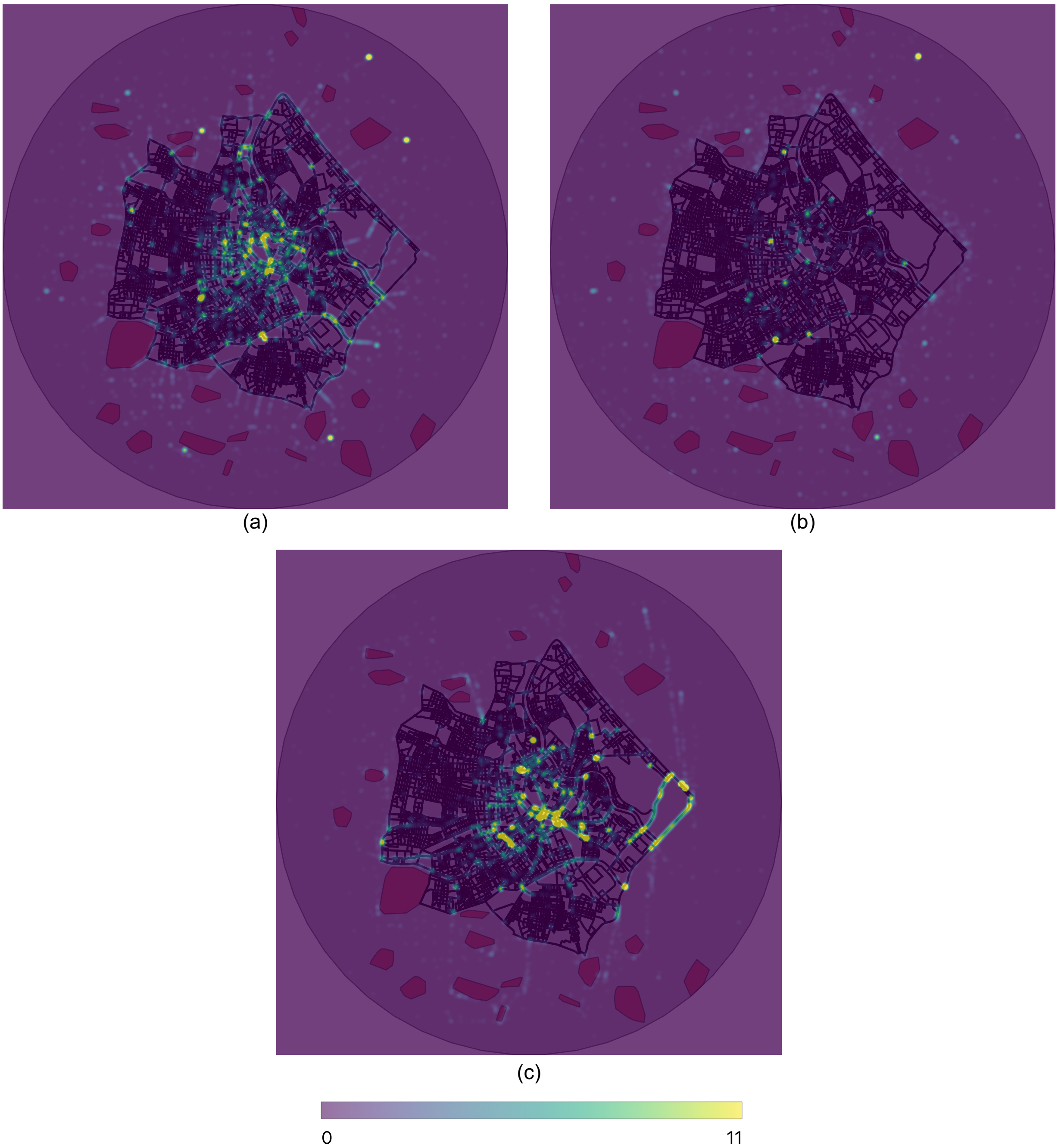

Figure 28: Cumulative intrusion heat maps for high density scenarios with a 40% traffic mix. It shows the number of drones within a radius of 150 metres. (a) Centralised, (b) Hybrid, (c) Decentralised.

3.2.5.4 SAF 2.1: Total number of severe intrusions

Severe intrusions are calculated as intrusions in which the minimum distance between drones is below 1.7 metres horizontal and 0.75 metres vertical distance. These figures are based on the dimensions of the DJI Matrice 600 [4]. Figure 29 shows the number of severe intrusions (likely collisions). The density and number of intrusions are seen in the horizontal and vertical axis, respectively. The number of severe intrusions increases with the density for all concepts. The centralised concept has the highest number of severe intrusions for all densities. This is because this concept does not perform any tactical conflict resolution, so aircraft just fly through a conflict. The effect of tactical conflict resolution on severe intrusions is seen by how the decentralised and hybrid concepts both stay consistently under the centralised concept and do not increase as much with traffic density.

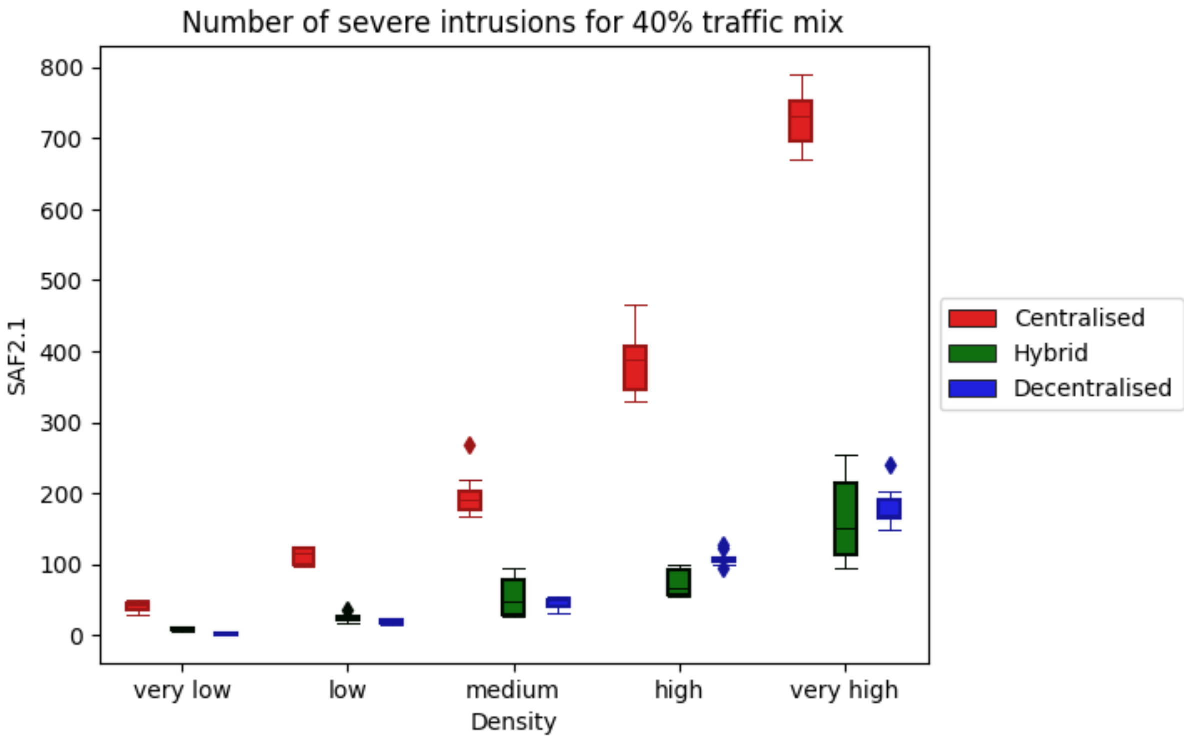

Figure 29: Number of severe intrusions

3.2.5.5 SAF3: Intrusion prevention rate

The intrusion prevention rate is calculated as the percentage of detected conflicts that do not lead to an intrusion. It is important to note that this measure does not differentiate between true and false conflicts. Metropolis 2 uses state-based detection. However, it has drawbacks in areas where aircraft must constantly change their state. This is one of the main characteristics of constrained airspace, to avoid buildings, aircraft must follow streets which may or may not be straight.

Figure 30 shows the intrusion prevention rate versus the density in the vertical and horizontal axis, respectively. The centralised concept maintains an intrusion prevention rate around 60 percent throughout all densities. This is a measure of the percentage of false conflicts because the centralised concept does not perform any tactical resolution. It shows that state-based conflict detection has some significant drawbacks in constrained airspace as more than half of the conflicts detected do not become intrusions. The hybrid concept prevention rate stays around and above 90 percent and slowly decreases with density. The decentralised concept maintains a constant prevention rate above 95 percent even for the very high-density scenarios. It is also noteworthy to mention that Figure 21 shows an increase of conflicts of an order of magnitude as compared to other concepts.

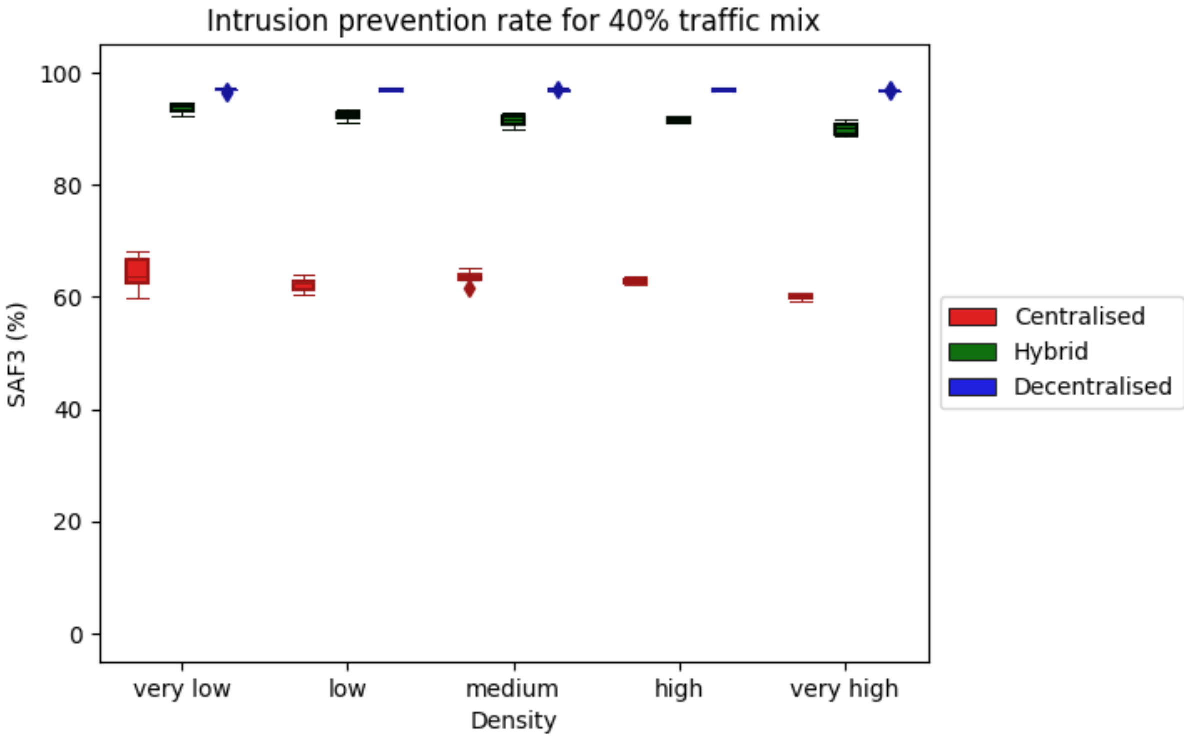

Figure 30: Intrusion prevention rate

3.2.5.6 SAF 6.2: Number of severe loitering NFZ violations

A severe loitering no-fly-zone (NFZ) violation is counted when an aircraft intrudes a loitering geofence by more than 1 metre. Figure 31 shows the number of severe loitering violations for the 40% traffic mix. The densities are on the horizontal axis and the violations are on the vertical axis. The centralised concept has the most loitering violations, where the difference with the other two concepts increases with density. This shows another limitation of centralised planning without any tactical replanning. All the loitering geofences were included in the planning algorithm, however, due to uncertainties the prediction was not completely accurate and therefore some aircraft that were predicted to be free of loitering violations in reality weren't. During planning only, the start time of the aircraft is known so the concept must make a prediction. The decentralised and hybrid concept perform tactical replanning. They both check if it is possible to create a new flight plan once the loitering geofence is activated. This is the reason why there are fewer violations with these concepts, compared to the centralised concept. Moreover, as the hybrid concept attempts to avoid constrained airspace, which is where the loitering geofences are, they have the lowest number of loitering intrusions. Aircraft in constrained airspace are better able to avoid loitering geofences because there is more free space when compared to traffic in the decentralised concept simulations.

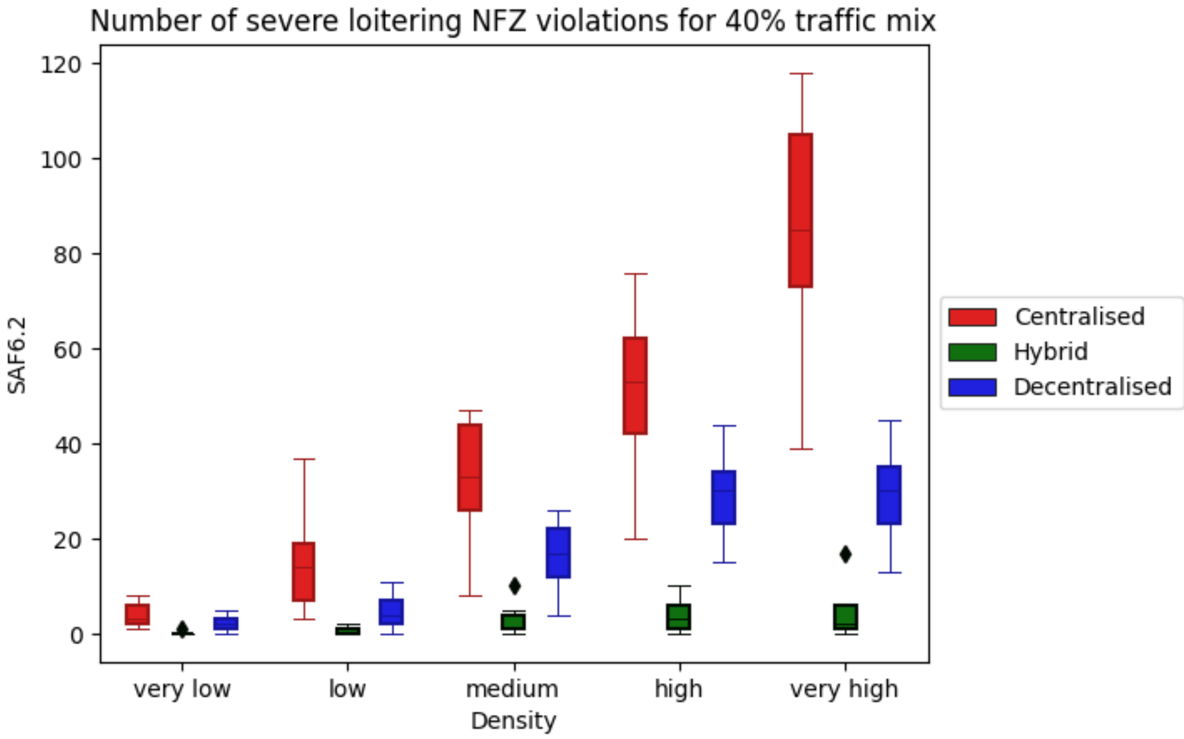

Figure 31: Number of severe loitering NFZ violations

3.2.5.7 SAF Final Remarks

Although the decentralised concept had the largest number of conflicts by an order of magnitude for all densities, it managed to average less intrusions than the centralised concept in the very low and low densities. For the higher densities the decentralised concept then had the highest number of intrusions. The hybrid concept managed to maintain the lowest number of intrusions because it performs tactical conflict resolution and because of the lower density in constrained airspace.

The centralised concept maintained the highest number of severe intrusions because it does not resolve any conflicts tactically. Both the decentralised and hybrid concepts used tactical resolution, so they were able to maintain a similar number of severe intrusions across densities.

The intrusion prevention rate shows that state-based conflict detection has some limitations when routes are not generally straight (60 percent of centralised concepts were false). The hybrid and decentralised concept both had relatively high intrusion prevention rates.

3.2.6 Priority

The following section presents the performance of the three concepts of operation for the prioritisation of flights in function of traffic density for the 40% traffic mix.

3.2.6.1 PRI1: Weighted cumulative mission duration

The first priority metric is the weighted cumulative mission duration, computed as the sum of all mission durations multiplied by a weight corresponding to the mission priority, where higher priority missions have a higher weighting. In the figure below, it can be seen that the decentralised and centralised concepts performed similarly, despite the difference in the planning procedure of missions. Priority for the decentralised concept was enforced on a tactical level, while priority for the centralised concept was enforced at the strategic, pre-planning level. However, it should be noted that the centralised concept routes were slightly less efficient than the decentralised concept routing, and thus marginally longer. However, the similar performance between these two concepts shows that priority can be successfully be implemented both tactically and strategically.

On overall, the hybrid concept had a lower performance in this metric. It should be noted, however, that even though the routes for this concept were notably longer than for the other two concepts, this difference is not maintained in the weighted mission duration results. Thus, by taking into consideration the increased length of the routes, the hybrid concept can be considered to have best taken into account the priority of missions, both on a tactical and a strategic level.

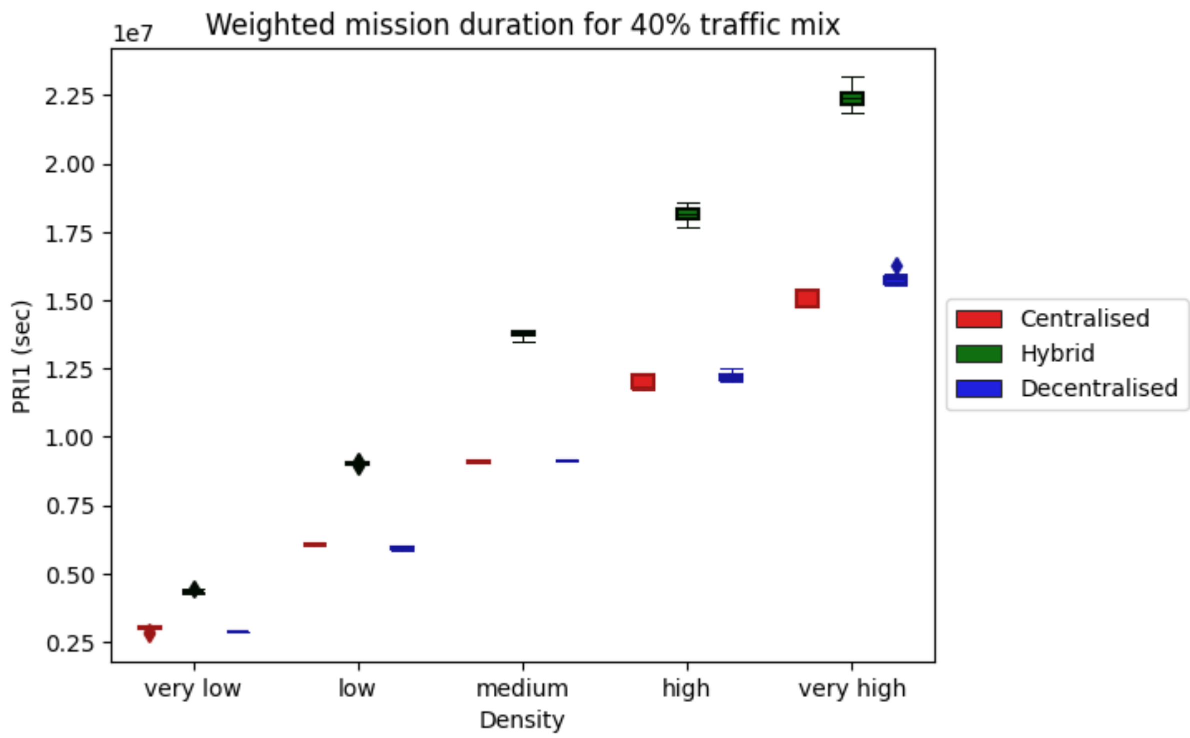

Figure 32: Weighted cumulative mission duration in function of traffic density.

3.2.6.2 PRI2: Weighted mission route length

The following metric is similar to the previously described PRI2, but in terms of route length. The same trends and explanations can be seen in the figure below, with the gap between the absolute route lengths of the concepts being narrowed when taking into account priority. Thus, while the centralised and decentralised performed similarly and well, the hybrid concept managed to best take into account priority in their mission planning.

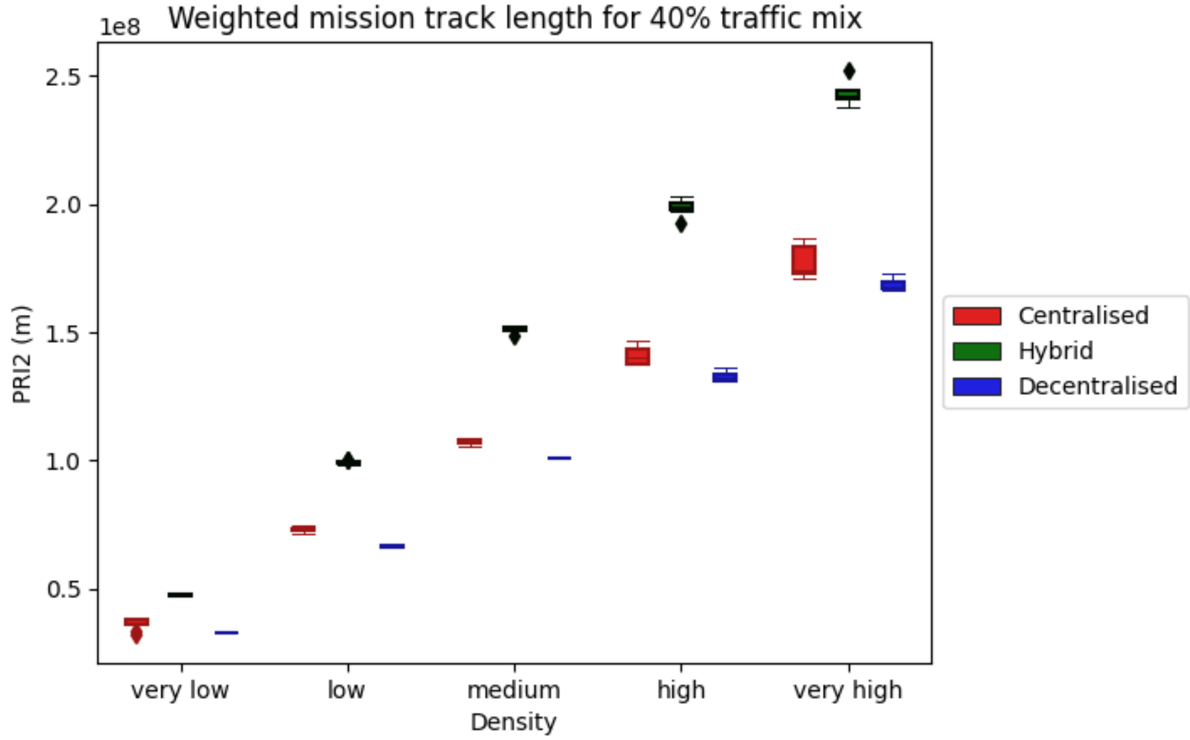

Figure Error! Unknown switch argument.**: Weighted cumulative mission track length in function of traffic density.**

3.3 Effect of traffic mix on metrics

The following section presents the effect that the traffic mix had on the metrics. With increasing proportion of aircraft originating at distribution centres, traffic density is less homogenous, locally increasing the conflict probability between aircraft. For metrics not present in this section, no significant effect of the traffic mix was found.

3.3.1 Access and equity

Except for a slight effect on the performance of the hybrid concept, neither the centralised nor the decentralised concept experience a noticeable effect of traffic mix on the access and equity performance. Only the most notable differences are shown, concerning the AEQ1 and AEQ2 metric.

Figure 34 shows the number of cancelled demands and Figure 35 shows demand delay dispersion for high traffic density as function of traffic mix. Both figures reveal a slight linear increase of metric values with increasing proportion of traffic originating from distribution centres (higher departure frequency). Since both metrics are based on the measure of the arrival delay, and knowing that the hybrid concept strategy is to protect safety by further separating the traffic (by delays and rerouting), explains the increase of the metric in the scenarios with higher departure frequencies.

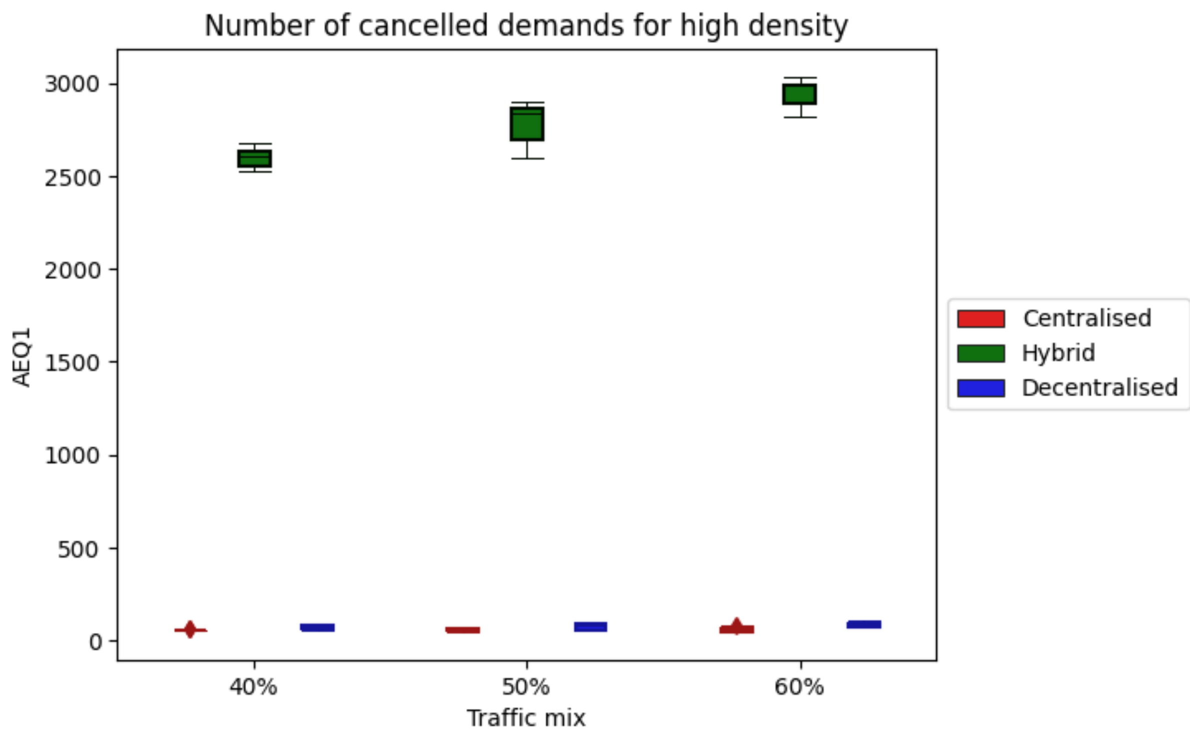

Figure 34: Number of cancelled demands for high traffic density as function of traffic mix.

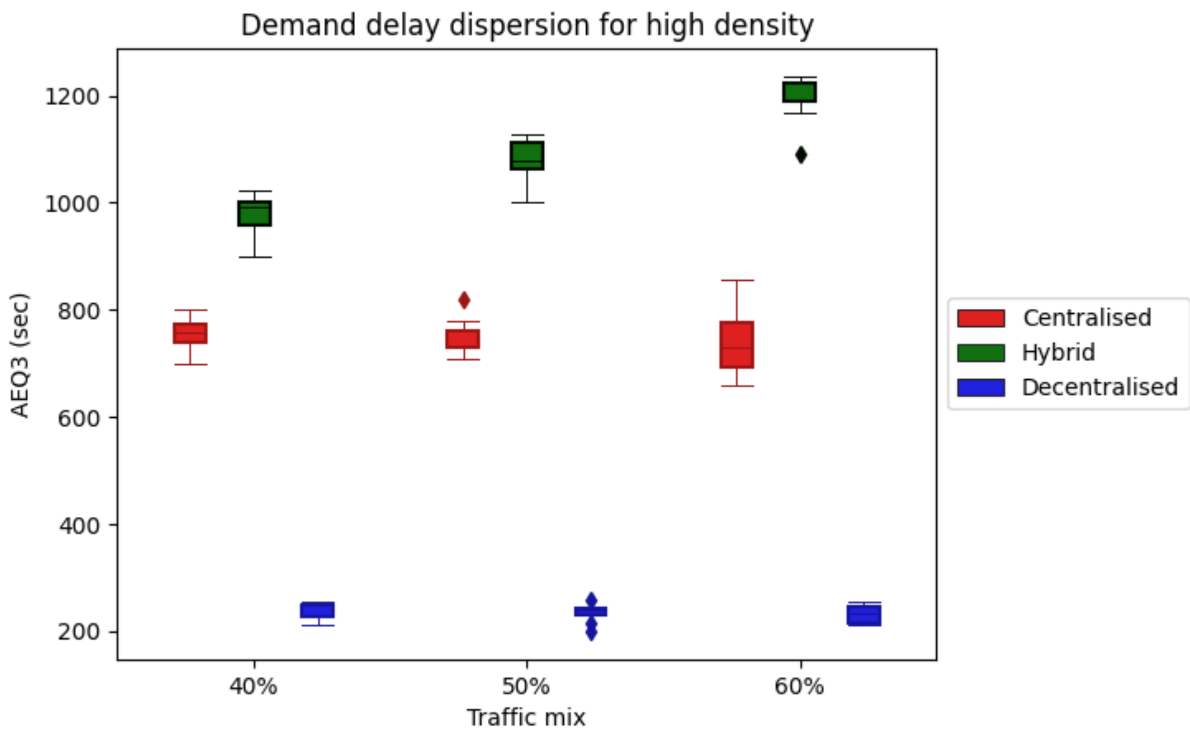

Figure 35: Demand delay dispersion for high traffic density as function of traffic mix.

3.3.2 Efficiency

The following section presents the observed differences in efficiency for the three concepts when plotting the results as a function of traffic mix. The only notable difference in efficiency can be observed in departure delay. With increasing proportion of traffic originating from distribution centres, missions originate from a smaller number of vertiports. Thus, the delays at these vertiports are increased, and so does the overall capacity.

The results presented below reflect the design choices of the concepts. The hybrid concept chose to use delay as a way to increase the safely level of the airspace, while the other two concepts did not. Thus, the delay increases as a more limited number of vertiports need to handle a higher proportion of the demand.

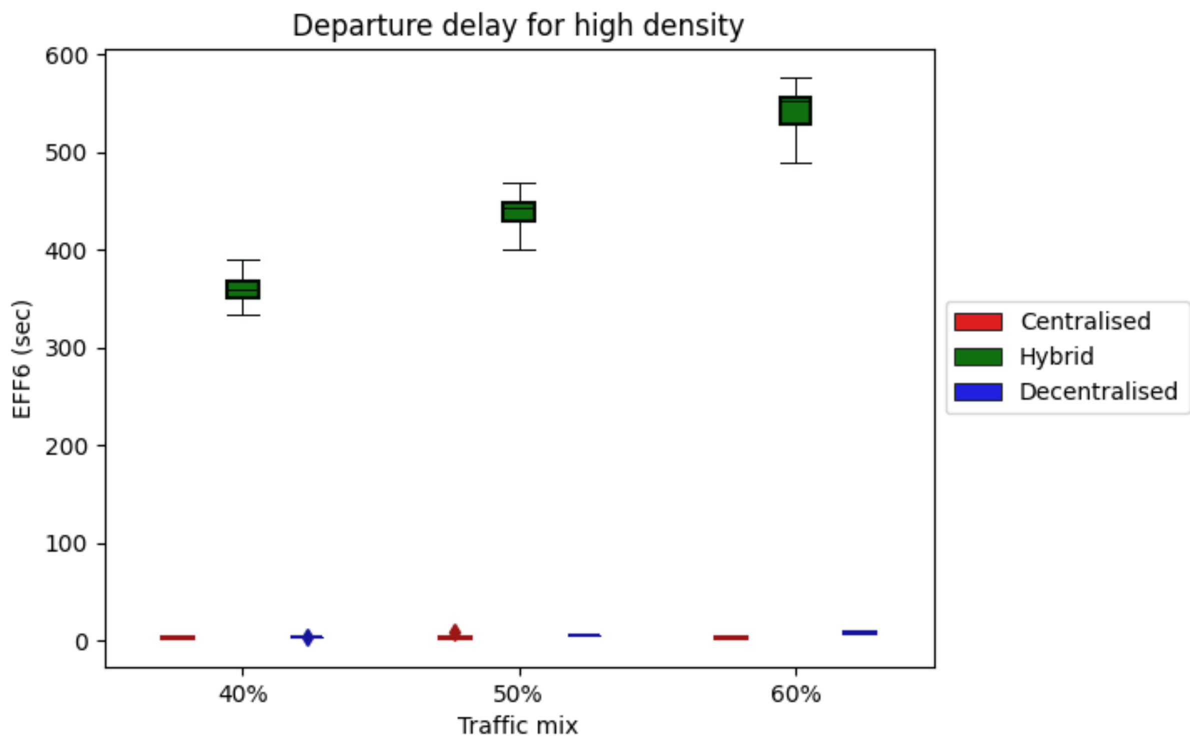

Figure 36: Departure delay for high traffic density in function of traffic mix.

3.4 Effect of rogue aircraft on metrics

The following section explores the effect of the number of rogue aircraft on the key performance indicators. These aircraft did not follow the imposed airspace rules, thus tested the robustness of the concepts to such actors. The presence of rogue aircraft was found to cause no significant effect on the metrics not present in this section.

3.4.1 Capacity

Rogue aircraft, as a disruptive event, have a negative effect on the capacity metrics CAP1 and CAP2 since they are measuring system efficiency and safety degradation as a proxy for system capacity.

These obvious results are, thus, not shown. However, magnitude of these degradations is used in the M2 project as a measure of the capacity resilience. Capacity resilience is defined as the ability to withstand and recover from planned and unplanned events and conditions which cause a loss of nominal capacity [7].

3.4.1.1 CAP3: Additional demand delay

The CAP3 metric is computed as an increase of demand delay (CAP1 for nominal scenario) with the introduction of rogue aircraft (CAP1 with 33, 66, and 100 rogue aircraft, R33, R66, and R100).

Figure 37 shows additional demand delay for high traffic density as function of rogue aircraft level. Although its dispersion is very big, it could be seen that on average additional demand delay increases with the increase of number of rogue aircraft for hybrid and decentralised concepts. Similar results are noticeable for other traffic densities, with decentralised being slightly less affected by the rogue aircraft I.e., more resilient.

The CAP3 metric of the centralised concept is not affect by the rogue aircraft, as it simply has no tactical separation management component.

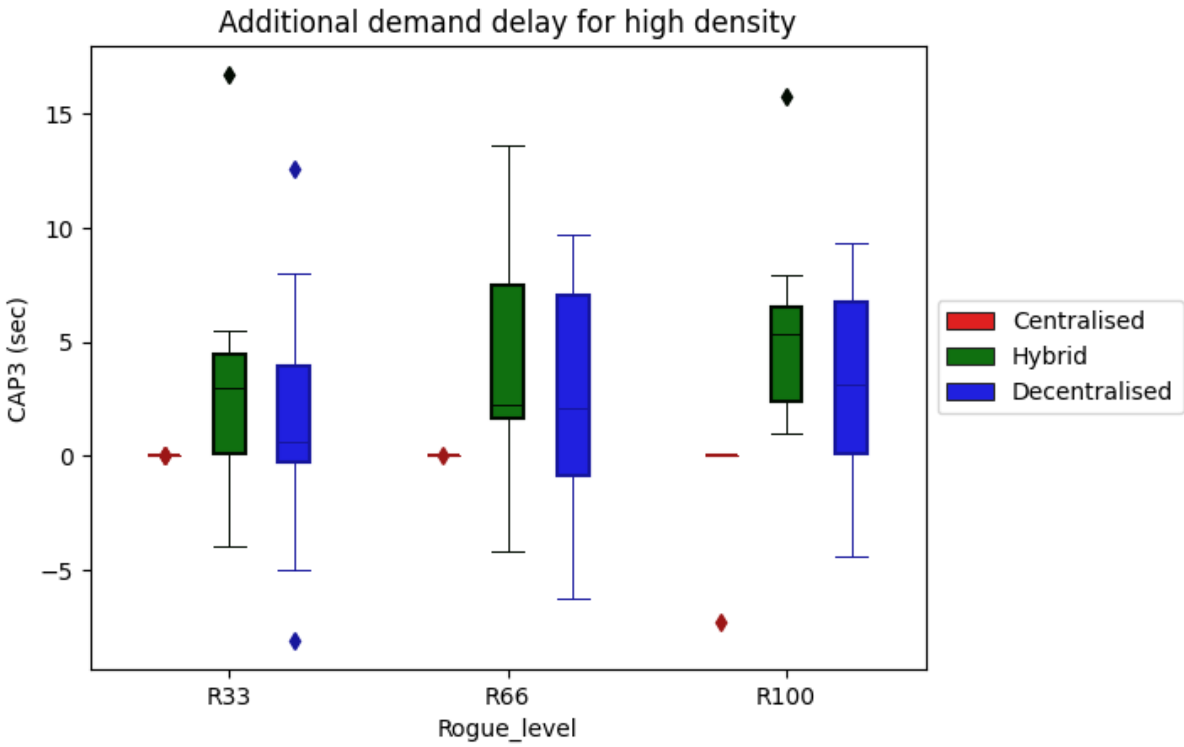

Figure 37: Additional demand delay for high traffic density as function of rogue aircraft level.

3.4.1.2 CAP4: Additional number of intrusions

Similarly, the CAP4 metric is computed as an increase of the number of intrusions (CAP2 for nominal scenario) with the introduction of rogue aircraft. It represents an indicator of the capacity resilience.

Figure 38 shows the additional number of intrusions for high traffic density as a function of rogue aircraft level. Once again, we notice that on average the additional number of intrusions increases linearly with the increase of number of rogue aircraft for all concepts (although linear increase could be hardly extrapolated for higher level of rogue aircraft). As a difference from CAP3, the gradient of increase for the hybrid concept is lowest compared to the two other concepts, which have a similar gradient. Furthermore, the centralised concept yields more additional intrusions than the other concepts at all rogue levels. This can be explained by the lack of a tactical separation management component in this concept.

Similar results are noticeable for other traffic densities, with the hybrid concept having in general better performance than the other concepts.

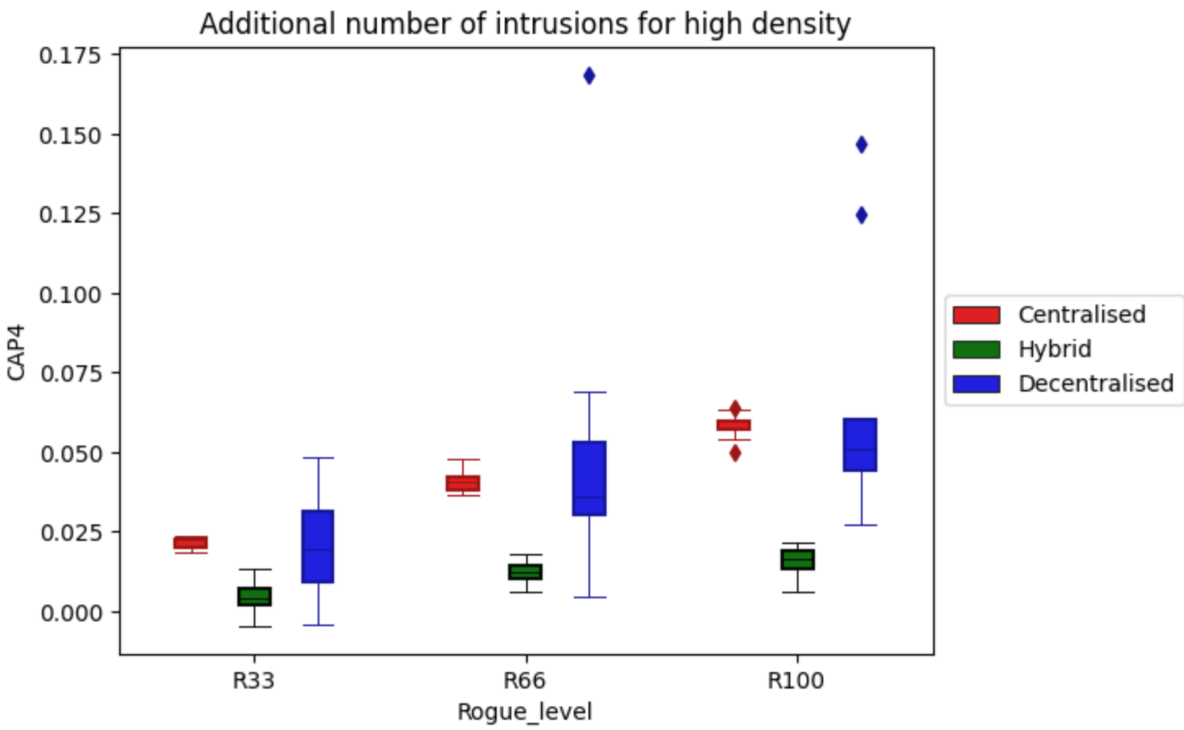

Figure 38: Additional number of intrusions for high traffic density as function of rogue aircraft level.

3.4.2 Safety

Rogue aircraft do make a difference in the safety metrics. This is most pronounced at high and very high traffic densities. This section will show the number of conflicts (SAF1), the number of intrusions (SAF2) and the number of severe intrusions (SAF3) as a function of the number of rogue aircraft in the air.

3.4.2.1 SAF1: Total number of conflicts

A conflict is counted when the state-based conflict detection predicts an intrusion with a certain lookahead time. Figure 39 shows the total number of conflicts for high density in the horizontal axis and the number of rogue aircraft in the horizontal axis. As expected, the number of conflicts increases when rogue aircraft are added to the simulation. In all concepts the difference is not so pronounced and is greatest only when going from no uncertainty to a rogue level. For example, the maximum number of conflicts for a centralised scenario was about 5.300. This value is always higher than the minimum value for the uncertain scenarios. However, the mean value does increase by about 200 conflicts for each rogue level. This can be explained by the fact that the centralised concept does not perform any tactical resolution, so any conflicts created by rogue aircraft do not create knock-on conflicts.

For the hybrid concept there is more of a noticeable change when increasing the number of rogue aircraft. The maximum number of conflicts when there are no uncertainties is about 6.700 conflicts which is lower than the minimum for R66 and R100. This could be because the hybrid concept performs tactical resolution when it encounters a rogue aircraft which in turn create knock-on conflicts.

In the decentralised concept the difference is also not so pronounced but there is a slight trend upward. Due to the high density and the large number of conflicts adding 100 more aircraft does not significantly increase the number of conflicts. This shows that all the concepts are relatively robust against rogue aircraft in terms of number of conflicts.

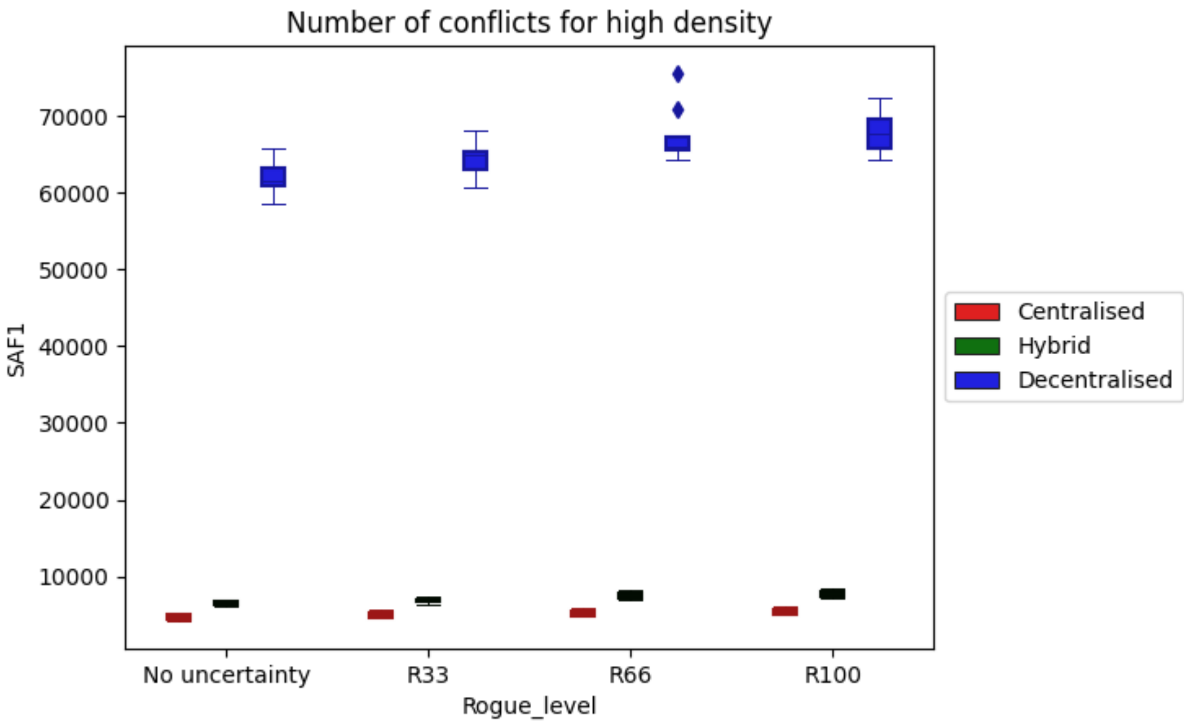

Figure 39: Number of conflicts

3.4.2.2 SAF 2: Number of intrusions

An intrusion is counted when an aircraft enters the protected zone of another aircraft, it is a horizontal distance of 32 metres and a vertical distance of 25 feet from the aircraft. Figure 40 shows the number of intrusions for high density in the vertical axis and the rogue level in the horizontal axis for the different concepts. Here, the effect of rogue aircraft is clearer than for the conflict metric. For the centralised and decentralised concepts, the number of rogue aircraft increases the number of intrusions. It is the same for the hybrid concept but to a lesser extent. The hybrid concept is more resilient to rogue aircraft because it avoids constrained airspace, so it has more space for resolving conflicts in open airspace. It is important to note that about half of the path of rogue aircraft was inside constrained airspace.

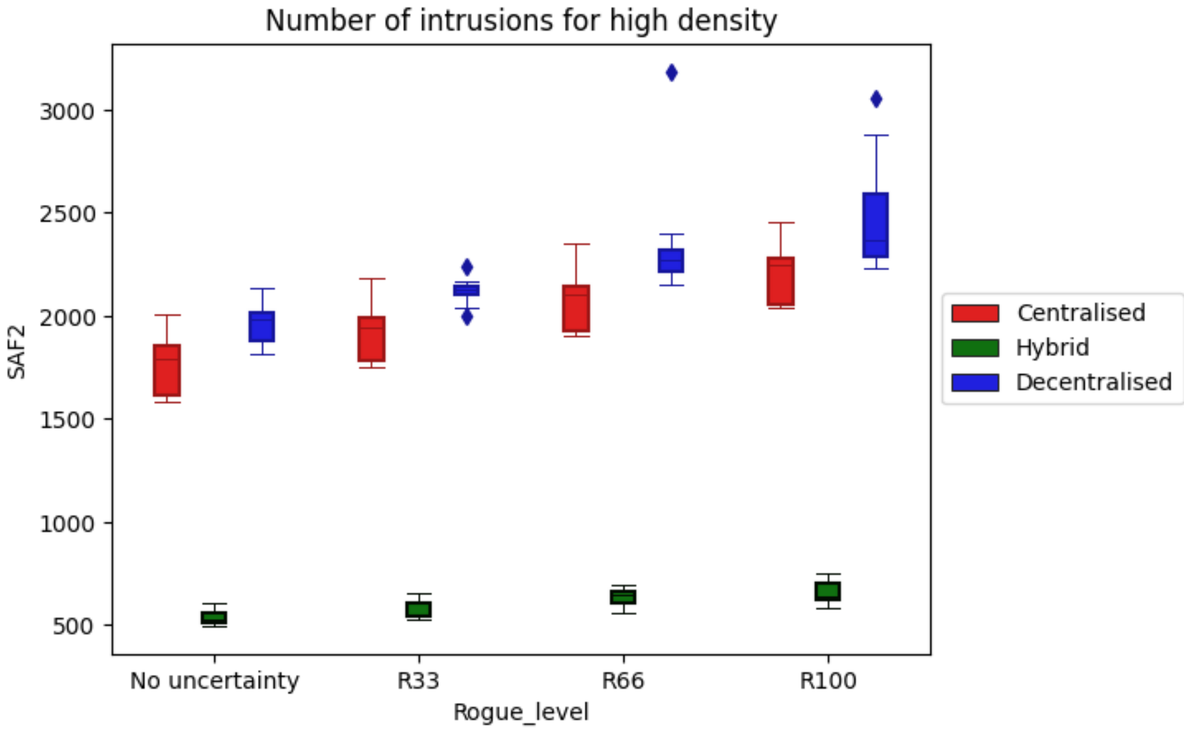

Figure 40: Number of intrusions for high density

3.4.2.3 SAF 2.1: Number of severe intrusions

A severe intrusion is one that would have likely resulted in a collision and is based on the dimensions of the DJI Matrice 600 [4]. Figure 41 shows the number of severe intrusions for the high-density scenarios on the vertical axis and the rogue level on the horizontal axis. The severe intrusions have a larger effect on the centralised concept because they do not perform tactical conflict resolution. For the decentralised concept there is a slight difference between the higher rogues (R66 and R100) and the lower rogues (no uncertainty, R33). The hybrid concept remains resilient to rogue aircraft and maintains the lowest number of severe intrusions. This is explained by the fact that the hybrid concept spreads traffic more evenly in the strategic phase as compared to the decentralised concept and it can perform tactical resolution so that it can solve any conflicts not predicted by a centralised entity.

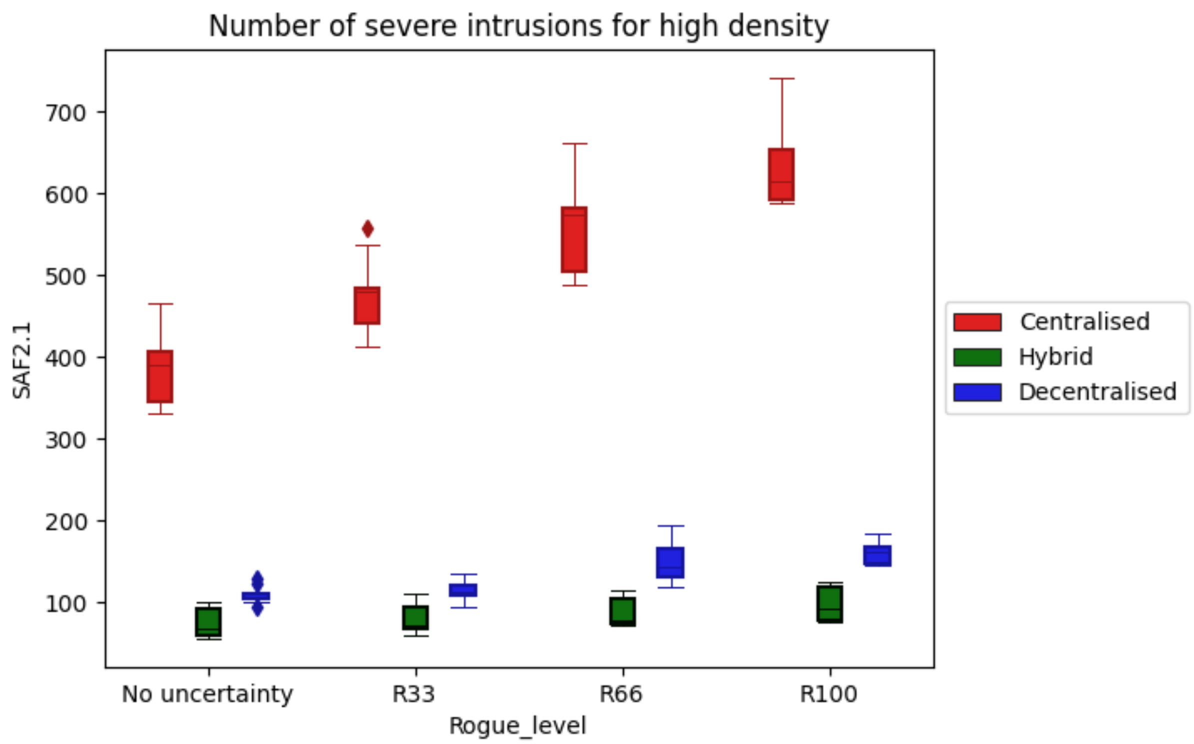

Figure 41: Number of severe intrusions for high density

3.5 Effect of wind of metrics

The following section presents the effect of the presence of wind on the metrics. The metrics presented in this section are the ones where changes were observed. For other metrics, no significant differences were found.

3.5.1 Access and equity

The effect of wind on the access and equity performance area is through reduced ground speeds, which translates into demand arrival delay.

3.5.1.1 AEQ2

The wind effect on the AEQ2 metric is shown in Figure 42 representing the distribution of the number of inoperative trajectories for high traffic density as function of wind level. This figure shows that the number of inoperative trajectories increases on average with an increase of the disruptive wind level, as the effect of increased arrival delay. This is noticeable for all concepts.

The negative effect of wind can be alleviated, if the centralized strategic component of the separation management, based on flight reporting, tries to learn the wind and exploit it in the flight planning phase (like it is done in ATM). However, in this project, neither the centralised nor the hybrid concept considered this. Note, also, that this would be a difficult task, as hyper-local wind effects would need to be taken into account, which are difficult to predict.

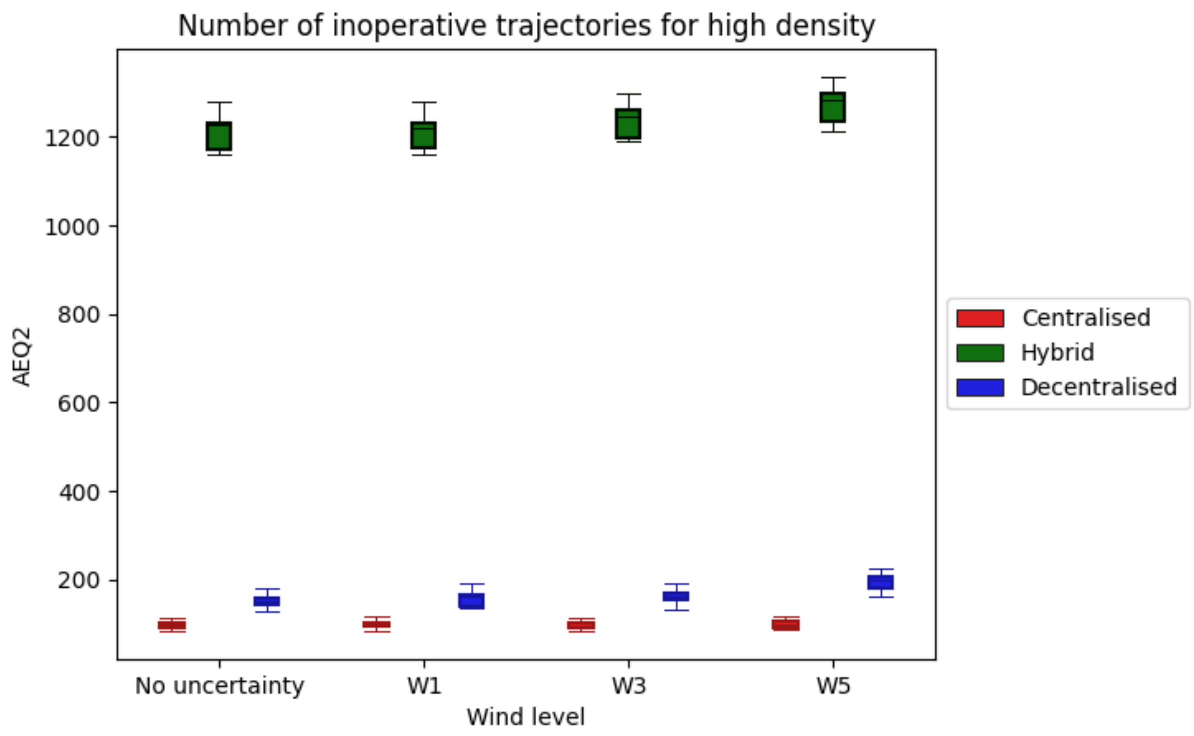

Figure 42: Number of inoperative trajectories for high traffic density as function of wind level.

3.5.2 Safety

This section will show the effects of wind on the safety metrics. It was mostly seen that the wind speeds were not large enough to have a severe effect on safety. However, there were some noticeable effects in the number of conflicts (SAF1) and the number of intrusions (SAF2).

3.5.2.1 SAF 1

A conflict is counted when there is a predicted intrusion within a lookahead time. Figure 43 shows the number of conflicts for high density scenarios on the vertical axis and the wind level on the horizontal axis. For the centralised concept increasing the wind level does not greatly affect the number of conflicts. The statistics are very similar when comparing W1 to no uncertainties. Starting from W1 to W5 there is an increase of about 100 conflicts per wind level. The centralised concept attempts to counteract the effects of the wind to ensure that it reaches waypoints at the predicted time. A wind level of 1 knots does not vary the speed greatly, so the aircraft is able to make up the difference. However, for the case of 3 and 5 knots, it is harder to counteract so there are slightly more conflicts.

They hybrid concept is affected slightly more by wind than the centralised concept as its mean value increased by 1000 conflicts when comparing no uncertainties with W5. Moreover, the decentralised concept is also affected slightly. However, because there are so many conflicts it increases the mean value by 5% when comparing no uncertainties to W5. However, the spread of the conflicts does not vary greatly with decentralised. The reason that these two concepts are slightly less resilient to wind is because they rely mostly on speed-based conflict resolution.

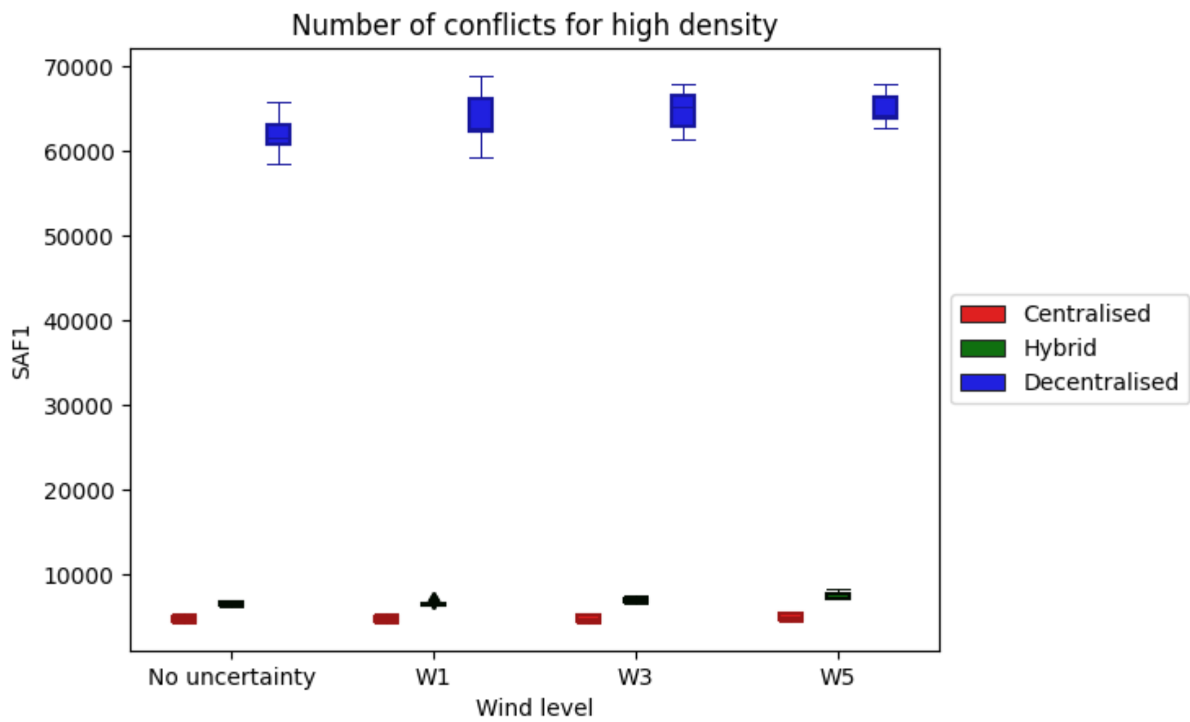

Figure 43: Number of conflicts for high density

3.5.2.2 SAF 2

An intrusion is counted when an aircraft violate the protected zone of another aircraft. Figure 44 shows the number of intrusions on the vertical axis and the wind level on the horizontal axis. The trends in this figure are similar to those in Figure 43, as the centralised concept is not impacted and the hybrid and decentralised concepts show some increase in the number of intrusions with increasing wind level.

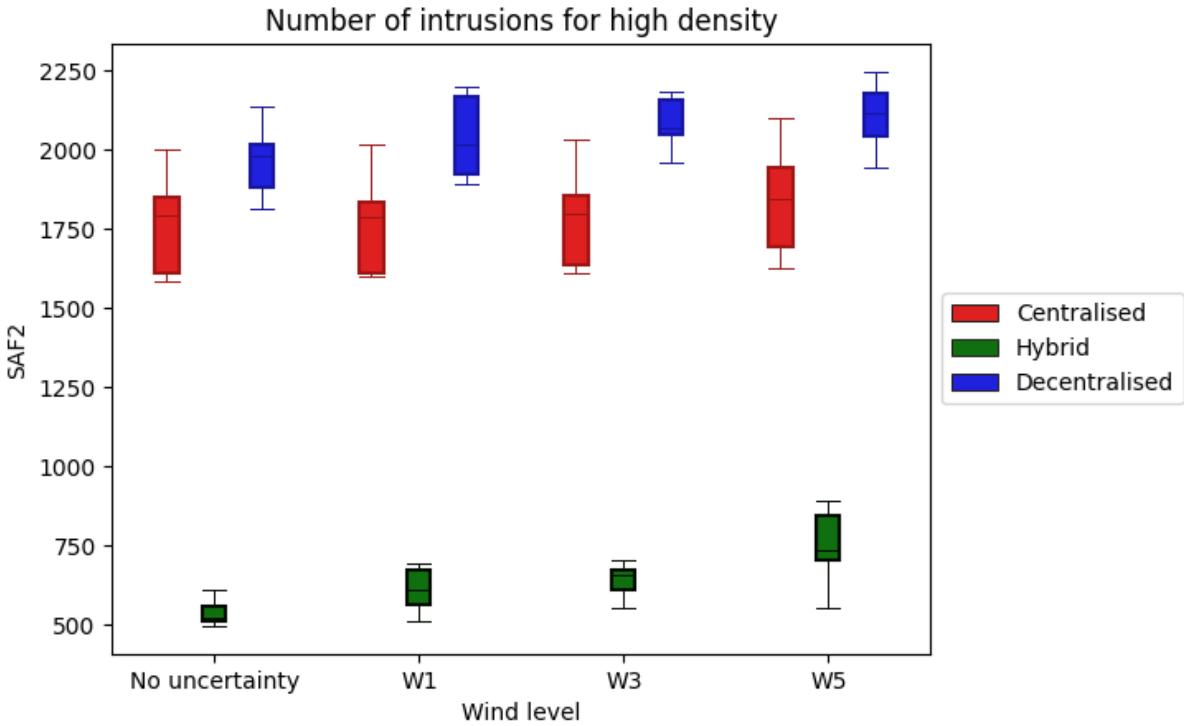

Figure 44: Number of intrusions for high density

3.6 Conflicts and loss of separation probability analysis

The following section presents the analysis made to determine the probability of a conflict or loss of separation occurring in function of traffic density for the three concepts. The analysis method is described by Sunil et al. [8], and describes that the number of instantaneous conflicts is a function of the number of aircraft currently flying and the conflict probability between any two aircraft, as shown in the following equation:

$$N_{conf} = \frac{N_{ac}(N_{ac}-1)}{2} p_{conf}.$$

This can be extended to the concept of losses of separation as a more objective way of measuring airspace safety, as conflicts are not representative of airspace safety (e.g., within the decentralised concept, conflicts have a communicative role in maintaining the safety of the airspace). However, as loss of separation events occur less frequently than conflicts, instead of using instantaneous intrusions, the intrusions over periods of 30 seconds were used, leading to the following equation:

$$N_{LOS\_30} = \frac{N_{ac}(N_{ac}-1)}{2} p_{LOS\_30}.$$

3.6.1 Instantaneous conflicts analysis

The figure below shows the results of the analysis performed on the number of instantaneous conflicts, with the number of concurrent aircraft in the airspace on the horizontal axis, and the number of observed instantaneous conflicts on the vertical axis. The figure shows the effect of strategic deconfliction, as most conflicts are predicted in advance and corrected for in case of the hybrid and the centralised concepts. The decentralised concept however has a reactive approach to conflict solving, and thus experiences a significantly higher conflict probability. The computed probability values are presented in the table below.

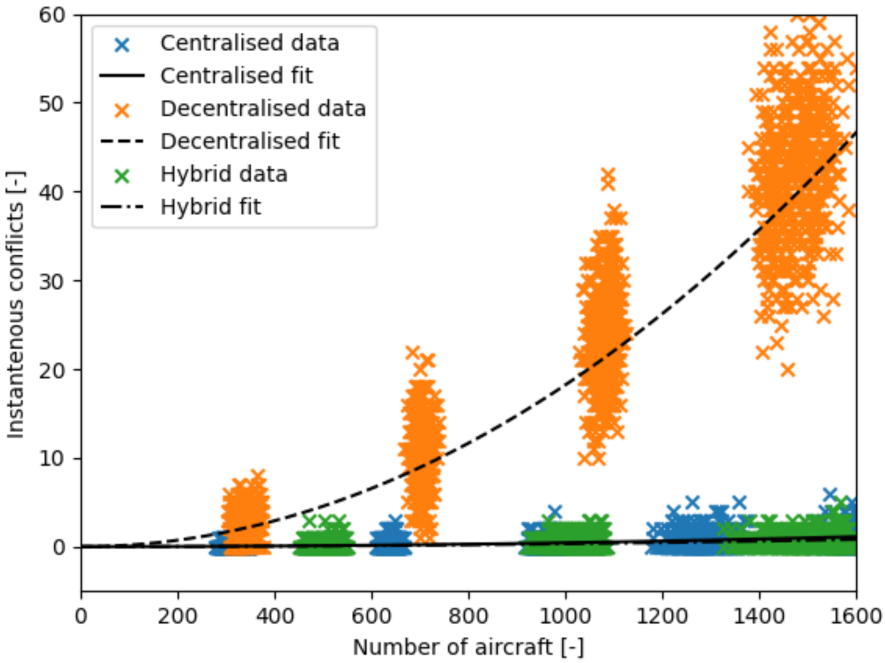

Figure 45 Number of instantaneous conflicts in function of number of aircraft for the three concepts.

Table 2: The probability that an aircraft pair experiences a conflict.

	Centralised concept	Hybrid concept	Decentralised concept
Conflict probability	8.745e-07	6.402e-07	3.644e-05

3.6.2 Loss of separation analysis

The previously described analysis method was also applied to loss of separation events. Separate graphs were made based on the location in which the losses of separation occurred: in open or constrained airspace. The figure below presents the results of the analysis in open airspace. On the horizontal axis is again the number of concurrent aircraft in the (open) airspace. On the vertical axis is the number of instantaneous losses of separation (within a 30-second time window). The differences between the concepts can be explained by the varied choices that were made regarding open airspace navigation and structure.

The centralised concept has the highest probability for a loss of separation, as the hexagonal structure implies that the airspace is composed of many 3-way intersections which are known to create merging and diverging conflicts. Furthermore, the structure necessitates a lot of turn manoeuvres when navigating, which adds to the prediction uncertainty of the strategic algorithm.

The decentralised concept performed better than the centralised concept. However, due to the presence of preferred corridors by aircraft and the lack of flight pre-planning, high-density hotspots resulted in a relatively high number of loss of separation events occurring, which is reflected in the results.

The hybrid concept performed best in terms of the probability of a loss of separation occurring within open airspace. It should be noted that this can for a large part be attributed to the high degree of alignment applied by the hybrid concept in open airspace: All aircraft predominantly flew in directed concentric rings (similar to beltways around cities). As a consequence, aircraft that are close together are near completely aligned (flying in the same direction at the same speed). This leads to a low conflict probability, at the cost of relatively large detours for these flights.

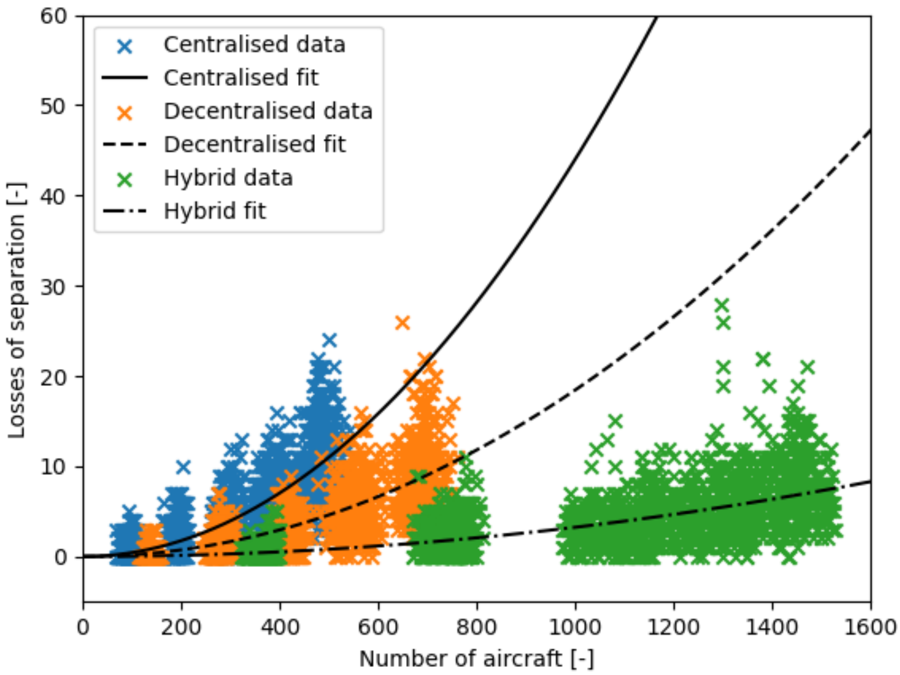

Figure 46 Losses of separation over a 30 second interval in function of number of aircraft for open airspace.

For constrained airspace, the differences between the concepts are not as clear as in open airspace. As all concepts had approximately the same structure within this type of airspace (imposed by the street network), the loss of separation probability was mostly determined by the separation method: strategic, tactical, or a combination of the two.

The results in the figure and table below show that all concepts perform relatively similarly in terms of the probability of loss of separation events, with the hybrid concept outperforming the centralised and decentralised concepts. However, it is interesting to point out that the latter two performed very close to each other, which implies that tactical and strategic separation perform similarly when only one is used. Note that the traffic counts for the hybrid results do not reach as high as the other two concepts. This is caused by the strategy of this concept to lead a large portion of the traffic around the constrained airspace instead of through it.

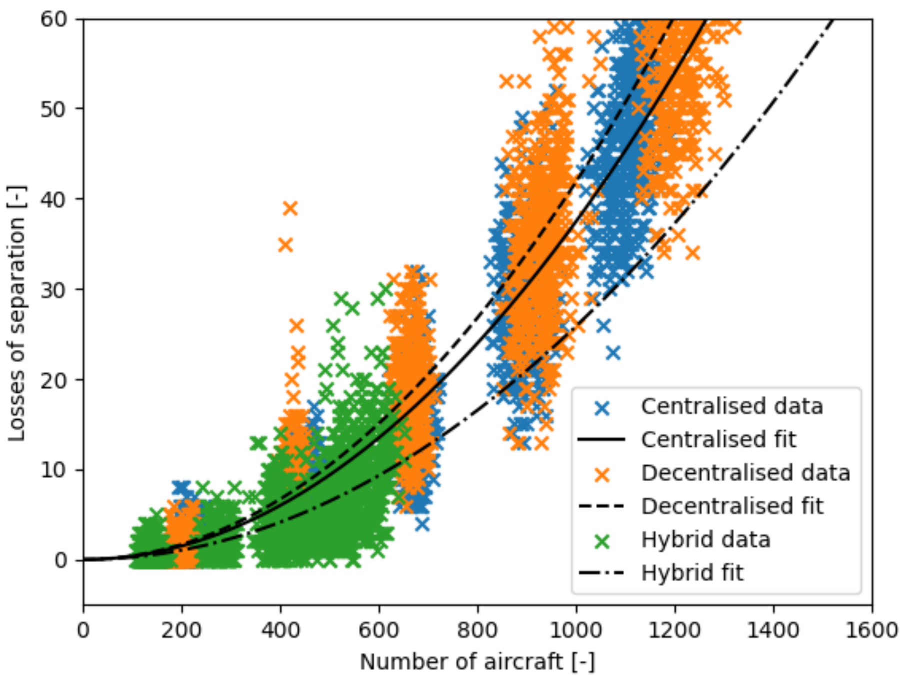

Figure 47 Losses of separation over a 30 second interval in function of number of aircraft for constrained airspace.

Table 3: The probability that an aircraft pair experiences a loss of separation for constrained and open airspace.

	Centralised concept	Hybrid concept	Decentralised concept
Constrained airspace	7.492e-05	5.173e-05	8.371e-05
Open airspace	8.800e-05	6.481e-06	3.689e-05

3.7 Hybrid concept weightless path-planning

The strategic planning of the hybrid concept favoured routes though open airspace even when it increased the path length. This was implemented by applying a weighting factor in the routing that decreased with the distance from the centre of the simulation area. Because this aspect of planning had a large influence on many of the results, it obscures the actual comparison between separation management concepts (from centralised to decentralised). Therefore, a reduced set of supplementary simulations were performed, to make the routing more comparable to the centralised and decentralised concepts. The hybrid airspace was designed as a large 3D graph with nodes and edges. For the supplementary study, the weighting factor related to the distance from constrained airspace was removed and all paths were treated the same by the planning algorithm. This was only done for the very low and low densities for the 40 percent traffic mix. Moreover, only three repetitions per density were simulated. In the following sections, only the metrics that showed difference between the special hybrid (no weights) and the nominal hybrid will be shown.

3.7.1 Access and Equity

Figure 48 shows the number of cancelled demands for the 40 percent traffic mix for the special and the nominal hybrid concept in the vertical axis. The horizontal axis contains the very low and low densities. The special hybrid concept was able to reduce the number of cancelled demands in the very low and low densities as compared to the nominal hybrid. However, it is still larger than both the centralised and decentralised concepts (section 3.2.1.1) for both the very low and low densities, the number of cancelled demands averages under 30 for these concepts in the very low and low densities. This shows that, as expected, the strategic planning of the hybrid concept still has a limiting effect on accessibility.

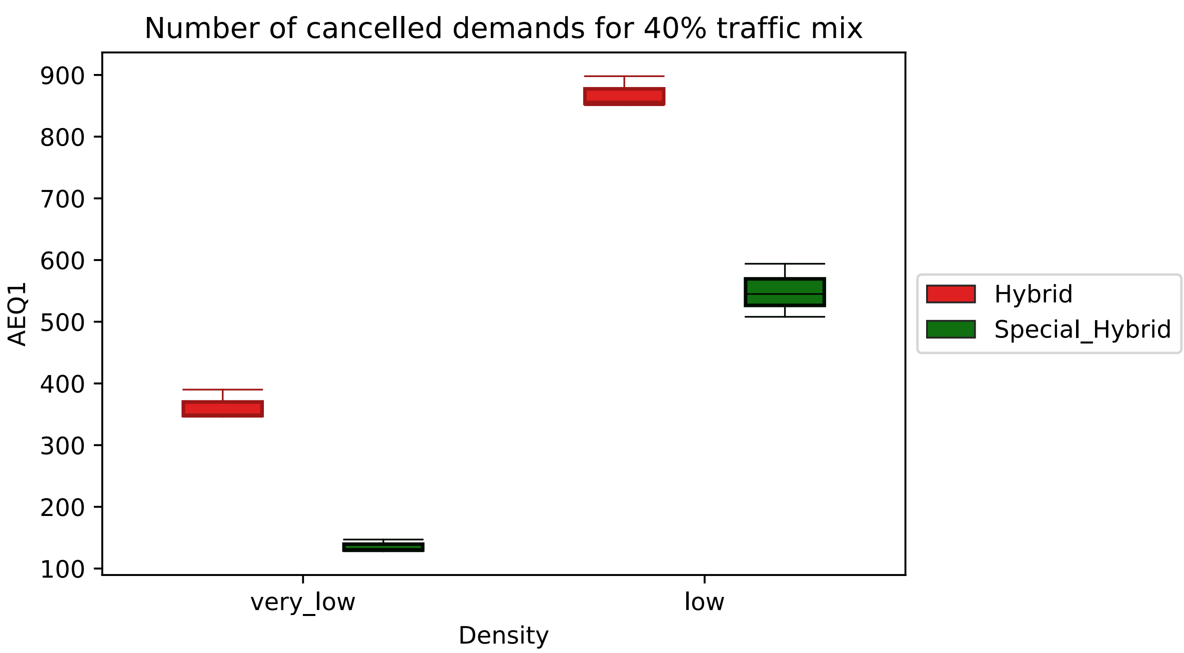

Figure 48: Number of cancelled demands for 40% traffic mix.

3.7.2 Capacity

Figure 49 shows the average demand delay for the 40 percent traffic mix of both hybrid concepts in the vertical axis and the very low and low density in the horizontal axis. This figure shows a similar trend as what was seen in section 3.7.1. The special hybrid concept is able to improve from the nominal case but it still is not able to match the centralised or the decentralised concept in the lower densities which suggests that the planning algorithm may struggle at the higher densities.

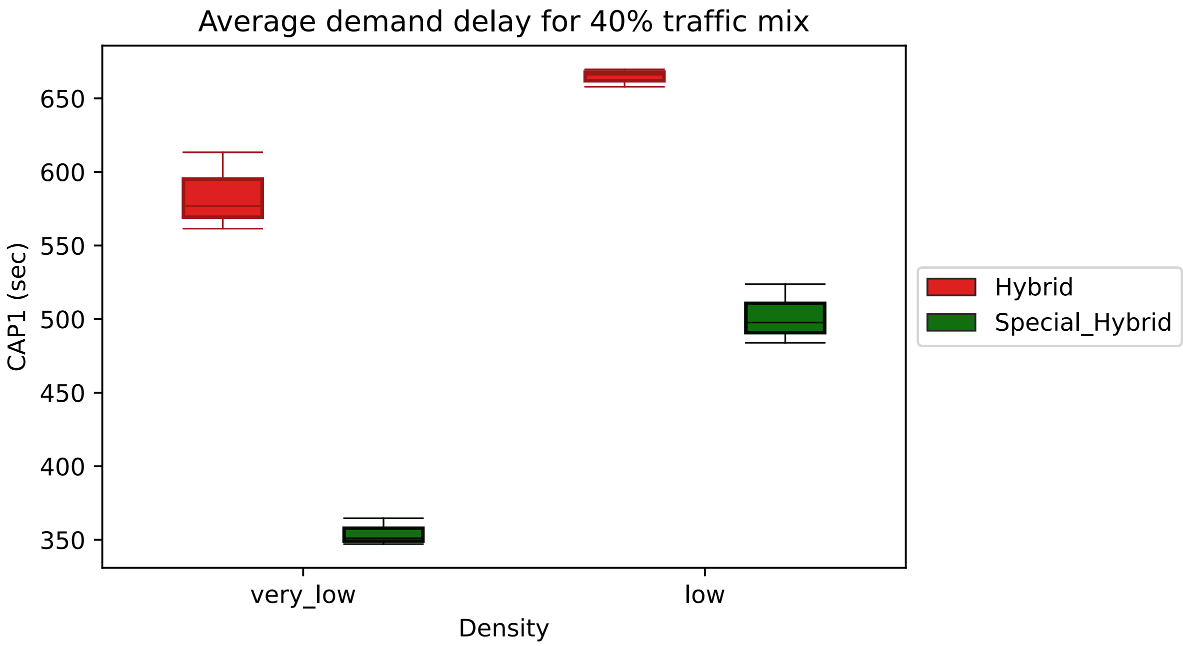

Figure 49: Average demand delay for 40% traffic mix.

Figure 50 shows the instantaneous traffic count in the special and nominal hybrid concept. The special hybrid density increases constrained airspace density when compared to the nominal concept. It also manages to be more comparable to the decentralised and centralised concepts that also have a maximum number of aircraft above 400 at the peak.

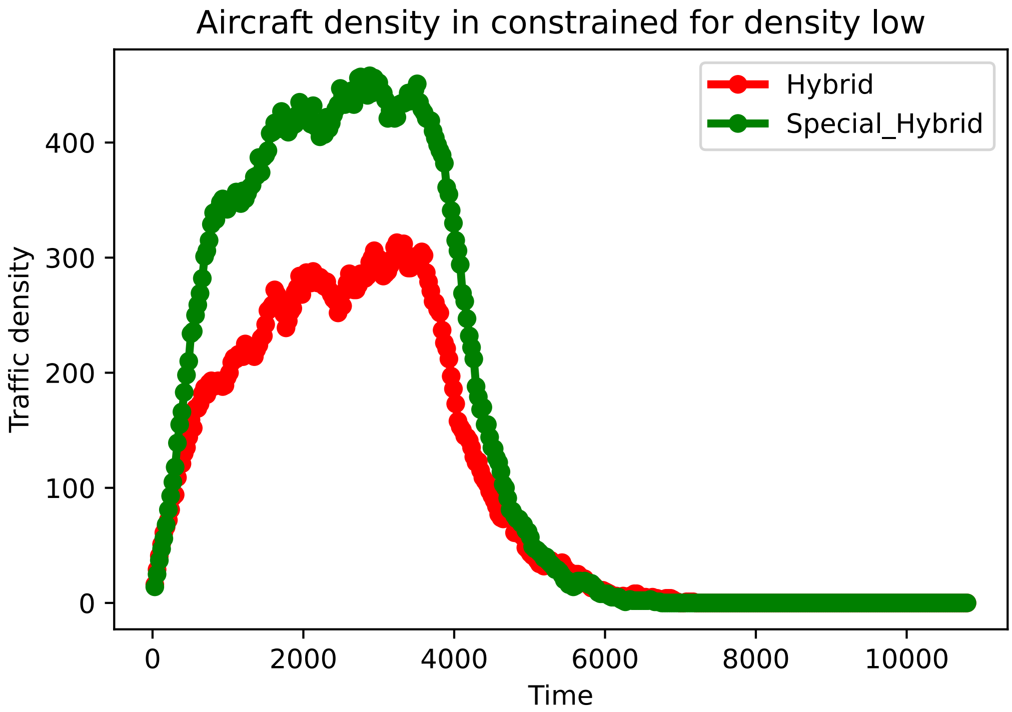

Figure 50: Aircraft count for hybrid concepts in low density scenarios.

3.7.3 Efficiency

Figure 51 shows the horizontal distance route efficiency for the 40 percent traffic mix in the vertical axis and the density in the horizontal axis. The figure shows that the special hybrid can route aircraft more efficiently. This is because the strategic planning no longer penalizes routes through constrained airspace. However, Figure 13 shows that the route efficiency for the other concepts remains relatively constant around 71 percent for centralised and 76 percent for decentralised. The special hybrid concept appears to decrease with increasing density which shows that the strategic planning may not have been efficient in the higher densities.

This can also be seen in Figure 52 which shows the departure delay in the vertical axis and the density in the horizontal axis. In this figure, the departure delay time increases for the special hybrid concept. This shows that the strategic planning of this concept will have likely increased delays at the higher densities.

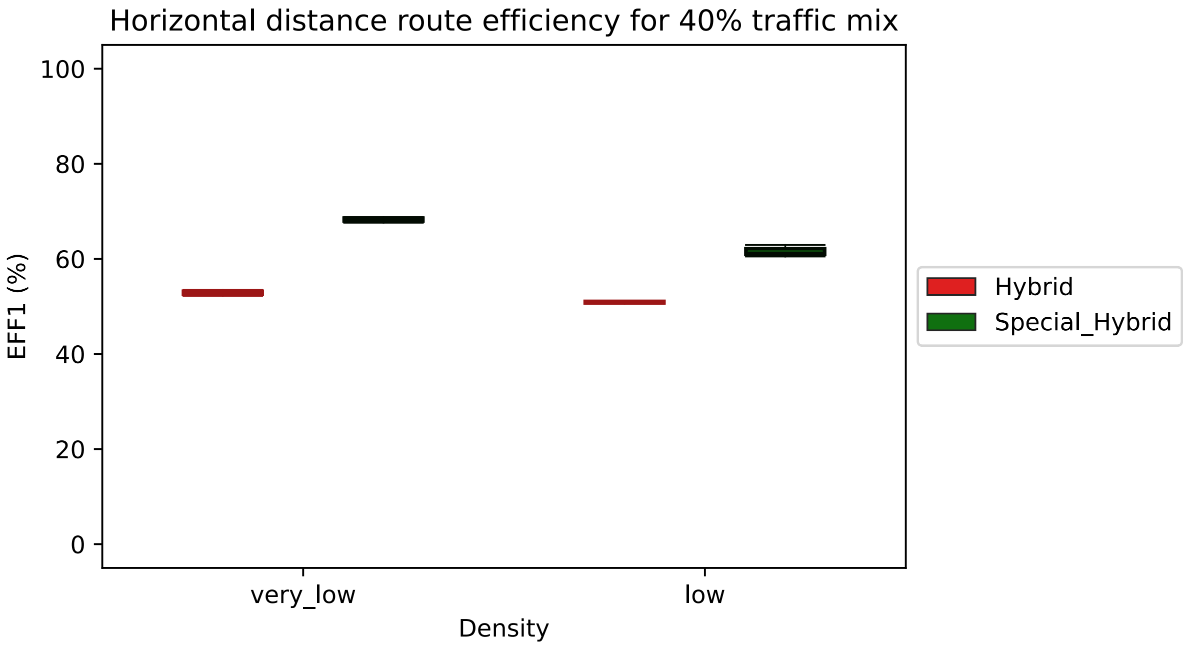

Figure 51: Horizontal distance route efficiency for 40% traffic mix

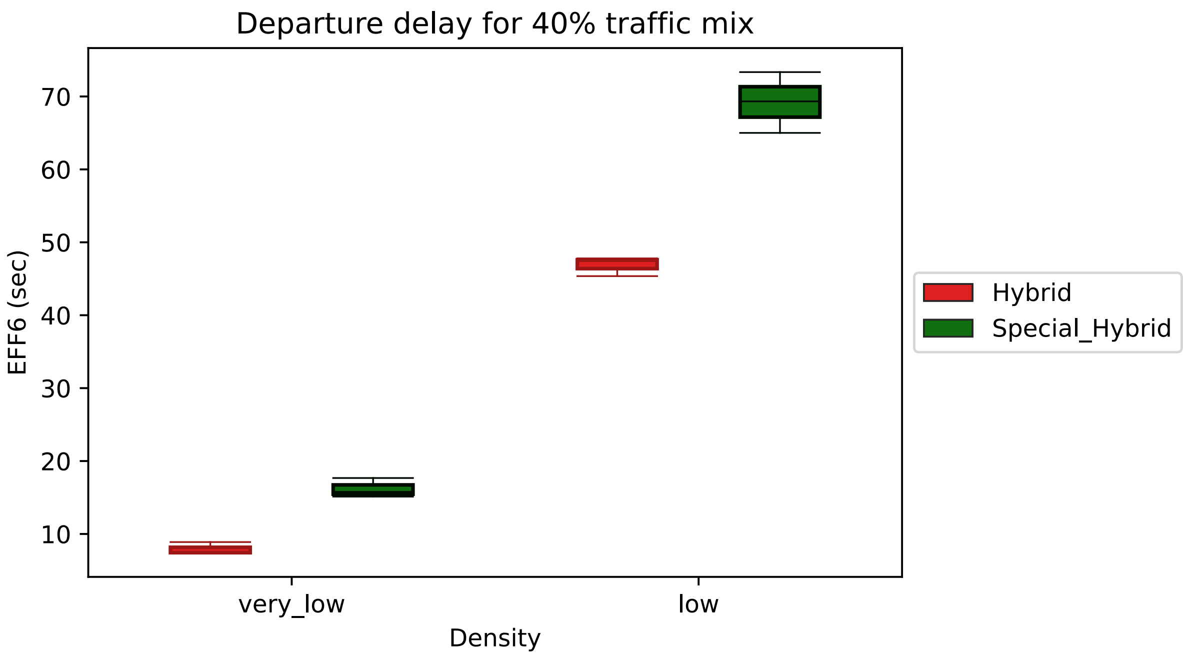

Figure 52: Departure delay for 40% traffic mix.

3.7.4 Safety

Figure 53, Figure 54, Figure 55 show the number of conflicts in total, constrained, and open airspace, respectively, in the vertical axis and the density in the horizontal axis. Figure 53 shows that the special hybrid concept has less conflicts than the nominal hybrid concept in the very low densities. However, in the low densities the average number of conflicts is larger in the special hybrid concept. This suggests that more data is necessary to ascertain the effect of the traffic density on total number of conflicts.

However, there are some clear differences when looking at the conflicts in constrained and open airspace. Because there was more traffic in constrained airspace, the number of conflicts is higher for the special hybrid in both densities. Conversely, because there was less traffic in open airspace in the special hybrid, the number of conflicts is lower for both densities. This same effect is seen in the number of intrusions (Figure 56, Figure 57, and Figure 58).

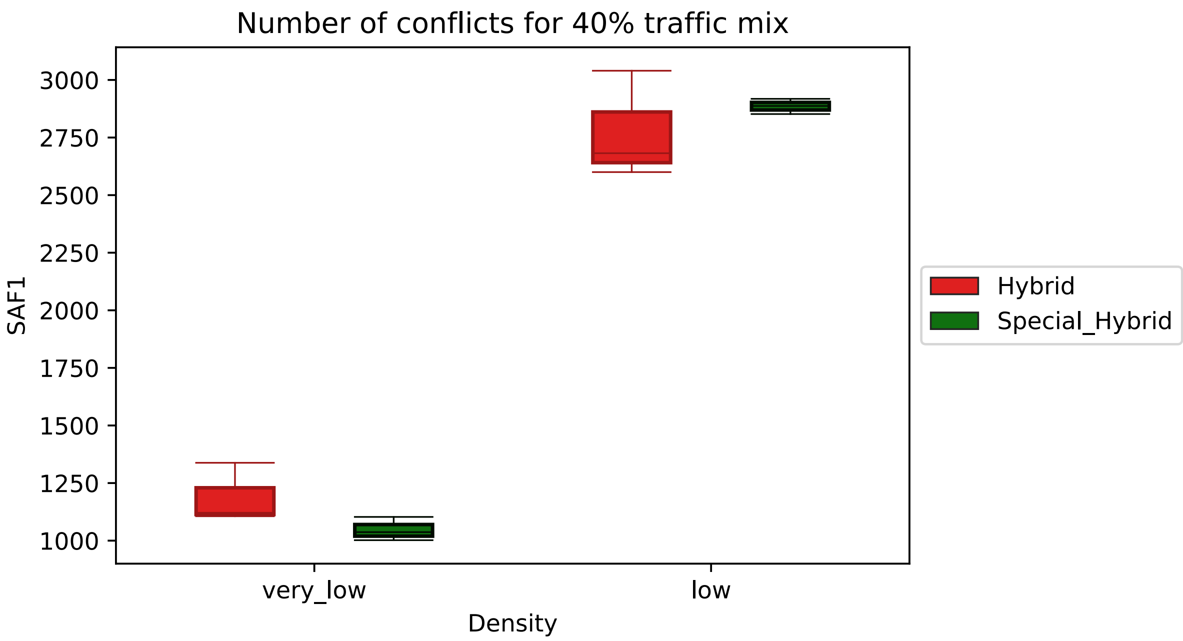

Figure 53: Number of conflicts for 40% traffic mix.

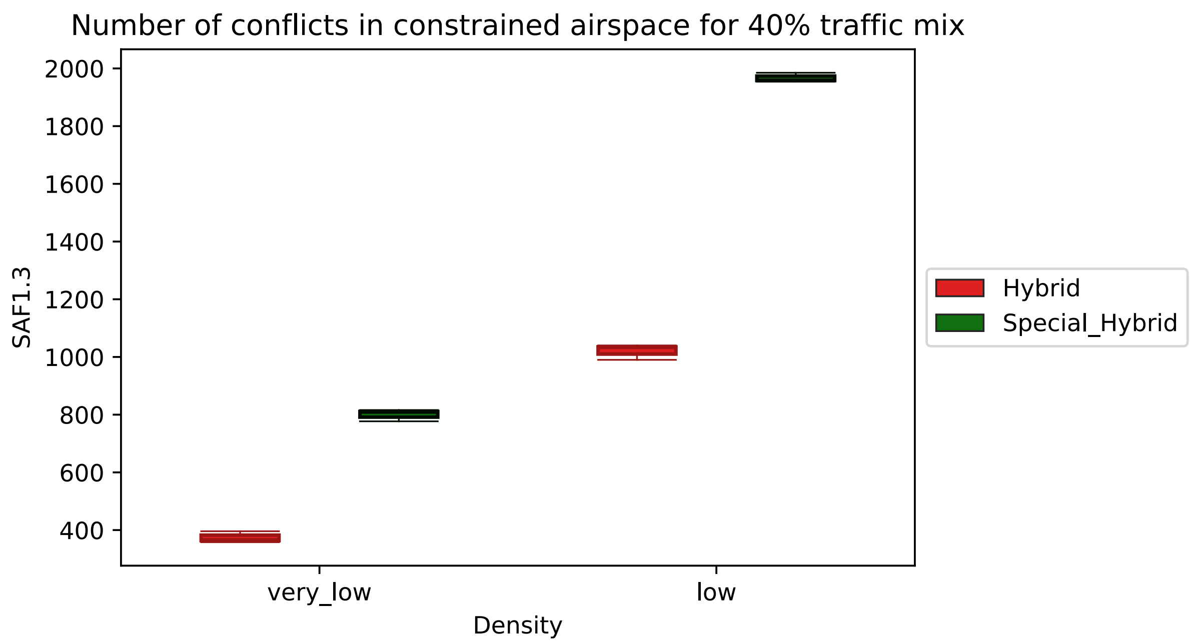

Figure 54: Number of conflicts in constrained airspace for the 40% traffic mix.

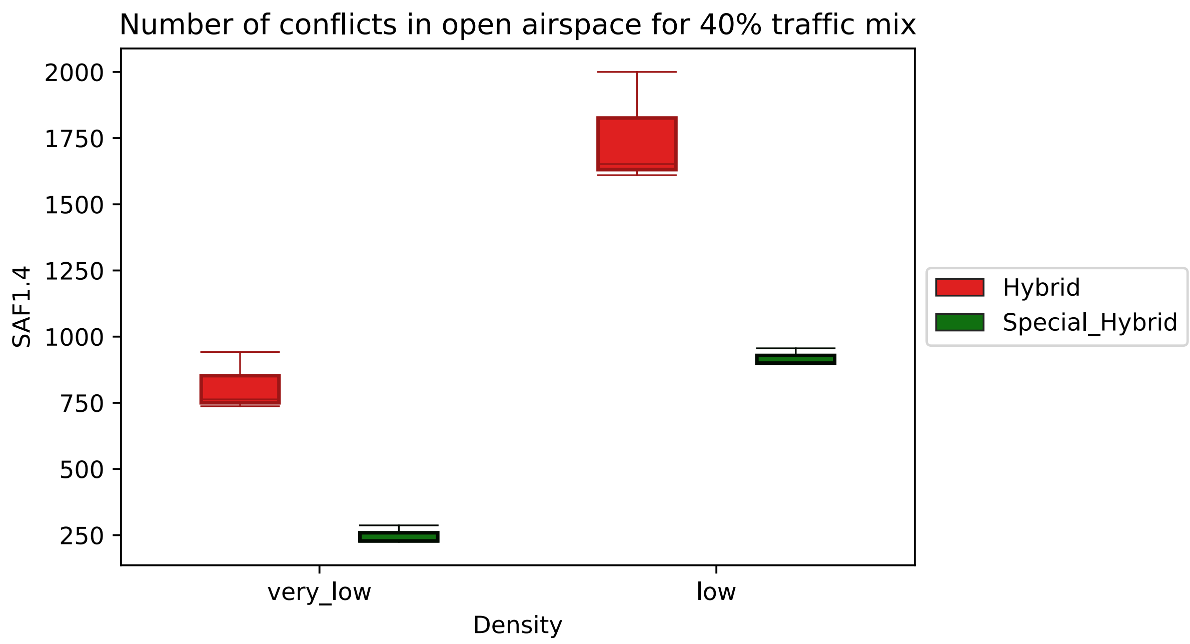

Figure 55: Number of conflicts in open airspace for the 40% traffic mix.

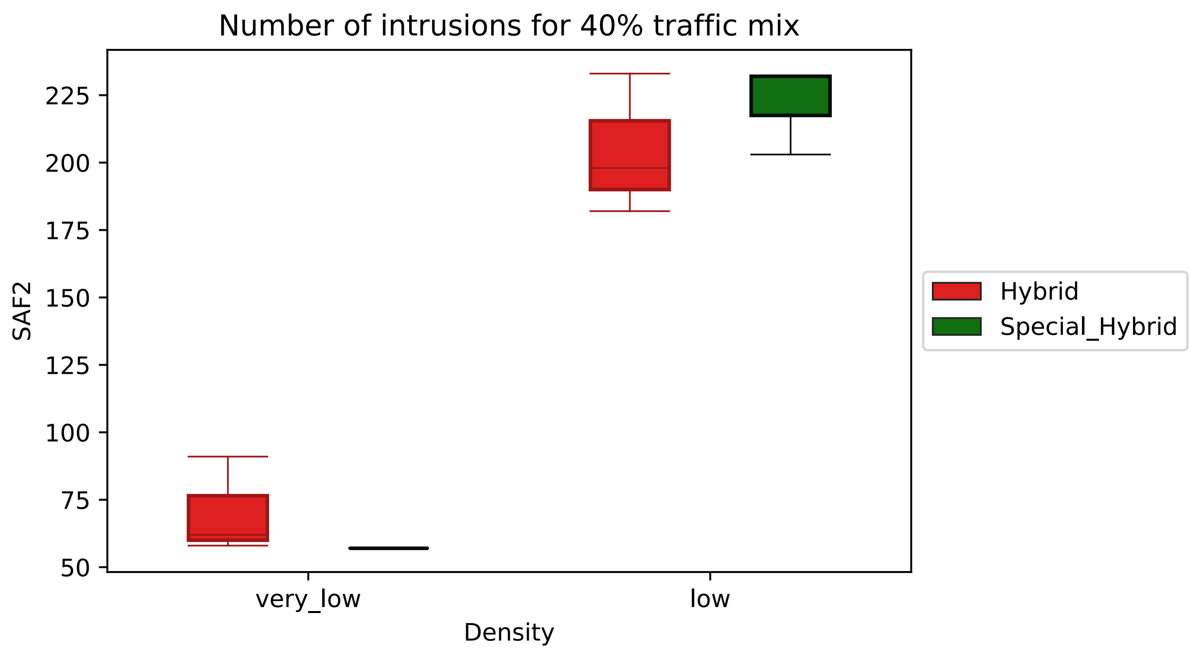

Figure 56: Number of intrusions for 40% traffic mix.

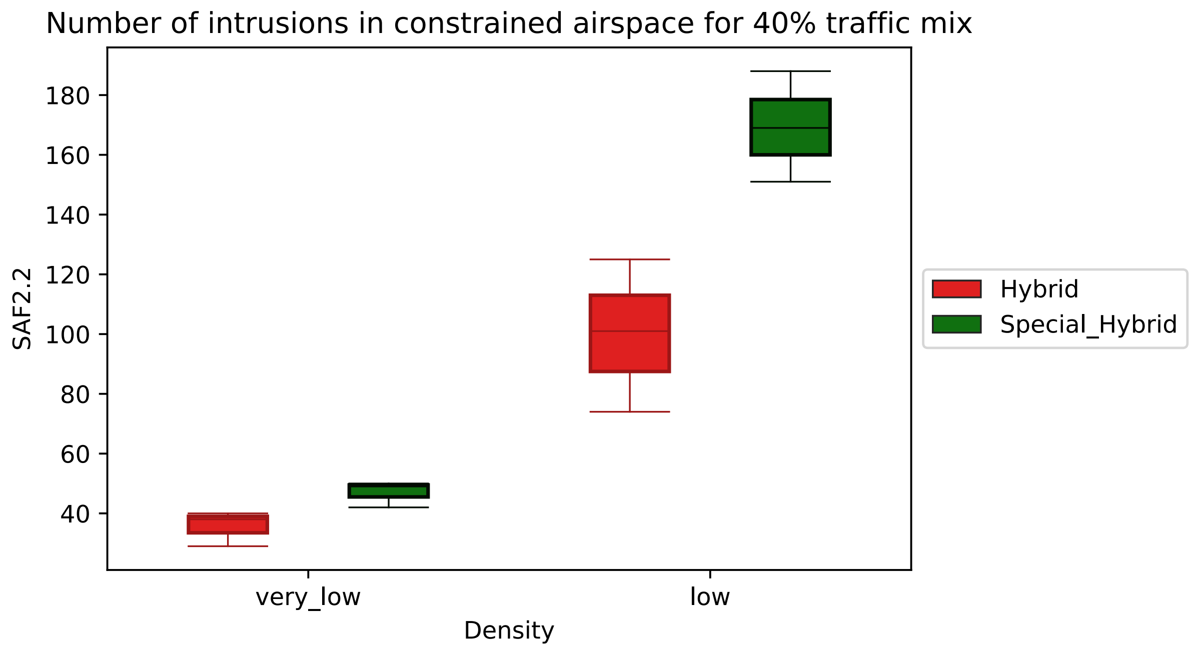

Figure 57: Number of intrusions in constrained airspace for 40% traffic mix.

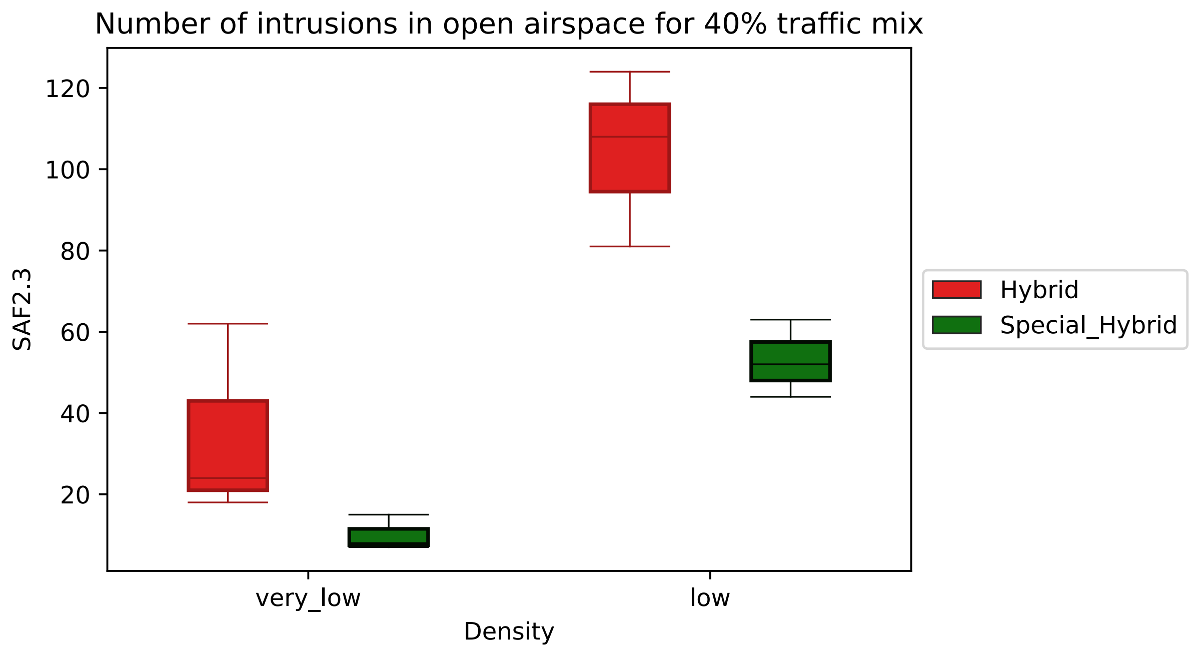

Figure 58: Number of intrusions in open airspace for 40% traffic mix.

3.8 Summary of KPI comparisons

The table below summarises the relative ranking of the three concepts in all metrics discussed in this chapter. It shows the highest performer, the 2nd highest and the lowest performer for each metric (in case of a tie, the two concepts' colours interleave); see Appendix C for the detailed results. Based on the presented results there is no clear indication of a concept that performs significantly better than the others on the majority of the metrics. Therefore, a more detailed trade-off between different performance areas is needed, see Chapter **Error! Reference source not found.**.

Table 4: Result summary.

Metric	Highest		Lowest
AEQ1	D	C	H
AEQ1.1	D	C	H
AEQ2	C	D	H
AEQ2.1	C	D	H
AEQ3	D	H	C
AEQ4	D	H	C
AEQ5	C	D	H

AEQ5.1	C	D	H
CAP1	C D C D	C D C D	H
CAP2	H	C D C D	C D C D
EFF1	D	C	H
EFF2	C	H	D
EFF3	C	H	D
EFF4	D	C	H
EFF5	C D C D	C D C D	H
EFF6	C	D	H
ENV1	C	D	H
ENV2	C D C D	C D C D	H
ENV3.2	H	C	D
ENV4	H	C	D
SAF1	C	H	D
SAF2	H	C D C D	C D C D
SAF2.1	D	H	C
SAF3	D	H	C
SAF4	D	C	H
SAF5	H	C	D
SAF6	D	H	C
SAF6.1	D	H	C
SAF6.2	H	D	C
SAF6.3	D	H	C
SAF6.4	D	H	C

SAF6.5	D	H	C
SAF6.6	H	C	D
SAF6.7	H	D	C
PRI1	C	D	H
PRI2	D	C	H
PRI3 priorities 1-4	C	D	H
PRI4 priorities 1-3	D	C	H
PRI4 priority 4	C	D	H
PRI5 priorities 1-4	C	D	H

4 Correlation analysis

Recall that the main research question put forward in Metropolis 2 project is: Who should be the separator? That is, what degree of centralization is (still) beneficial for safe and efficient traffic? The results of the simulation trials described above reveal that many metrics (primarily efficiency, safety, capacity, and equity) are affected not just by the differences between the concepts, but also by other choices that were made differently between the concepts, with which they primarily put a different weight on capacity and efficiency of the traffic flows. The results presented in Chapter 3 show that these design choices often overshadow the impact of the degree of centralisation on the metrics. These differences can be made more apparent by looking at combinations of metrics together. The following section will present a correlation analysis between some of the metrics (the full set for all metric pairs is available at [5]).

4.1 Concept implementation correlations

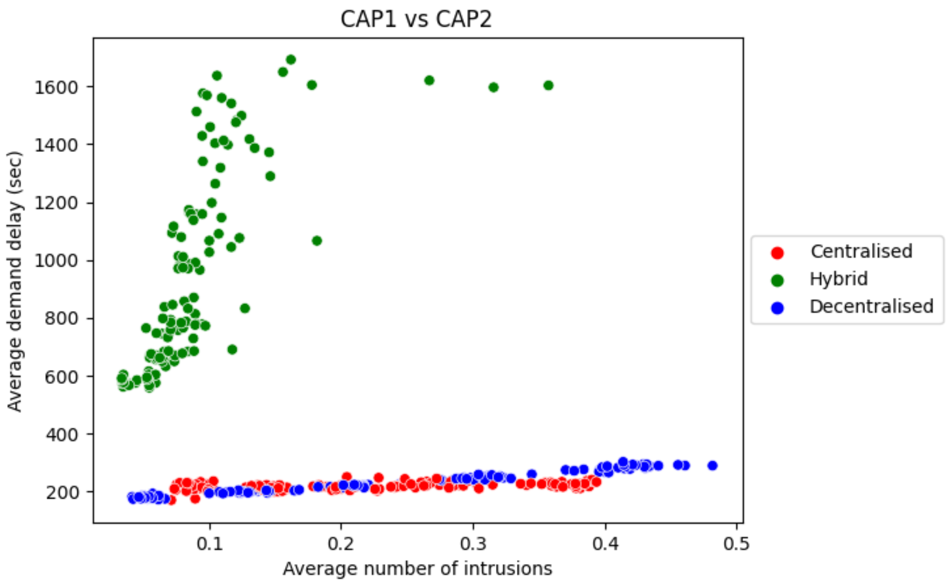

Figure 59: Trade-off between average demand delay and average number of intrusions per flight

From Figure 59 we can observe that the hybrid concept tends to demonstrate higher levels of safety (lower values of the average number of intrusions), however, it comes at the price of having much higher levels of demand delay. In fact, the hybrid system has a minimum demand delay of around 600 seconds; higher than either of the other concepts reach at any traffic density. This can be attributed to the routing paradigm employed by the hybrid system, which favours flying around the dense city centre. This invariably increases the demand delay, but lowers the number of intrusions. Nevertheless, it is worth mentioning that judging by the three outliers in the upper-right quadrant, the hybrid concept also encountered situations where it could not provide a guaranteed safety level. On the other hand, the centralized and decentralized concepts show much lower demand delays, but at the price of increased average number of intrusions that predominantly occur in the complex constrained airspace of the city centre.

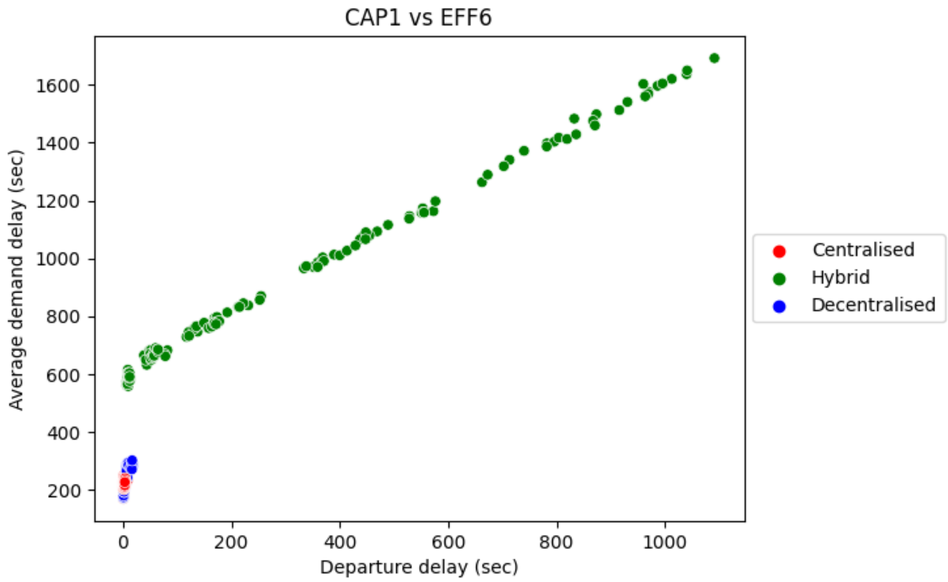

Figure 60: Trade-off between average demand delay and departure delay KPIs

Figure 60 shows how the average demand delay correlates with the departure delay in the concepts. This figure demonstrates how the average demand delay in the hybrid concept grows linearly with departure delay. It also shows that even when there is no departure delay for the hybrid concept there is still an average demand delay of around 600 seconds due to the higher average length of routes for the hybrid concept. Meanwhile, the decentralised and centralised concepts had lower demand delay because they attempted to find more direct routes to the destination, not avoiding the city centre. They also maintained a relatively low departure delay. This is because the decentralised concept delayed departure by a maximum of five minutes. However, the centralised concept effectively spread aircraft to allow for a low departure delay.

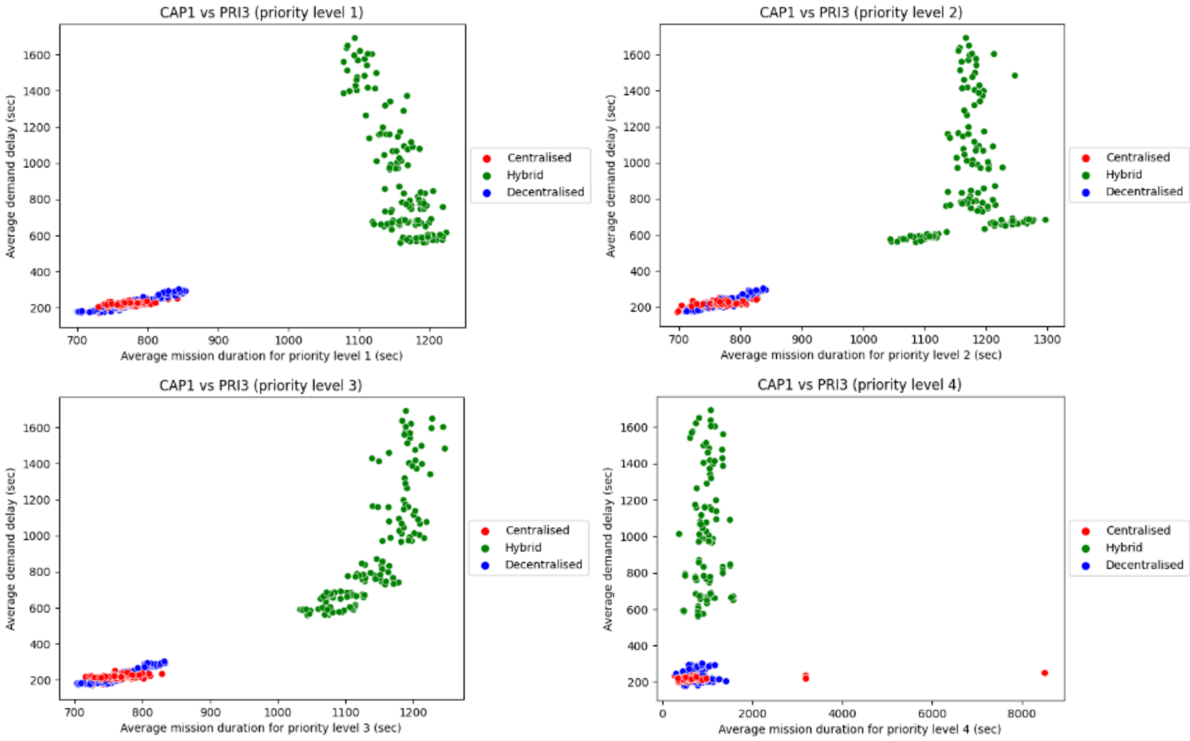

Figure 61: Trade-off between average demand delay and average mission duration for priority levels 1-4 KPIs

Figure 61 shows the trade-off between average demand delay and average mission duration for various priority levels. The centralised and decentralised concepts both are comparable. However, the centralised concept does have a consistently lower variation in terms of average demand delay, which suggests that this concept applies a more equitable demand delay across priorities. Usually, the centralized concept has better performance than other concepts when it comes to the average mission duration, however, we can see a couple of outliers in priority level 4 (emergency vehicles) where the centralized concept shows subpar results that were caused by vehicles leaving the simulation area. The hybrid concept is clearly performing worse at priority levels 1-3 (low, medium, and high priorities respectively) than other concepts, but shows a comparable performance at priority level 4 (emergency vehicles) in terms of mission duration. However, the minimum average demand delay of around 600 seconds is unaffected by the priority due to the routing algorithm.

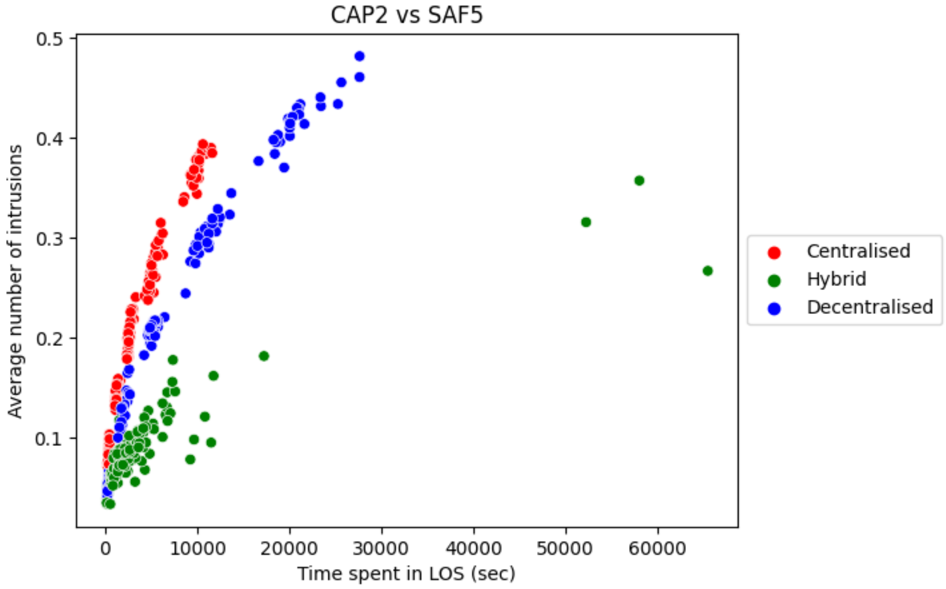

Figure 62: Trade-off between average number of intrusions and time spent in LoS KPIs

Figure 62 shows a trade-off between two safety-oriented metrics: average number of intrusions and time spent in the Loss of Separation state. Because both metrics relate to the total number of losses of separation that occurred in a given simulation, this graph also shows the lowest values for the hybrid concept, with the exception of several outliers. What is relevant to observer, however, is that for a given number of intrusions, there is a difference in the total time spent in loss of separation, between the hybrid concept and the other two concepts. At each traffic density the time spent in loss of separation is lowest for the centralised concept, as it lacked tactical separation management, which could potentially take actions which prolonged losses of separation.

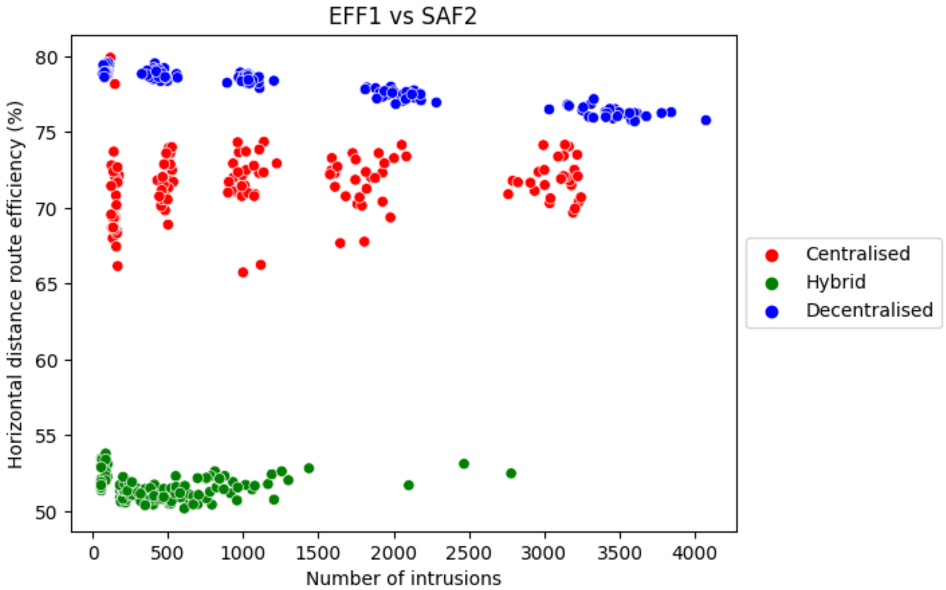

Figure 63: Trade-off between horizontal route efficiency and number of intrusions KPIs

Figure 63 shows another example of a trade-off between safety and efficiency metrics. Here, the horizontal route efficiency is compared to the number of intrusions. As discussed earlier, due to the specifics of the routing strategy of the hybrid concept, which prioritizes sending users to fly around the busy city centre, hybrid performs best when it comes to safety, so the number of intrusions is lower. However, the centralized and the decentralized concepts show much better performance in terms of horizontal route efficiency. Here it can be observed that the centralized concept has a slightly lower number of intrusions than the decentralized concept (every cluster of points for the centralized and decentralized concepts roughly represents one traffic density), but slightly longer horizontal routes.

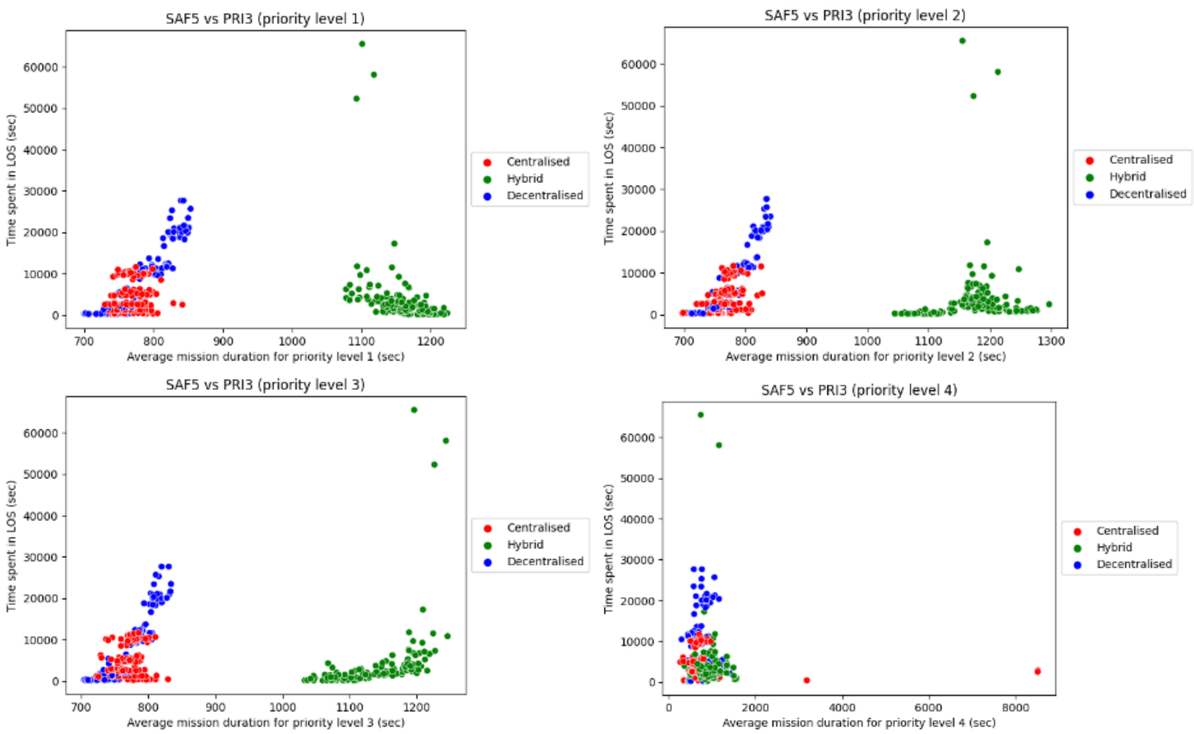

Figure 64: Trade-off between time spent in LoS and average missions duration for priority levels 1-4 KPIs

Finally, Figure 64 shows another example on how safety is balanced against efficiency for various priority levels. At the first three priority levels (1, 2, and 3 priority levels, respectively) the hybrid concept tends to have longer missions due to its tendency to reroute operations around the city centre. This approach also makes operations safer, as evidenced by vehicles spending less time in LoS (except several outliers with excessive time spent in LoS). The centralised concept shows time spent in LoS comparable to the hybrid concept, but at the price of somewhat smaller mission durations. However, when it comes to the highest priority level (i.e., emergency) operations, the hybrid concept starts showing better average mission duration values, comparable with other concepts, while the centralized concept starts producing outliers with excessively long mission durations. It can be seen that both the centralized and decentralized concepts produce outliers, and while the decentralized concept looks to be performing slightly worse that the other two, it appears to be more stable.

Overall, several differences between concepts are more related to the concept implementation. For example, the hybrid concept had weighted optimization of routes leading to a large proportion of flights avoiding the constrained airspace which means that aircraft had overall longer delays in arriving. Similarly, the highly structured beltway-like airspace around the city centre, which resulted in most traffic being nearly perfectly aligned on large roundabouts, flying in the same direction and at the same speed as the vehicles around it.

4.2 Degree of centralisation correlations

In this section combinations of metrics are presented that do show trends that can be attributed to the degree of centralization.

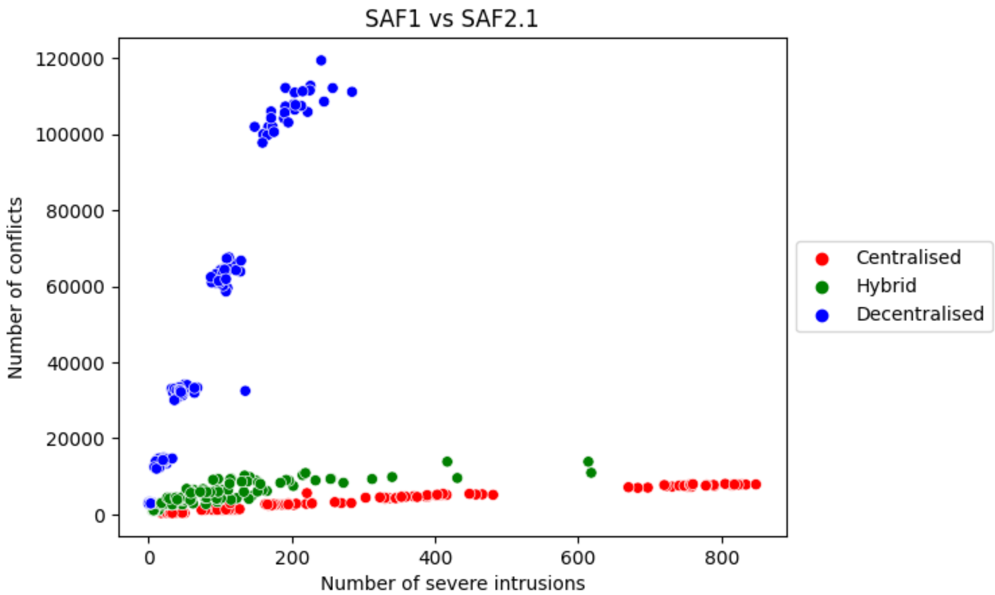

Figure 65 Trade-off between number of conflicts and number of severe intrusions KPIs

Figure 65 demonstrates a trade-off between two safety metrics: number of conflicts and number of severe intrusions. As discussed earlier, these two metrics exhibit dependencies that relate to the degree of centralisation of each concept. While the number of conflicts decreases with a higher degree of centralization due to more advanced strategic planning, number of severe intrusions grows as the quality of tactical conflict resolution decreases. It shows that concepts with higher degrees of centralization are better at preventing conflicts, but that this benefit dissipates when observing the differences in the number of losses of separation as a consequence of these conflicts.

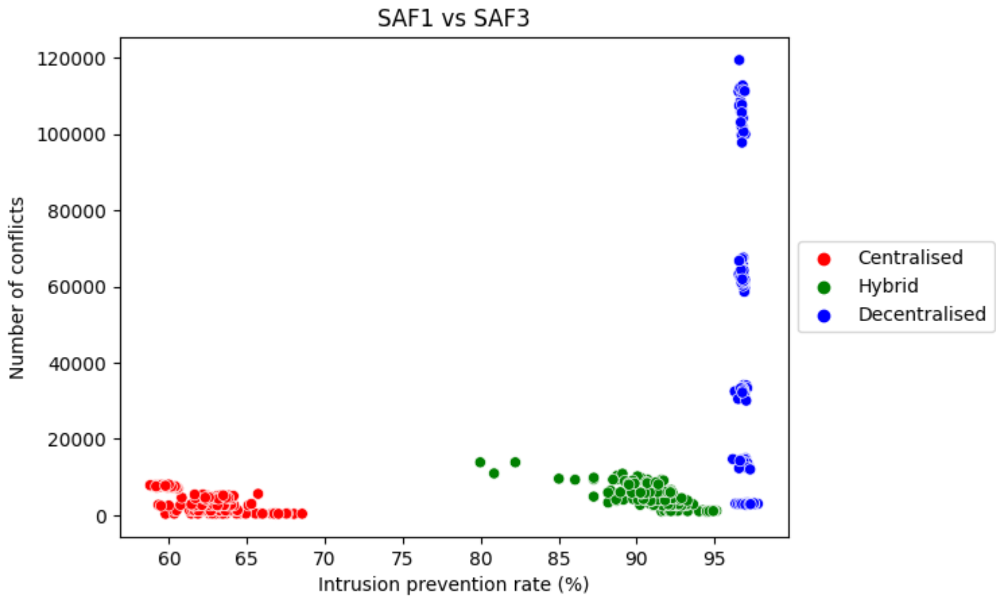

Figure 66 Trade-off between number of conflicts (lower – better) and intrusion prevention rate (higher – better) KPIs

Similar to Figure 65, Figure 66 shows that a higher degree of centralisation primarily affects the number of conflicts (predicted losses of separation), but not (or to a lesser extent) the actual number of losses of separation. As expected, the graph shows that the centralised concept demonstrates the lowest number of conflicts, but due to the absence of tactical conflict resolution, relatively many of these conflicts lead to losses of separation. The hybrid concept shows similar number of conflicts, but more are resolved by the tactical algorithm. The decentralized concept shows a significant growth with traffic density in the number of conflicts, but the majority of these conflicts are resolved. This illustrates the reactive character of purely tactical separation management: similar performance in terms of losses of separation is reached by each concept, but with a disproportionally high number of conflicts for the decentralised concept. These conflicts provide the mechanism for tactical separation to reactively provide the level of safety that strategic algorithms achieve by preplanning.

5 Trade-off and discussion

The following chapter presents the overall analysis of the results for the key performance areas and discusses how the degree of centralisation affects the performance of aircraft. Furthermore, a trade-off between the features of the concepts is presented.

5.1 Access and equity

The access and equity key performance area sought to analyse the fairness experienced between aircraft operators and includes metrics such as delay distribution and the number of flight cancellations. In this area, the results show that the hybrid concept achieved the lowest overall performance, with many demands being cancelled, meaning that flights either never made it to the destination or experienced excessive delay. Furthermore, the hybrid concept also had the highest proportion of inoperative trajectories (missions that are beyond the capabilities of the simulated aircraft in terms of range and endurance) and presented a quadratic trend in the increase of demand dispersion with respect to traffic density.

The results for the number of cancelled demands and inoperable trajectories are a direct consequence of the design philosophy of each concept. The hybrid concept chose to prioritise safety above all else, and thus equity performance was lowered through the use of long trajectories that would avoid the congested and constrained city centre. The best performers in these metrics, the centralised and decentralised concept, attempted to design trajectories closest to the shortest theoretical routes, thus staying within the performance constraints of the aircraft and minimising delay due to diversions. Thus, these results are not a direct result of the degree of centralisation.

However, an effect of the degree of centralisation can be seen in the demand delay dispersion, where the decentralised concept performed the best. Aircraft experienced a more equal distribution of delay over all missions, as delays were only used to ensure that aircraft can safely take off without causing loss of separation events. The centralised concept, while maintaining a constant dispersion level with increasing density, resulted in an overall more unequal distribution of delays as a direct consequence of the use of strategic deconfliction algorithms. However, this is also an effect of the use of priority in determining which aircraft were delayed, a feature absent within the decentralised concept.

For the hybrid concept, the delay dispersion increases with aircraft density, meaning that low priority aircraft are excessively delayed when more traffic is present in the airspace. While higher priority missions should indeed experience less delay, it is inequitable to delay missions beyond a reasonable level, thus rendering them cancelled. This proves that the excessive use of strategic planning for safety can indeed lead to a less equitable airspace.

Thus, in terms of access and equity, the decentralised concept performed best in terms of the presented metrics. However, the centralised concept had a very similar performance, while also taking into account mission priority, thus striking a better compromise between equity and priority.

5.2 Capacity

The capacity key performance area brought together metrics that show the effects of the concept design choices on how many aircraft can be accommodated within the airspace. Aircraft density, or total number of aircraft is not necessarily the sole indicator for this area, as delay and loss of separation event rate also show if the airspace has reached its capacity limit.

As previously mentioned, due to the high priority given to safety, the hybrid concept used delay as a deconflicting strategy. Thus, within this concept, aircraft experienced a higher departure delay than in the other two concepts, which grows quadratically with increasing traffic density. The other two concepts achieved a similar average delay level for missions, which shows that the degree of centralisation does not appear to affect demand delay.

In terms of intrusions per flight, the design philosophy of the hybrid concept is best seen in action, as it is the safest concept. Thus, it can be said that the safety capacity of the hybrid concept was not reached within the range of simulated aircraft densities, with the highest probability of an intrusions being 10% compared to about 30-40% for the other two concepts. The decentralised and centralised concepts experience a linear increase in the number of intrusions per flight in function of aircraft density, with the rate being higher for the decentralised concept. Thus, it can be said that these concepts reached their safety-given maximum capacity within the simulated traffic density range.

Lastly, due to the very long trajectories that the hybrid concept designed for missions, the overall number of aircraft in the airspace was greater than for the other two concepts, mainly due to aircraft having to travel longer and thus staying in the air for more. Furthermore, the high usage of open airspace meant that more aircraft could be deployed. However, the achieved capacity in constrained airspace was lower in constrained airspace for the hybrid concept. The decentralised and centralised concepts performed similarly for both open and constrained airspace due to the similarity in the aircraft trajectories.

Thus, the conclusion in terms of achieved capacity is that, due to the higher use of open airspace, the hybrid concept achieved a higher airspace capacity than the centralised and decentralised concepts. This can however not be linked to the degree of centralisation, as it is most probably a consequence of the airspace structure.

5.3 Efficiency

All the efficiency metrics are consistent in the portrayed results: decentralisation leads to increased efficiency, as individual operators optimise for shorter routes. Central planning and optimisation of routes leads to a compromise between efficiency and safety. The centralised concept managed to strike a better balance between these two areas, while the hybrid concept prioritised the latter, thus performing worst in terms of efficiency.

However, central planning has a beneficial effect on the vertical route efficiency. As altitude allocation can be planned in advance, aircraft have less of a need to use the altitude dimension for conflict avoidance. As a result the decentralised concept achieved the lowest vertical route efficiency, while the centralised concept achieved the highest.

It can be concluded that the degree of centralisation affects efficiency through a compromise with safety that strategic planning tries to achieve. However, it mainly correlates with the weighting given to each, as strategic planning can be tuned to also prioritise efficiency.

5.4 Environmental impact

Within the Metropolis 2 project, the environmental impact key performance area considers energy use and the ecological impact of aircraft when operating within the constraints of the three concepts of operations. Due to the higher route length and duration, aircraft use more energy for missions in the hybrid concept compared to the other two concepts. The centralised concept still achieves the best overall energy consumption, as flights climb and descend less, as opposed to the decentralised concept, where flights use the altitude dimension for overtaking and conflict avoidance.

The other components of this key performance area mostly relate to the altitude at which aircraft fly. If aircraft fly lower, they increasingly produce both auditory and visual discomfort. Thus, due to the decentralised concept giving priority to efficiency, flights would try to stay as close to the ground as possible, producing the highest average noise levels when compared to the other two concepts. Furthermore, as the decentralised and centralised concepts travelled more within constrained airspace, it could be said that the environmental effects due to noise are more impactful, as the city centre has a higher population density than the outer areas. Note that both of these aspects are more related to airspace structure than degree of centralisation of the concepts.

Overall, a clear trend can be observed, increased centralisation positively influences environmental metrics due to the control the central authority has over aircraft trajectories. However, within a decentralised concept, airspace and routing rules could be imposed to lessen the noise levels at the cost of route efficiency.

5.5 Safety

The safety key performance area is quantified in terms of conflicts and loss of separation events experienced by aircraft during the simulations. It is clear that the degree of centralisation has a positive effect on the number of conflicts that occur, with the decentralised concept experiencing a quadratic increase in this metric in function of aircraft density. However, it should be noted that this is the mechanism though which the decentralised concept achieves safety within the airspace, by detecting conflicts and reactively solving them.

In terms of losses of separation, the hybrid concept achieved the overall best performance mostly due to the strategy to avoid the constrained airspace area. While this strategy is a valid one, practiced in road traffic in most cities of the world, it does not directly follow as a result of the degree of centralisation. When isolating the effect of the use of open airspace, and only considering the loss of separation events within constrained airspace, the three concepts performed relatively similar in terms of the probability of a loss of separation event occurring. The hybrid concept still performed slightly better, probably due to the presence of both strategic and tactical conflict resolution.

An interesting result that can be seen is that, even though the centralised concept prevented conflicts through strategic planning, the loss of separation performance was similar to the decentralised concept, thus proving that strategic planning is not reliable enough, even in a controlled simulation environment.

Central planning does perform better when considering uncertain events, such as geofences enacted with little anticipation. However, the results show that a reactive strategy to such events is preferred as opposed to strategically accounting for them, as prediction uncertainties can cancel out the benefits of knowing and predicting in advance.

Another interesting result lies in the intrusion prevention rates achieved within the concepts. While this metric shows that the decentralised concept performed the best, it also shows that a very large proportion of conflicts are false-positives when using a state-based conflict detection algorithm. This shows the need for better conflict detection methods to be used, especially within urban airspace, where aircraft are expected to perform frequent turns even in open airspace.

Overall, it is clear that the degree of centralisation affects the safety level of the airspace. The presence of both reactive and strategic conflict resolution strategies benefits the overall safety level, while only using one type of strategy is not enough.

5.6 Priority

The priority key performance area tries to capture the ability of the three concepts of operations to accommodate the prioritisation of certain missions. The results show that, while the hybrid concept had greatly longer routes than the other two concepts, when accounting for mission priority, it achieves a lower difference when compared to the centralised and decentralised concepts. Thus, accounting for prioritisation on both a strategic and tactical level is beneficial for this key performance area.

The centralised and decentralised concepts perform similarly in terms of priority, which shows that, just as with safety, the presence of both strategic and tactical conflict resolution elements is beneficial for a better prioritisation system for flights.

5.7 Rogue aircraft and wind

Simulations that included rogue aircraft and the presence of wind were performed to test the robustness of concepts. Results show that the concepts are generally robust to such uncertainties regardless of key performance area, due to the presence of the tactical element in the hybrid and decentralised concepts, and the use of required times of arrival for each waypoint in case of the centralised concept. Thus, strategies to achieve robustness with respect to uncertainties can be implemented within any degree of centralisation.

However, the centralised and decentralised concepts did experience more intrusions per aircraft than the hybrid concept, probably due to the effect of the different use of open airspace compared to the hybrid concept. For these two concepts, rogue aircraft had a higher probability of producing conflicts and loss of separation events in constrained airspace.

It should also be noted that many uncertainties, especially more severe ones (hyperlocal weather, departure delays, system malfunctions, …) were not considered in this study. Incorporating such uncertainties is likely to affect each of the investigated concepts in different ways.

5.8 Trade-off conclusion

Overall, a clear choice between the three concepts cannot be made, as each concept performed well in some key performance areas and worse in others. Furthermore, it was shown that the design of the airspace as well as the route planning strategy have a great effect on all performance areas.

Thus, the answer to the question of what degree of centralisation is needed for the deployment of U-space still needs further research to be reached. What is clear is that a combination of proactive and reactive systems is beneficial to the overall efficiency and safety of very-low-level urban airspace, and that a hybrid system will most probably have to be used. Decentralised, tactical conflict resolution performs similarly to strategic deconfliction even when uncertainties are largely not present. However, the flexibility of reactively solving situations locally, combined to the benefits of having the ability to centrally organise traffic flows were clearly outlined in the results of the project.

For the concluding part of the project, the live demonstration, the hybrid concept will be selected, as despite its implementation issues its approach best reflects the above conclusion.

6 Conclusion

The Metropolis 2 project aimed to determine the effect of the degree of centralisation of U-space air traffic control on the efficiency, safety, and priority factors of high density very low-level urban airspace. Three concepts of operations were designed and simulated: a centralised concept that focuses on strategic planning, a hybrid concept that makes use of both strategic and tactical planning, and a decentralised concept that mainly uses tactical conflict resolution to deconflict the airspace.

The results of the project show that all concepts had strong and weak points, with the hybrid concept excelling in airspace safety, the centralised concept achieving the best overall route efficiency, and the decentralised concept providing the most equitable access to U-space for all operators while also achieving efficiency levels close to the centralised concept. Thus, a clear recommendation for the implementation of either of the concepts as designed within the Metropolis 2 project cannot be made, as neither achieved an acceptable level of performance in all key performance indicators.

However, a more in-depth analysis of the results reveals that the hybrid use of both central planning and tactical deconfliction has the potential to achieve better results than preponderant use of either. The benefits of strategic planning are clear, with traffic being better distributed within the network both in the vertical and horizontal dimensions, which greatly reduces the number of conflicts. However, tactical conflict resolution is needed to account for planning inaccuracies and to increase capacity and can also be used to ease the load on the central agent.

The implementation of the hybrid concept also showcased that avoiding the congested city centre can be a viable strategy for increasing safety at the cost of efficiency. However, the way this strategy was implemented determined a large proportion of flights to require ranges and endurances that are over the capabilities of current small aerial vehicles. Thus, the success of a "ring-road" concept for urban airspace is dependent on future innovations in the technology required to facilitate longer range operations.

In conclusion, a future separation management system for urban airspace with high traffic densities will require a combination of proactive and reactive elements, that has the ability to strategically optimise traffic flows, while employing reactive strategies as much as necessary to ensure equitable use of airspace, and robustness to uncertainties in environment and operations. The Metropolis 2 project found that central flight planning is beneficial for the overall safety and efficiency of U-space operations. However, excessive planning and constraints can lead to inequity among operators. Thus, decentralised tactical planning should also be used as a tool to make up for the inaccuracies of the central planning system, while also shifting some of the separation responsibility to operators.

7 References

[1] Metropolis 2, "D3.1 Scenario and Metrics Definition Report, Edition:02.00.01," 2022.

[2] U. S. E. P. A. a. O. o. Noise, "Information On Levels Of Environmental Noise Requisite To Protect Public Health and Welfare With An Adequate Margin Of Safety," 1974.

[3] F. A. Ltd, "Sound Pressure Level Test Report, Flytrex M600 Pro".

[4] DJI, "DJI MATRICE 600 PRO Specs," DJI, [Online]. Available: https://www.dji.com/gr/matrice600-pro/info#specs. [Accessed 20 4 2022].

[5] "Simulation dataset and output data for research project Metropolis 2," Metropolis 2, 05 2022. [Online]. Available: doi:10.4121/19323263.

[6] EUROCONTROL, "ATM Strategy for the Years 2000+," 2003.

[7] SESAR Joint Undertaking, "Project B04.01 - Performance Framework for SESAR 2020 Transition," 2016.

[8] E. Sunil, J. Ellerbroek, J. M. Hoekstra and J. Maas, "Three-dimensional conflict count models for unstructured and layered airspace designs," *Transportation Research Part C: Emerging Technologies,* no. 95, pp. 295-319, 2018.

Appendix A Metrics computation

Metric	Title and Computation methodology
Access and Equity	
AEQ1	Number of cancelled demands. Computed as the number of aircraft that did not spawn plus the number of aircraft that have an arrival delay larger than a threshold. The threshold in use is 5 minutes for emergency missions (priority 4), 15 minutes for not-loitering and not–emergency (priority<4) missions and 25 minutes for loitering missions.
AEQ1_1	Percentage of cancelled demands. Number of cancelled demands divided by the total number of aircraft described in the flight intention.
AEQ2	Number of inoperative trajectories. Computed as the number of all the flights for which the flight time (as extracted from the FLST_LOG) is greater than the drone autonomy. The drone autonomy was set to 30 minutes.
AEQ2_1	Percentage of inoperative trajectories. Number of inoperative trajectories divided by the total number of spawned aircraft.
AEQ3	Demand delay dispersion. Computed as the standard deviation over the arrival delay of all aircraft which arrived at their destination, where the arrival delay is the difference between realized arrival time and ideal expected arrival time.
AEQ4	The worst demand delay. The average delay was computed as the mean of the arrival delays of all aircraft which arrived at their destination. The metric is equal to the maximum absolute difference between the arrival delays of all aircraft which arrived at their destination and the computed average delay.
AEQ5	Number of inequitable delayed demands. The metric is computed as the number of aircraft that did not spawn plus the number of aircraft that arrived in their destination and the absolute difference between their arrival delays and the average delay is larger than a threshold. The threshold is set to 50 seconds.
AEQ5_1	Percentage of inequitable delayed demands. Number of inequitable delayed demands divided by the total number of aircraft described in the flight intention.
Capacity	
CAP1	Average demand delay. Computed as the average of the arrival delays of all aircraft which arrived at their destination.
CAP2	Average number of intrusions. Number of intrusions divided by the total number of spawned aircraft.

CAP3	Additional demand delay. Computed only for scenarios with the rogue uncertainty. Compute as the average demand delay for a scenario with a rogue uncertainty minus the average demand delay for the regarding baseline scenario.
CAP4	Additional number of intrusions. Computed only for scenarios with the rogue uncertainty. Compute as the average number of intrusions for a scenario with a rogue uncertainty minus the average number of intrusions for the regarding baseline scenario.
Efficiency	
EFF1	Horizontal distance route efficiency. Computed as the sum of the baseline horizontal route length divided by the sum of the actual horizontal route length. Only aircraft that arrived in their destination were considered.
EFF2	Vertical distance route efficiency. Computed as the sum of the baseline vertical route length divided by the sum of the actual vertical route length. Only aircraft that arrived in their destination were considered.
EFF3	Ascending route efficiency. Computed as the sum of the baseline ascending vertical route length divided by the sum of the actual ascending vertical route length. Only aircraft that arrived in their destination were considered.
EFF4	3D distance route efficiency. Computed as the sum of the baseline 3D route length divided by the sum of the actual 3D route length. Only aircraft that arrived in their destination were considered.
EFF5	Route duration efficiency. Computed as the sum of the baseline flight time divided by the sum of the actual flight time. Only aircraft that arrived in their destination were considered.
EFF6	Departure delay. Computed as the average of the departure delay for all aircraft that arrived in their destination, where the departure delay in the difference between the planned departure time and the actual departure time of the aircraft.
Safety	
SAF1	Number of conflicts. Computed as the count of conflicts that occurred.
SAF1_2	Number of conflicts per flight. Computed as the number of conflicts divided by the number of spawned aircraft.
SAF1_3	Number of conflicts in constrained airspace. Computed as the count of conflicts that occurred in constrained airspace.
SAF1_4	Number of conflicts in open airspace. Computed as the count of conflicts that occurred in open airspace.

SAF2	Number of intrusions. Computed as the count of loss of separation events that occurred.
SAF2_1	Number of severe intrusions. Computed as the count of severe loss of separation events that occurred. A loss of separation is assumed to be severe if the minimum horizontal distance between the two aircraft is less than 1.7 meters and their vertical distance is less than 0.75 meters.
SAF2_2	Number of intrusions in constrained airspace. Computed as the count of loss of separation events that occurred in constrained airspace.
SAF2_3	Number of intrusions in open airspace. Computed as the count of loss of separation events that occurred in open airspace.
SAF3	Intrusion prevention rate. Computed as the count of conflicts that did not result in a loss of separation divided by the total number of conflicts.
SAF4	Minimum separation. The minimum distance between two aircraft during all of the loss of separation events.
SAF5	Time spent in LOS. Computed as the sum of the time spend in loss of separation over all loss of separation events that occurred.
SAF5_1	Average time spent in LOS. Computed as the average of the time spend in loss of separation over all loss of separation events that occurred.
SAF6	Number of geofence violations. Computed as the count of geofence violations that occurred.
SAF6_1	Number of severe geofence violations. Computed as the count of severe geofence violations that occurred, where a geofence violation is assumed severe if the maxim intrusion is over 1 meter.
SAF6_2	Number of severe loitering NFZ violations. Computed as the count of severe geofence violations that occurred in loitering No-Fly Zones, where a geofence violation is assumed severe if the maxim intrusion is over 1 meter.
SAF6_3	Number of severe buildings/static geofences violations. Computed as the count of severe geofence violations that occurred in building geofences and static No-Fly Zones, where a geofence violation is assumed severe if the maxim intrusion is over 1 meter.
SAF6_4	Number of severe open airspace geofences violations. Computed as the count of severe geofence violations that occurred in open airspace, where a geofence violation is assumed severe if the maxim intrusion is over 1 meter.
SAF6_5	Number of severe buildings violations. Computed as the count of severe geofence violations that occurred in building geofences, where a geofence violation is assumed severe if the maxim intrusion is over 1 meter.

SAF6_6	Number of severe loitering NFZ violations, with origin/destination in NFZ. Computed as the count of severe geofence violations that occurred in loitering No-Fly Zones and in which case the origin or the destination of the intruding aircraft was in the regarding geofenced area, where a geofence violation is assumed severe if the maxim intrusion is over 1 meter.
SAF6_7	Number of severe loitering NFZ violations within 3 minutes of the NFZ activation. Computed as the count of severe geofence violations that occurred in loitering No-Fly Zones and in which case the maximum intrusion occurred within 3 minutes of the geofence application, where a geofence violation is assumed severe if the maxim intrusion is over 1 meter.
Environmental	
ENV1	Work done. Computed as the sum of work done of every aircraft that spawned. The work done per aircraft is computed as the flight time plus the ascending distance divided by the nominal vertical speed.
ENV2	Weighted average altitude. Computed as the sum of all the length of the route segments of all the aircraft as logged in the REGLOG multiplied by the altitude (in meters) of the segment, divided by the sum of the of all the length of the route segments of all the aircraft as logged in the REGLOG.
ENV3_1	Sound exposure. Computed for 4481 points in the constrained airspace. For every point, it is computed by aggregating the total sound intensity of all sound sources at that given point over the time. Aircraft flying under 30 feet (aircraft in the take-off and landing stages) were not considered.
ENV3_2	Number of points with significant sound exposure. Number of situations where the total sound intensity at a given point at a given time stamp is more than the sound exposure threshold. The assumed reference noise of one drone flying at 30 feet is 73.19dB, while the threshold is set at 55dB. Aircraft flying under 30 feet (aircraft in the take-off and landing stages) were not considered.
ENV4	Altitude dispersion. The ratio between the difference of maximum and minimum length flown at a flight level and average length flown at level. The flight levels in use are starting at 30 feet and going up to 480 feet with a step of 30 feet.
Priority	
PRI1	Weighted mission duration. Computed as the sum of flight time of the aircraft multiplied by a weight dependant on their priority. The weight is 1 for priority 1, 2 for priority 2, 4 for priority 3 and 8 for priority 4.

PRI2	Weighted mission track length. Computed as the sum of the 3D distance of the aircraft multiplied by a weight dependant on their priority. The weight is 1 for priority 1, 2 for priority 2, 4 for priority 3 and 8 for priority 4.
PRI3	Average mission duration per priority level. Computed as the average flight time, separately for every priority level.
PRI4	Average mission track length per priority level. Computed as the average 3D route length, separately for every priority level.
PRI5	Total delay per priority level. Computed as the average arrival delay, separately for every priority level.

Appendix B Dataframe structure and attributes

- Flst_log_dataframe: 'Flight_id', "scenario_name", "ACID", "Origin_LAT", "Origin_LON", "Dest_LAT", "Dest_LON", "Baseline_deparure_time", "cruising_speed", "Priority", "loitering", "Baseline_2D_distance", "Baseline_vertical_distance", "Baseline_ascending_distance", "Baseline_3D_distance", "Baseline_flight_time", "Baseline_arrival_time", "DEL_time", "SPAWN_time", "FLIGHT_time", "2D_dist", "3D_dist", "ALT_dist", "DEL_LAT", "DEL_LON", "DEL_ALT", "Ascend_dist", "work_done", 'Arrival_delay', 'Departure_delay', 'Spawned', 'Mission_completed'
- Loitering_nfz_datframe: "Scenario_name","ACID", "NFZ_name","NFZ_area", "Applied_time"
- Los_log_dataframe: "LOS_id", "Scenario_name", "LOS_exit_time", "LOS_start_time", "LOS_duration_time", "LAT1", "LON1", "ALT1", "LAT2", "LON2", "ALT2", "DIST","crash","in_time","constrained"
- Conf_log_dataframe: "CONF_id", "Scenario_name", "CONF_detected_time", "CPALAT", "CPALON","in_time","constrained"
- Geo_log_dataframe: "GEO_id", "Scenario_name", "GEOF_NAME", "MAX_intrusion", "Intrusion_time", "Violation_severity", "Open_airspace", "Loitering_nfz", "Node_in_nfz", "In_nfz_applied", "in_time"
- Env_metrics_dataframe: "Scenario_name","ENV2","ENV4"
- Env3_1_metric_dataframe: "Scenario_name","ENV3_1"
- Env3_2_metric_dataframe: "Scenario_name","ENV3_2"
- Dens_dataframe: "scenario_name", "Time_stamp", "Density"
- Dens_constrained_dataframe: "scenario_name", "Time_stamp", "Density_constrained"
- Metrics_dataframe: "Scenario_name","#Aircraft_number", "#Succeful_aircraft_number", "#Spawned_aircraft_number", "AEQ1", "AEQ1_1", "AEQ2", "AEQ2_1", "AEQ3", "AEQ4", "AEQ5", "AEQ5_1", "CAP1", "CAP2", "EFF1", "EFF2", "EFF3", "EFF4", "EFF5", "EFF6", "ENV1", "ENV2", "ENV3_1", "ENV3_2", "ENV4", "SAF1", "SAF1_2", "SAF1_3", "SAF1_4", "SAF2", "SAF2_1", "SAF2_2", "SAF2_3", "SAF3", "SAF4", "SAF5", "SAF5_1", "SAF6", "SAF6_1", "SAF6_2", "SAF6_3", "SAF6_4", "SAF6_5", "SAF6_6", "SAF6_7", "PRI1", "PRI2"
- Prio_metrics_dataframes: "Scenario_name","Priority","PRI3","PRI4","PRI5"