D4.2. DACUS: Validation test results, KPI, and suitability metrics & report

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DACUS

DACUS

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Abstract

This document presents the DACUS deliverable D4.2 Validation Report (VALR). It contains the results of the validation experiments that have been carried out by different project partners under the umbrella of the DACUS project.

Four validation experiments have been performed regarding the use of risk assessment and social impact prototypes that have been developed during the DACUS project operating at different stages of the Demand-Capacity Management (DCM) process for drone operations in the urban environment (U-Space), including strategic, pre-tactical and execution phases.

The results obtained are described in annexes of this report for each specific exercise, and then aggregated into global results, making reference to the research challenges identified the DACUS "drone DCB concept and process" (D1.1) and the DACUS "performance framework" (D5.3).

Deviations from DACUS D4.1 "Scenarios for validation experiments", as well as conclusions and recommendations for the next phase are also provided.

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Executive summary

The DACUS exploratory research project addresses the development of a *service-oriented Demand and Capacity Balancing (DCB)* process for drone traffic management in the urban environment. The analysis that was performed responds to both operational and technical needs to identify tangible and realistic solutions that can both integrate the functionalities and solutions being considered by advanced SESAR U-space services within a highly populated urban region.

The project investigated novel capacity management indicators based on both societal (Noise/Visual impact) and Risk based indicators (risk of injury arising from vehicle collision or failures) integrated in a consistent DCB solution to manage demand and capacity influence factors combined with a suitable environment (such as dynamic airspace structures), processes (such as separation management), and services (such as drone Operation Plan Preparation).

After the elaboration of a DCB Concept of Operations that relies on knowledge from the ATM domain and expertise from current drone operations, the project implemented service models and prototypes to simulate DCB processes. The models were extensively validated and tested to ensure that they are able to help assessing demand against suitably calibrated thresholds to ensure safe and expeditious operations in the urban space. Drone Operation Plans (DOP) published and shared through a common information repository (a '*single source of truth*') are consumed by demand management services to provide timely and continuous capacity monitoring services throughout the mission lifecycle.

Simulations of the drone operations lifecycle at different phases of the planning process (strategic, pre-tactical, execution) helped demonstrate whether it is feasible to assess the demand and capacity imbalances, i.e. hotspots, using the new risk and social impact metrics.

Hotspot situations were identified for suitable sized operating grid cells (typically 1km x 1km in size) using population density and other socially oriented indicators. The appropriate DCB actions which may help to mitigate those imbalances were evaluated using quantitative performance metrics and indicators. Simulation exercises were performed to apply and assess the effectiveness of a variety of DCB measures as part of the DCM mitigation process at different phases of the planning process including:

- Speed management in 'hotspot cells'
- Temporary increase in the maximum altitude for the operational ceiling, at certain hours of the day - when the majority of hotspots are identified
- Organisation of traffic using directional flight layers to allow traffic to traverse 'hotspot cells' (introduced dynamically to organise traffic within those cells during the hotspot periods only)
- Introduction of specific routes in place of free-route operation in response to overloads (organised per flight layers depending on the course being flown)
- Ground-based departure delays to operations to reduce 'hotspot' counts

The impact of uncertainty associated to mission planning and weather effects, as well as the activation of pre-defined contingency actions were also assessed at various steps of the planning process. Actions in response to two types of contingency event (unavailable or closed landing location and degradation in navigation performance) and micro-weather effects were evaluated in simulation scenarios.

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Mitigation strategies considered during the experiments included:

- Return to base using *nominal* waypoints
- Divert to an alternate location and activate conflict management procedures
- Land immediately and activate contingency volume.

The ability to use the models and services that were prototyped and extensively validated as part of the DACUS project suggests that the benefits for citizens that were identified during the research are manifold; the process is capable of monitoring the social impact (both noise and visual impact) of drone operations in urban areas; and it is able to incorporate multi-criteria decision-making in the application of measures to manage imbalances. All of this is done while ensuring that risk levels do not increase and that operations do not result in safety issues when drones are allowed to operate at very low altitudes in densely populated areas.

Specifically, the DACUS project offers the following benefits for the drone operators:

- DCB processes prioritize free-route operations whenever operating conditions permit.
- Measures can be triggered rapidly - as soon as the demand picture is available.
- Uncertainty from multiple sources (operational uncertainty, weather conditions, contingency events, navigational performance, etc.) can be integrated in the traffic situation monitoring and management process.

Key results indicate that mitigation actions of various types are able to manage collision risk and to a lesser extent social impacts to the urban population (Noise / Visual) in an efficient manner, with plenty of scope to allow drone operators to perform missions as they desire. Since the scope of the research was limited, other factors would be interesting topics for further research (e.g. privacy, environmental factors, protection of key areas such as hospitals, schools or wildlife reserves and trade-off analysis for noise, collision risk, capacity efficiency, resilience etc.).

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1 Introduction

1.1 Scope of the document

This document provides the Validation Report (VALR) relating to a series of experiments that aimed at testing the suitability and performance of prototype Demand-Capacity Management (DCM) tools working in nominal and sub-nominal operating conditions to manage proposed drone operations in the U-Space environment.

It describes the results of exercises that were defined in the DACUS D4.1 – Scenarios for validation experiments document [1], including details on how they have been conducted for different phases of the drone operation management process, and provides a set of relevant conclusions and recommendations.

DACUS aims to develop a service-oriented Demand and Capacity Balancing (DCB) process to facilitate drone traffic management in urban environments. The project intends to integrate relevant demand and capacity influence factors (such as CNS performances availability), definitions (such as airspace structure), processes (such as separation management), and services (such as Strategic and Tactical Conflict Resolution) into a consistent DCB solution, which is tested for various planning phases by the experiments that are included in this report.

The document intends to establish a set of Key Performance Indicators for the areas described in the DACUS D5.3 Performance Framework [2] and evaluates the initial drone DCB concept described in the DACUS D1.1- drone DCB Concept and Process document [3] based on the series of validation experiments that were performed. Where possible, the analysis and results also aim at supporting an analysis of separation intelligence balance and refinement of CNS requirements linked to separation minima criteria as well as a risk-based demand management methodology for operations in the urban environment.

1.2 Intended readership

This document is intended to be used by:

- SJU programme manager.
- DACUS project members - in particular: WP4 partners dealing with the execution of the validation exercises and the validation report, WP1 related to the DACUS concept and WP5 for the DACUS performance framework.
- SESAR2020 and the international research community addressing drone operation planning, capacity, safety, and societal impacts in the urban environment.

1.3 Background

A limited amount of research has been performed to date that assesses the applicability and utility of demand capacity balancing concepts for drone that intend to operate in the Very-Low-Level (VLL) urban environment (U-Space).

Consequently, the DACUS project has embarked on a task through which the definition and validation of a concept for Demand Capacity Management, based on a set of risk-based prototypes, could be introduced in a U-space environment to help manage a high density of drone operations in different operating conditions in a safe and expeditious manner.

Work performed as part of WP1 of the DACUS project resulted in the publication of a first DACUS Concept of Operations which helped to identify a set of initial functions and prototype services that could be used to evaluate the performance and impact of DCB through a series of validation exercises. As part of the WP1 activity, the scope of these experiments and the main algorithms, prototypes and simulation techniques that could be used to analyse their performance was identified:

- **AI demand prediction model**: used to generate drone operations, considering assumptions on demand and weather analysis for target urban areas.
- **Collision Risk model**: that calculates the expected ground fatality risk (*Collision Risk*) and estimates the maximum capacity that might be achieved to support U-Space drone operations over a specified time-period.
- **Societal Impact model(s)**: to evaluate the *Noise* and *Visual Impact* of drone flights that are operating above populated areas (urban environments).
- **Fast-time simulation platform**: using an extension of the commercially available RAMS Plus ATM gate-to-gate fast-time simulation model to provides micro-scale modelling features for drone performance, conflict detection and zone-based functional behaviour.

To align with other research in the U-Space domain, DACUS expands on proposals that have been published in the CORUS ConOps [5] to consider a continuous and pro-active process that aims to pro-actively monitor the evolving traffic situation and identify situations when demand capacity imbalances are expected to occur. This includes planning in the strategic, pre-tactical and execution phases of drone operations based on the most up-to-date information that is available from the set of drone Operation Plans (DOP) – where the accuracy of DOP increases as the planned time of execution approaches.

Specifically, a series of primary and secondary processes were identified in the DACUS ConOps which can be applied to U-Space DCB across all operational phases:

1. **Operation Plan Preparation** services facilitate the creation and publication of the intended DOP for all types of drone mission that might be planned during the day, including contingency plans that can be activated if an emergency or unexpected situation occurs. These can be created by the drone operators themselves or using third party services.
2. **Operation Plan Processing** services to verify that the DOP are consistent and respect any airspace or other constraints that may exist in the region.
3. **Strategic Conflict Resolution** services consolidate newly filed DOP with the current set of published DOPs and identify if the risk of a conflict is higher than a proposed limit, in which case appropriate actions may be suggested to, or by the drone operator to solve this.
4. **Dynamic Demand Capacity Management** services provide a key role throughout the entire DCB process to predict the demand at various planning phases by combining the available 4D trajectories with predictions of new or incomplete/uncertain ones. Demand prediction can

take account of other influencing factors such as weather, navigational performance, airspace constraints etc.

Unlike the Demand Capacity Management process that is currently used by NM for traditional ATFCM network planning (which uses demand or flight occupancy counts as the main indicator to manage demand for traffic volumes - based on airport, airspace, route, or waypoint capacities), the DACUS DCM process is investigating the use of risk-based metrics for use in DCM. In the scope of the current DACUS research and the associated validation activities, these indicators include *Noise*, *Visual Impact,* and *Collision Risk* metrics. These are evaluated based on traffic routing and the population levels in the areas over which they fly. In the case of the Collision Risk metric, additional influences including the weight/size of the vehicles and sheltering factors that may reduce the risk of injury to the population due to a collision or failure of drones are also taken into consideration.

Where feasible, contingency measures are included in DOP which can be implemented in the case of unexpected events, changes to the weather or emergency situations and airspace structures can be included, for example to limit or prohibit certain types of operation in sensitive areas of the city (e.g. near hospitals or above large gatherings of people). These can also be dynamically generated to respond to last-minute issues or emergencies if required.

Hence, the Dynamic Capacity Management service can evaluate if demand can be executed safely and efficiently for a given region taking into consideration the existing performance thresholds in each airspace volume. In case of imbalances, DCB measures can be proposed or set up independently of the DCM service and applied to the Operation Plans or shared with the Operation Plan Processing service as needed.

The following figure provides an illustration of the services / prototype functions that can be captured in the various DACUS validation experiments with specific models/services that are used in the DACUS activity highlighted in blue.

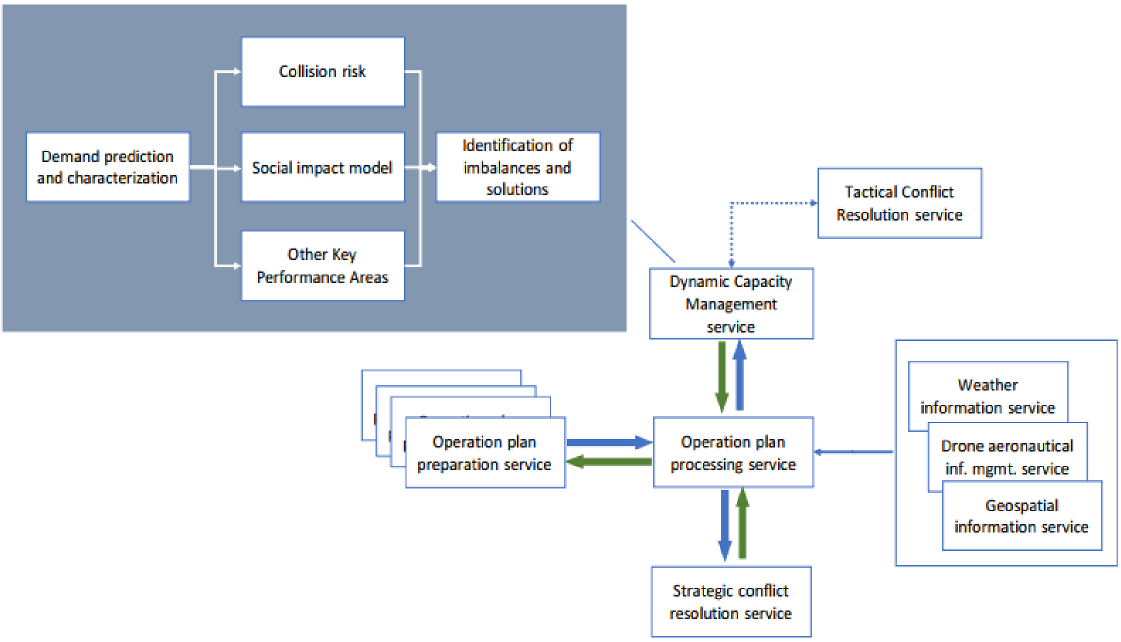

Figure 1: High level overview and models used (*in blue*) for the DACUS drone DCB process

Finally, as part of the DACUS validation, a model of the Tactical Conflict Resolution service is also included using the *droneZone* variant of the RAMS Plus model-based simulation platform. Whilst this is not strictly a part of the DCB function, it will allow for tactical conflict situations following DCB actions to be measured, to determine if the performance of the tactical conflict management function (through pairwise flight resolution actions) is able to manage the remaining issues, and to determine the maximum number of operations that are feasible in different operating conditions (nominal, sub-nominal, bad weather etc).

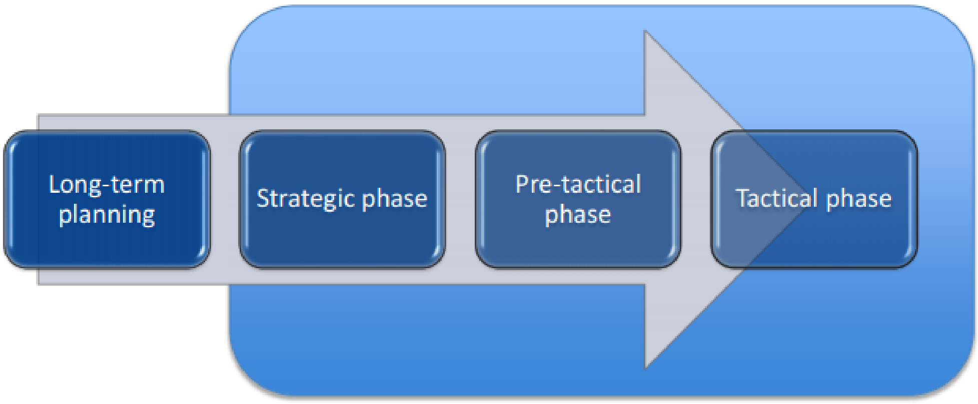

Figure 2: Overview and scope (*in blue*) of the DCB phases evaluated in DACUS

In the scope of DACUS, the four sets of validation exercises to evaluate DCM performance at various stages of the planning process shown above (as described in the D4.1 document [1]) have been performed. Results of those validation activities are included both by experiment and in an aggregated manner in this document for scenarios executed in Toulouse (*experiment 1+3*) Frankfurt (*experiment 2+3*) and Madrid (*experiment 4+3*).

1.4 Structure of the document

The document is structured as follows:

- **Executive Summary**

  Provides a short summary of the document.

- **Section 1 (*this section*) – Introduction**

  Describes the purpose of the document, the intended readership, the background, and provides explanations of the acronyms used throughout the document.

- **Section 2 – Context of the validation**

  Presents the context of the validation and a short description of the experiments, validation aspects, objectives, assumptions, etc.

- **Section 3 – Validation results**

  Provides the results and achievements of the exercises.

- **Section 4 – Conclusions and Recommendations**

  Presents the conclusions of the validation exercise and from the analysis of the results.

- **Section 5 – References**

  Provides a list of references.

- **Appendix A – Experiment #1: Assessment of social impact and automatic DCB measures** provides detailed results of the experiments carried out to assess the application of Noise and Visual impact prototype models to support drone Demand-Capacity Management services and the use of DCB actions to help mitigate social impacts.

  Appendix B – Experiment #2: Route planning prototype to represent uncertainty in demand considers the nominal processes of Flight Plan Processing, Contingency Planning and describes how the resulting demand and uncertainty predictions will be validated. Impacts of local 'micro-weather' conditions on drone operations and vertiport capacity/closures are also assessed.

  Appendix C – Experiment #3: Collision risk model and mitigation methods contains a description of the results of different scenarios tested in the strategic phase in Experiment 3 to evaluate the acceptable capacity by means of the comparison of the collision risk with a Target Level of Safety.

  Appendix D – Experiment #4: Application of DCB measures in the pre-tactical and execution phases uses a fast-time simulator in collaboration with DACUS DCM services to validate the DCB process in diverse scenarios. The effectiveness of different DCS strategies is also evaluated.

1.5 Acronyms and terminology

Term	Definition
ADD	Architecture Definition Document
AN	Availability Note
ATM	Air Traffic Management
ATM MP	Air Traffic Management Master Plan
DCB	Demand-Capacity Balancing
DCM	Demand-Capacity Management
DOP	drone Operation Plan
EATMA	European ATM Architecture

E-ATMS	European Air Traffic Management System
E-OCVM	European Operational Concept Validation Methodology
IBP	Industrial Based Platform
IRS	Interface Requirements Specification
INTEROP	Interoperability Requirements
KPA	Key Performance Area
KPI	Key Performance Indicator
OSED	Operational Service and Environment Definition
PI	Performance Indicator
PIRM	Programme Information Reference Model
SESAR	Single European Sky ATM Research Programme
S3JU	SESAR3 Joint Undertaking (Agency of the European Commission)
SPR	Safety and Performance Requirements
SUT	System Under Test
SWIM	System Wide Information Model
TLS	Target Level of Safety
TRL	Technology Readiness Level
TS	Technical Specification
UC	Use Case
UCIS	U-space Common Information System
VALP	Validation Plan
VALR	Validation Report
VALS	Validation Strategy

Table 1: Acronyms and terminology

2 Context of the Experiments

2.1 Experiment Purpose and approach

The experiments conducted in DACUS address three main topics: Firstly, to '**validate the requirements of the selected U-space services**' elaborated in the DACUS D3.1 document [5], which addressed the challenges of their implementation; Secondly to analyse how those services and the prototypes built to implement them can '**respond to the research challenges identified in the DACUS ConOps'**; Thirdly '**to assess the applicability of indicators included in the DACUS performance framework'** (many of which are now included in the PJ19.4 Companion Document, so the added value is higher in the context of SESAR) [6].

2.2 Summary of the Experimental Plan

To validate the models, capabilities and prototypes developed in DACUS, the following experiments were envisioned in the D4.1 VALP "Scenarios for Validation Experiments" document [1]:

- **Experiment #1: Assessment of social impact and automatic DCB measures –** considers the strategic and pre-tactical phases of the planning process, with the focus being on the application of the DCB services related to the management of ***Noise*** and ***Visual*** impact due to drone operations in urban environments. Thus, the main objective of this experiment is to test the *feasibility* and the *reliability* of the use of Noise and Visual impact metrics for the DCM service.
  The analysis also considers Noise and Societal Impact metrics correlation as well as the number of hotspots compared to the assigned thresholds. Finally, this experiment investigates the feasibility of proposing automatic DCB measures from DCM service calculation. Measures investigated in the experiment #1 scenarios include the *use of departure delays* to manage the number of flights in hotspot areas and the *modification of operating altitudes* to help reduce the noise and social impact hotspots identified by the DCM services.

- **Experiment #2: Route planning prototyping to represent uncertainty in demand** considers the nominal processes of *Flight Plan Processing*, *Contingency Planning* and the resulting *demand and uncertainty predictions* will be validated. Furthermore, the influence of the demand and uncertainty predictions on the collision risk and efficiency will be tested, as well as the feedback loop for additional information such as collision risk, weather conditions and efficiency indicators into the flight plan processing and its consequences for hotspot occurrence. The effect of weather conditions on vertiports capacity will also be studied, including rerouting and/or cancellation of flights in response to weather constraints.
  In scenarios that included unanticipated events which required contingency strategies to be actions (e.g. capacity reduction of losses of landing locations and/or degradation/failure of CNS) measures including *returning to base* using a set of nominal waypoints, *diversion to alternate landing locations* or *immediate landing* with suitable contingency volumes activated while landing occurs are evaluated.

- **Experiment #3: Collision Risk model and mitigation methods** applies the *collision risk model* in the strategic phase to test the effect of considering different CNS performances and defining

different airspace structures and operating procedures to manage the maximum acceptable capacity in different scenarios.
Experimental scenarios estimate the maximum theoretical airspace capacity for various levels of traffic demand without any strategic measures being applied, and further investigate how collision risk can be reduced through the introduction of strategic conflict management measures. These measures consider how enhanced separation between aircraft, using increased conflict margins, or structuring operations using directional flight operating layers of various thicknesses can help to reduce the risk of conflicts in hotspot areas.

- **Experiment #4: Application of DCB measures in the pre-tactical & execution phases** uses a fast-time simulator to *validate the DCB process* in diverse scenarios and under nominal and sub-nominal operating conditions. It is focused on the tactical phase and the main objective is to analyse the *impact on the DCB process* when a perturbation occurs, as well as the *effectiveness of different DCB measures*. The effectiveness of different DCB strategies is assessed using the performance areas included in the DACUS Performance Framework [2].
  Measures to evaluate in the simulation scenarios include the use of *speed control* in hotspot zones, *increase of the operational ceiling* to allow traffic to fly higher during periods with many hotspots, altitude organization using temporary *directional flight layers* to *strategically deconflict traffic*, *compulsory routes* when traversing hotspot areas and *ground delays* to traffic to both reduce flight counts in hotspot zones as well as to reduce or solve pairwise conflicts before flight operation commences (*strategic conflict management*).

Experiments #1 and #3 are designed to allow the team to validate and help calibrate the models and anticipated thresholds when analysing traffic from a risk/social impact-based perspective.

Once the models have been suitably calibrated and tested, the remaining **experiments #2 and #4** apply the models and services in an operational context, alongside the other U-Space services and at different phases of the drone Operations Planning process (see Figure 2 previously).

The dependencies and inter-relationship between the various experiments is illustrated in the figure below:

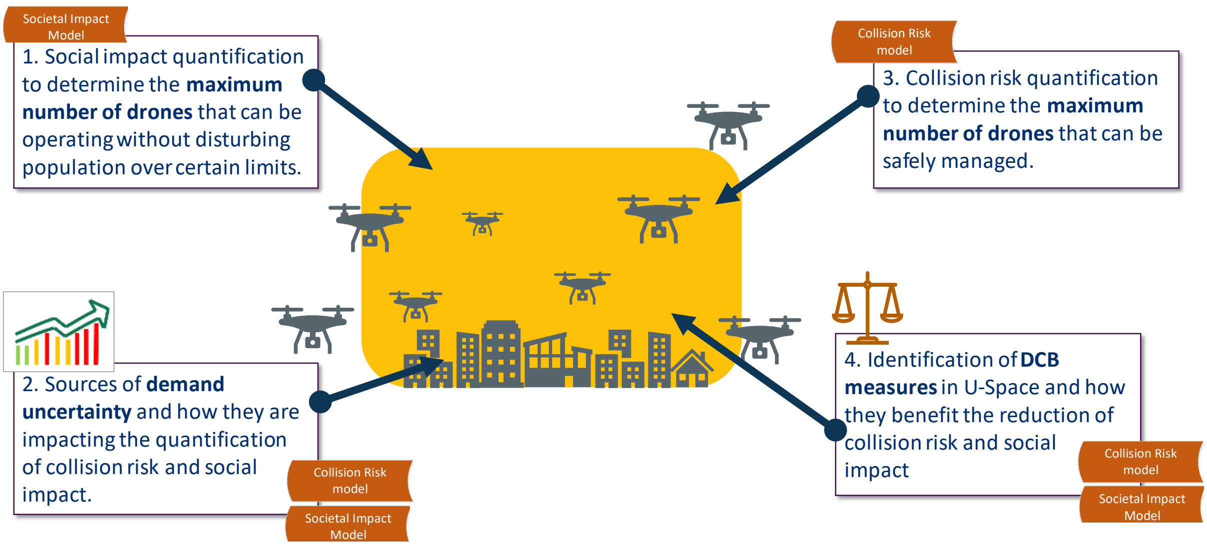

Figure 3: Relationship between DACUS experiments

2.3 U-Space services and capabilities in relation to the experiments

In the four sets of experiments carried out by the DACUS research partners, the following services and prototype capabilities have been considered at varying phases of the drone operation planning process in the urban environment:

Capability	Main Functions	Involved in	U-space service
AI demand prediction model	Calculation of foreseen demand prediction and uncertainty based on AI	Experiment #1 Experiment #2	Dynamic Capacity Management
Collision Risk model	Monitoring collision risk indicators Identification of hot-spots and airspace status	Experiment #2 Experiment #3 Experiment #4	Dynamic Capacity Management
Societal/Noise Impact model	Monitoring social risk indicators relating to noise impact, identification of hot-spots and airspace status	Experiment #1 Experiment #2 Experiment #4	Dynamic Capacity Management
Societal/Visual Impact model	Monitoring social risk indicators relating to visual impacts, identification of hot-spots and airspace status	Experiment #1 Experiment #2 Experiment #4	Dynamic Capacity Management
Trajectory Planning capability	Generation of 4D probabilistic trajectories with uncertainty	Experiment #2 Experiment #4	Operational Plan Preparation & Processing (*Mission Management / Flight Planning Management*)
Contingency Planning capability	Generation of contingency based 4D probabilistic trajectories with uncertainty	Experiment #2	Operational Plan Preparation & Processing (*Flight Planning Management*)
Micro-Weather prototype	Supportive functions for large number of simultaneous operations	Experiment #2	Feeder (*Micro-Weather*)

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Capability	Main Functions	Involved in	U-space service
Conflict detection & resolution	Strategic Conflict Management	Experiment #3 Experiment #4	Strategic Deconfliction (using pre-flight measures to reduce the number of conflicts, including increased separation between vehicles, use of flight layers, increased operating ceiling and ground delays to solve pair-wise conflicts)
Conflict detection & resolution	Tactical conflict detection / resolution	Experiment #4	Tactical Deconfliction
Demand-Capacity Balancing	Implementation of DCB strategies	Experiment #1 Experiment #3 Experiment #4	Demand-Capacity Management and Balancing

Table 2: Relation of experiments with U-space services and capabilities

Readers should note that while strategic conflict management services are not modelled as a stand-alone suite of services, the analysis of conflict management strategies in experiment #3 and DCB strategies that incorporate strategic actions aimed at solving conflicts in the scenario (and thereby the collision risk indicator) are included within the DCM services and corresponding measures in experiment #4.

Experiment #3 investigates how the introduction of strategic actions such as increase separation or airspace structures effects the risk of conflicts.

Experiment #4 provides empirical evidence how mitigation measures which *adapt planned flight profiles shortly before flight in support of strategic conflict management actions*, can reduce the number of conflicts considerably - These include increasing the maximum operating ceiling (44% conflict reduction), use of temporary directional flight layers to strategically separate traffic in high conflict regions (27% reduction) and the use of ground delay to strategically solve identified conflict pairs (5% reduction).

2.3.1 Relationship with DACUS high level objectives

Experiment #1 and **experiment #3** focus on the DACUS high level objectives 1 and 2 that were identified in the project proposal as shown below:

DACUS Objective 1 – Develop a drone specific **Demand and Capacity Balancing** (DCB) process.
Develop a drone DCB process, from strategic to tactical phase, integrating uncertainty of planned operations and guided by the definition of a U-space performance scheme that includes the development of metrics for airspace capacity appropriate for an environment with no human controller.
Success Criteria 1. Definition of a complete DCB process taking as inputs all critical influence factors (including uncertainty of both demand and capacity) and producing a clear set of measures for

adjusting both capacity (e.g. via dynamic airspace management) and demand for the period of operation. The forecasted execution of the resulting picture would comply with the specific performance objectives set in CORUS 23 and DACUS Performance Framework, especially in the areas of safety, environment, and efficiency.

DACUS Objective 2 – Develop innovative U-space services and enabling models (e.g. Societal Impact model, Risk model) in support of DCB.
Develop innovative services algorithms and enabling models and technologies as functional blocks of DCB process, able to support large number of simultaneous operations and to design and manage efficient and safe drone trajectories.
Success Criteria 2. Development of services algorithms that: a) Cope with the defined airspace structure and rules; b) Work together to provide a harmonized DCB and flight planning management; c) Integrate all identified influence factors for capacity evaluation; d) Build on the optimal balance between on-board and centralized separation intelligence and on dynamic separation minima. The U-space services addressed are: Dynamic Capacity Management, Mission Planning Management, Flight Planning Management, Micro-weather, Strategic De-confliction and Tactical De-confliction. This success criterion also includes the development of enabling models and technologies in support of the services, such as risk model for capacity estimation.

For these two high-level objectives, DACUS has developed prototype models based on *Collision Risk*, *Noise,* and *Visual impact* measures that can support Demand Capacity Management (DCM) services.

Experiments #1 and **#3** are used to validate these models in isolation.

Using these experiments, together with recommendations from other sources (e.g. the JARUS Specific Operations Risk Assessment - SORA [8]), suitable thresholds can be assessed beyond which hotspots can be identified. Appropriate actions can be considered using a variety of strategies to help mitigate the reported issues either as a part of the isolated use-cases or in a situation where the tools and services are deployed alongside other U-Space services.

As there are currently no specific limits defined for noise and visual Impact when operating drones in the urban environment, **experiment #1** will also consider various levels of drone operations in the Toulouse metropole region to help determine the impact on the surrounding population and to propose suitable thresholds that could be used during the DCM/DCB process. Analysis of the application of theoretical DCB measures, such as limiting the permitted operating altitude in certain areas or delays to selected operations, is also performed to help determine the effect or potential benefits from a noise/ visual impact perspective.

In **experiment #3**, multiple simulation scenarios are performed in the strategic phase to help identify risk levels for the urban population due to drone operations for different European locations. The effect of a mixture of operation types combined with testing of different CNS performance is used to help to determine the maximum capacity or minimum separation between aircraft, where better CNS performance systems are expected to reduce the conflict risk and should therefore increase the capacity of the airspace for a given TLS (For the purpose of the DACUS experiments, $1x10^{-6}$ fatalities/flight hour, as defined in the SORA methodology was selected. However on-going research projects such as BUBBLES [15] are considering placing higher constraints on this threshold).

Experiments #2 and #4 apply the DCM services at various phases in the DCB process (objective #1) to demonstrate and help validate the end-to-end application of measures to manage demand in the urban area. In experiment #2, DCM services are consulted to identify hotspots at the strategic phase. However, in the scope of the experiment no DCB actions were performed, and this may be an interesting future topic for research.

In experiment #4, the DCB process was evaluated at the pre-tactical phase, where DCM services are used to review the most up to date set of Drone Operation Plans just prior to the execution of the flight. In response to any hotspot cells that were identified by the DCM services, different dynamic DCB measures were tested as described in Annex 4 of this document.

In the initial design of the experiment #4 scenarios a real-time dynamic process was planned to support DCM/DCB in the pre-tactical phase. In these scenarios, the DroneZone FTS simulation tool was connected to the USpace Common Information System (UCIS) and DOP were dynamically published by the simulator at different time offsets prior to flight. DCM services were also connected to UCIS and consume the latest set of DOP to perform hotspot analysis in line with a set of dynamic triggers – either when a specific number of DOP had been published or after a predefined time step. Once triggered, the DCM services analyse the current set of DOP for the target region (Madrid) to identify hotspot cells caused by the traffic demand. The FTS tool would then retrieve the hotspot information through a dedicated service in UCIS and dynamically apply one of the DCB measures to those cells to respond to the overloads in line with the selected strategy.

In practice, due to a combination of technical and time constraints it was not feasible to complete the integration with the DCM services responding in a real-time mode. For this reason, it was agreed to perform the integrated functions in an 'off-line' mode which allowed the DCM services to complete prior to the allocation of the selected DCB strategy. This emulation of the real-time interaction was necessary to allow the DCM services sufficient time to execute the analysis for the traffic samples being provided. Nevertheless, the emulation was suitable to help validate the DCB process and impacts of different dynamic actions for all the strategies considered in the DACUS research. However, additional research in future projects would be of interest to enhance the DCM service prototypes to be able to respond in real-time and support the dynamic allocation of DCB strategies in an interactive manner using the simulator tool.

As part of **experiment #3**, specific analysis of the DACUS high level objective 5 (shown below) is also performed.

DACUS Objective 5 – Refine Communication, Navigation and Surveillance, and Information (CNS-I) requirements for urban environments.
Refine Communication, Navigation and Surveillance (CNS) requirements in support of tactical and procedural separation, with a focus on urban environment.

Success Criteria 5. Produce a refined set of CNS requirements introducing changes with regards to current drone CNS references. These changes must be substantiated by simulation results that produce evidence of the CNS performance needs to ensure safety while maximizing capacity, considering the defined rules of the air and separation procedure, the dynamic separation minima, and the performance tolerances.

Experiment #3 also considers how different airspace structures (such as layers or route networks) and VLL operating rules can impact the collision risk in different airspace regions (DACUS high level objective 3 shown later in this section).

Once the DACUS DCM models have been validated in isolation, **experiment #2** and **experiment #4** provide simulations for the deployment of those models in an operational context at different phases of the drone Operation Planning lifecycle and in collaboration with other U-Space services.

In this way **experiments #2** and **#4** will assess the effectiveness and consistency of the DCM services in the management of risk and societal based measures when operating drones in the urban environment. These experiments address the *DACUS high level objectives 1 and 2* (described earlier) by deploying those services in a realistic environment for a variety of mission types for both *nominal* and *sub-nominal* operating environments:

> *Nominal* operating conditions consider that there are no specific airspace constraints to the planned operations, that the CNS infrastructure and services are operating as normal and that weather conditions are good.
>
> *Sub-nominal* scenarios, one or more of these factors can be adapted, resulting in a degraded environment in which the missions should operate (e.g. high winds causing reduction in capacity, or closure of some vertiports, precipitation, airspace restrictions due to key events/emergencies or degraded CNS services).

The effect of *Uncertainty* in the drone Operation Plan (DOP) and the inclusion of *Contingency* actions that may be applied in the case of unexpected events or emergencies is also included in these experiments.

Experiments #2 and **#4** also aim to address the remaining high-level objectives that have been targeted in the DACUS project (i.e. DACUS high level objectives 3 and 4 shown below).

An additional objective relating to *the influence of micro-weather effects* such as wind effects on the lea-side of tall buildings, urban canyoning etc. and capacity reduction or closure of vertiports due to weather (not originally foreseen in the research) are also considered as part of experiment #2.

DACUS Objective 3 – Define Very Low Level (VLL) airspace structure and rules and boundary conditions for urban environment.
Define a structure for Very Low Level (VLL) airspace and a set of airspace rules that optimises the trade-off between capacity and safety, including the definition of areas where the separation will be procedural and areas where tactical separation will need to be applied, and considers factors such as noise impact amongst other Key Performance Indicators (KPIs).
Success Criteria 3. Definition of a complete set of rules of the air, airspace structure (addressing separation areas and role of separator) and boundary conditions (including public acceptance,

business, and regulatory aspects) for urban environment that allows unambiguous operations and requirements for the development of associated U-space services.

DACUS Objective 4 – Optimise decision making between on-board capabilities and U-space separation services.
Find the optimal balance between on-board separation intelligence and U-space separation service intelligence in tactical separation depending on the type of airspace (with or without conflict resolution in strategic and/or tactical phases), type of separation (drone-drone or drone-manned aviation), CNS performances and the separation process that applies in each type of airspace area.
Success Criteria 4. Obtain simulation results that allow the evaluation of diverse separation approaches in terms of drone performance indicators as defined in DACUS Performance Framework

Experiment #2 considers the application of the new risk-based DCM tools in the strategic planning phase for a mixture of operation types in the Frankfurt region. As there is a large international airport nearby, this includes a complex airspace structure and requires clear operating rules and boundary conditions that need to be taken into consideration in the simulation scenarios.

The simulation scenarios integrate other U-Space services including **AI-based mission planning**, **Operation Plan Processing**, **Flight plan Management**, and **macro/micro weather** services.

Additional scenarios incorporating uncertainty and contingency are included to help assess the potential impact on the overall planning and DCM processes as well as on the consistency of the different types of hotspots being identified by the DCM services.

Experiment #2 also uses additional prototypes to support macro and micro modelling in the Frankfurt region to evaluate the impact of wind/turbulence effects in the neighbourhood of tall buildings in the city on the drone Operation Planning/DCM process and impacts of weather in reducing the capacity or closing access to vertiports at different times during the simulations.

Experiment #4 focuses on the pre-tactical and execution phases of the process in which a variety of DCB strategies can be assessed either independently or in combined solution scenarios. Simulations of drone operations in the Madrid region are used to test the impact or effectiveness of DCB measures of varying types during the operational phase.

The scenarios are also designed to help to assess the balance between separation/risk-based management of operations through procedural measures and the use of tactical separation management during the execution phase. DCB strategies considered in **experiment #4** scenarios include modifications to the operating ceiling, speed management, directional layers, temporary route networks and delays to operations in response to hotspots that have been identified by the DCM services. Results from the analysis carried out in **experiments #1** and **#3** (for example: layer strategies, departure delay or operating altitude adaptations) are carried over into the **experiment #4** scenarios to help to assess them in the tactical execution phase, and close coordination with findings from **experiment #2** are maintained (e.g. consolidation of hotspot grid cell sizes and temporal dimensions for use in the DCM models etc.).

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The main goal of **experiment #4** is to evaluate the impact of DCB measures on hotspots of various types that have been identified by the DACUS DCM services (Noise/ Visual impact and Collision Risk) on operational capacity, efficiency and safety in the U-Space environment using KPI for U-Space operations identified in the DACUS D5.3 Performance Assessment Framework [2].

2.3.2 Research Challenges

During the elaboration of the DACUS ConOps [3] and the VALP scenarios for validation experiments [1], several Research Challenges (RC) have been selected, along with one additional objective that is related to the influence of micro-weather for drone operation in the urban environment.

The Research Challenges addressed during the different DACUS experiments include:

Research Challenge 1 - Contingency plans as part of the Collision Risk Model
The inclusion of contingency plans within the scope of the Collision Risk Model for UAS operations, which is the main model to determine the maximum number of drone operations in a certain urban area, is subject to further research. drone Operation Plans (DOP) will contain the volumes of airspaces in which the UAS operator plans to conduct the operation under normal procedures and also those volumes of airspace outside the flight trajectory where contingency procedures are applied. The Collision Risk Model could use both of them, in the form of 4D trajectories, to calculate not only the envisioned level of risk under nominal circumstances but also how risk can change if contingency plans need to be implemented. Research on how to deal with these multiple sets of trajectories and the impact on the level of risk should be conducted.

Research Challenge 2 - Consistency of the Collision Risk and Societal Impact Models
Given that drones in urban environments will operate in close proximity to the population, as well as the ground infrastructure, a special emphasis is placed on including both *risk* and *social* indicators as an integral part of the DCB process. The Collision Risk Model will assess overall flight safety and the safety of third parties to ensure it remains acceptably high; the Societal Impact Model will consider social impact factors (such as noise, pollution, and visual impact) will remain below an acceptable threshold (which will be assessed as part of the DACUS validation effort). Both models could have different spatial and temporal variability (e.g., the Societal Impact Model could capture citizens' movement patterns or real-time citizens' positions which could be particularly complex). However, the two models should be combined to help determine the *maximum number of drones which are acceptable* for a given region *from a risk and societal based perspective*. Hence it is necessary to ensure that the outcome of both models can be consistently integrated both in spatial and time domains.

Research Challenge 3 - Consolidation of metrics to determine the maximum number of UAS operations
Several challenges related to the need of evolving from traditional capacity indicators to *risk* and *societal* indicators are subject to further research. Indicators that reflect how citizens are affected by drone operations should be investigated. The need to define what is considered as a "populated area" was identified as part of the DCB concept. This notion should not be simplified to indicators such as population density. For example, to illustrate this idea: Urban areas such as residential suburbs could have high population densities, but residents are not necessarily highly impacted by drone operations as they either stay most of the time inside buildings or are not present during typical working hours. Additionally, trade-off between acceptable risk and societal thresholds with other indicators related to how mission efficiency is impacted by the increase in the number of operations also needs to be further investigated. Previous research projects showed that there is a threshold beyond which the average mission efficiency starts to decrease as the number of drone flights increases within a defined area. Thus, some drone operations would no longer be feasible based on this efficiency/capacity loss.

Research Challenge 4 - Applicable DCB measures and their effectiveness
U-space DCB concept redefines the set of DCB measures which are applicable in urban environments. Although previous research initiatives have analysed some of these measures and their expected benefits, there is a need of assessing consistently their effectiveness not only from the perspective of the network performance but also by assessing how each measure will impact the diverse business models that will coexist in the cities. This needs to be tested in a context in which "*free-route*" operations are facilitated as a general principle. As an example, one of the measures consists of allowing operations above the limit of the VLL airspace (and below minimum operating altitudes for manned aircraft) in those areas where demand exceeds the capacity. However, as it has been identified that cellular network coverage decreases dramatically above the VLL airspace (because network antennas are tilted down), this could be a limiting factor which constraints the effectiveness of that DCB measure.

Research Challenge 7 - Prioritization of drone operations within the DCB process
The thinking in the U-space ConOps is that within any priority level, the selection of flights to act on for DCB or strategic conflict resolution, and how to act on them, should be driven by minimizing the overall impact when all flights are considered. However, this raises the possibility that a particular flight/set of flights/set of mission types (etc.) are always considered the best target for change. Hence the ConOps proposed the idea of using "*Virtue Points*" which would be awarded to operators whose flights were selected to be delayed or rerouted due to DCB actions in the previous periods. These points could then be accumulated by operators and used at a future time to raise the priority of a flight when involved in the DCB process.

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Research Challenge 7 - Prioritization of drone operations within the DCB process
The idea was explored further, and one proposal that was put forward was that *Virtue Points* could also be awarded for other reasons, such as DCB actions that would maximise capacity – however, this remains a somewhat controversial idea at this stage. The notion of *Virtue Points* was included in the DACUS DCB ConOps. However, it is still to be defined whether to include this concept within the process, or if other methods of maintaining equity among operations need to be found. Nevertheless, if this concept is considered feasible, it would be of interest to investigate how to manage its impact on capacity as part of the DACUS research. **Note:** in practice the notion of prioritization (or exemption) of missions was able to be included however comparisons of the impact of selective prioritization was not able to be assesses.

Research Challenge 8 - Operation Plan as up-to-date information for the entire DCB process
The U-space DCB concept recognizes the drone Operation Plan as the "*single point of truth*" which maintains a continuous and up-to-date information source regarding the situation and expected evolution of drone operation in the selected region. However, the document also highlights the difficulties for the drone Operator to participate in a continuous process to keep the Operation Plan updated during the flight execution, or to receive requests to change the Operation Plan in different timeframes along the process. To address this issue, DACUS proposes to reduce up to the minimum the interactions with the drone operator to request these updates. The reconciliation between this idea of the Operation Plan as "*single point of truth*" of the drone operation and entirely managed by the drone operator and the need to reduce the interactions up to the minimum is subject to further research. **Note:** in practice during the DACUS validation process, a common information repository for drone mission profiles was used, however real-time, interactive consultation was not feasible in the scope of the project.

Research Challenge 12 - Impact of weather conditions in the DCB process
The analysis of how the weather conditions (general and/or localised around major structures etc.) could affect the decisions taken on the DCB process. Performing research into these effects is also of interest to enhance research into weather-related effects on drone operations in the urban area. As an example, the impact of weather conditions in the urban environments' infrastructure could constrain certain take-off and landing locations (vertiports) in urban areas at different times of the day.

DACUS Objective 4 – Assess the optimal balance between on-board separation and U-Space separation services

One of the DACUS high level objectives (Objective 4) aims to find the optimal balance between on-board separation intelligence and U-space separation service intelligence in tactical separation depending on the type of airspace (with or without conflict resolution in strategic and/or tactical phases), type of separation (drone-drone or drone-manned aviation), CNS performances and the separation process that applies in each type of airspace area

To respond to the research challenges listed above, the DACUS partners designed experiments which specifically consider different aspects of these challenges at various stages in the planning and execution process as illustrated in the following table:

	OBJ 4	RC 1	RC 2	RC 3	RC 4	RC 7	RC 8	RC 12
EXP#01			EXP1-OBJ2	EXP1-OBJ1	EXP1-OBJ3			
EXP#02		EXP2-OBJ1	EXP2-OBJ3 EXP2-OBJ6				EXP2-OBJ2	EXP2-OBJ4 EXP2-OBJ5 EXP2-OBJ7
EXP#03			EXP3-OBJ1 EXP3-OBJ4	EXP3-OBJ2 EXP3-OBJ3	EXP3-OBJ2 EXP3-OBJ3			
EXP#04	EXP4-OBJ2			EXP4-OBJ3 EXP4-OBJ4 EXP4-OBJ5	EXP4-OBJ1 EXP4-OBJ6 EXP4-OBJ7 EXP4-OBJ8	EXP4-OBJ9 EXP4-OBJ10		EXP4-OBJ11

Figure 4: Summary of Research Challenges considered by the DACUS validation experiments

2.3.3 Summary of experimental scenarios and objectives/RC covered by the exercises

As previously described, the different experiments used in the DACUS assessment process are designed to ***a) address the high-level requirements identified by the project*** and ***b) to help to evaluate how the various research challenges can be addressed*** using the associated models and services at different phases of the drone DCM process.

This is done using a variety of modelling techniques for different regions and under varying demand and operating conditions. For each scenario, specific *experimental objectives* have been elaborated, along with suitable success criteria that contribute to the overall assessment for the high-level objectives. These are described on an experiment-by-experiment basis in the remainder of this section.

Moreover, research challenges and high-level objectives are also be considered in multiple exercises using different experimental approaches to provide a better transversal view of the suitability of the proposed approach.

2.3.3.1 Experiment #1

For **experiment 1,** which is set in a single operating environment for the Toulouse metropole region, the overall objective is to analyse how noise and visual impacts from the social aspect can be used to determine acceptable thresholds for drone operation in populated urban areas.

Different scenarios with increasing traffic load and varying mixes of vehicles are used to help to understand how Noise and Visual impacts manifest in the urban environment and to determine suitable thresholds beyond which mitigation actions may be required to maintain these impacts at socially acceptable levels.

Once established, the noise/ visual impact model can be deployed in other experimental scenarios along with the proposed thresholds to help with the identification and analysis of hotspots of varying types, and the effects of a variety of mitigation actions., such as altitude variation or departure delay.

Traffic used during experiment #1 includes all types of RPAS vehicle including a variety of rotorcraft and fixed wing aircraft with varying size, performance, and equipage.

The experiment identifies three sub-objectives, each of which is designed to evaluate specific research challenges as shown previously in Figure 4:

Validation Objective Id	**EXP1-OBJ1**
Research Challenge assessed	**RC3 –** *Consolidation of metrics to determine the maximum number of UAS operations*
Description	Assess the feasibility of using metrics related to the ***noise*** and ***visual impact*** of drone operations to determine the urban areas in which the demand should be limited, i.e. metrics for the identification of social impact hotspots.
Success Criteria 1	Proposed metrics (parameters selected) allow the identification of (localisation and measures) hot-spots based on the 4D trajectories, where the identification of any one hot-spot encompasses: • It's localisation. It's duration, and • A measure of the impact.
Scenarios	Based on an estimation of package and food deliveries, mainly, we have generated a reference scenario for which all delivery are made by drones (see Appendix A section A.1). We have derived 6 more scenarios by progressively decreasing the number of package and food deliveries (most of the operations). Also, we have generated one scenario with only package delivery and one scenario with only food delivery.

Validation Objective Id	**EXP1-OBJ2**

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Research Challenge assessed	**RC2 –** *Consistency of the Collision Risk and Societal Impact Models*
Description	Assess the consistency of the process to identify *social impact* hotspots and *risk-related* hotspots (from experiment #3) in terms of consistent timeframes and portions of airspace.
Success Criteria 1	The size of cells for noise and visual impact allows us to propose DCB measures with regards to the hotspots identified.
Success Criteria 2	Cadence of measurements is relevant to capture all the hotspots (e.g., every minute, every 5 minutes).
Scenarios	Based on an estimation of package and food deliveries, mainly, we have generated a reference scenario for which all delivery are made by drones (see Appendix A). We have derived 6 more scenarios by progressively decreasing the number of package and food deliveries (most of the operations). Also, we have generated one scenario with only package delivery and one scenario with only food delivery.

Validation Objective Id	**EXP1-OBJ3**
Research Challenge assessed	**RC4 –** *Applicable DCB measures and their effectiveness*
Description	Assess the consistency of the process to identify *social impact* hotspots and *risk-related* hotspots (from experiment #3) in terms of consistent timeframes and portions of airspace.
Success Criteria 1	Application of different DCB measures (e.g., drone flight height, change of trajectory reduces the number of hotspots or moves them.
Success Criteria 2	To be able to propose a ranking in the DCB measures efficiency. In the long term, the chosen DCB measure 'should' always reduce the number of hotspots.
Scenarios	One scenario with only package delivery and one scenario with only food delivery.

In addition to the success criteria identified for the three experimental sub-objectives shown above, an additional but essential output from the experiment #1 scenarios is the availability of validated models that can be used to evaluate the *Noise* and *Visual Impact* effects of drone traffic operating on the population of urban environments at various times of day, and for different regions of interest.

This also assumes that the population density for those regions is available in a suitable *gridded format* that is consistent with the grid/cell sizes that have been determined as part of the Exp1-Obj1 objectives.

Note that comparison or alignment of these grids with those found from experiment #3 is also a desirable outcome, and these grids should be able to be re-used in the other planned experiments (i.e. experiments #2 and #4).

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2.3.3.2 Experiment #2

Experiment 2 considers the use of DCM services supporting collision risk and social impact measures when deployed in the Frankfurt region at the strategic and pre-tactical planning phases. The scenario integrates DCM with other U-Space services and macro/micro weather effects in an integrated operational environment. Simulation focus is on the consistency of the DCM services, with varying levels of traffic demand and complexity (generated by AI-based traffic generation tools) and the impact of uncertainty/contingency in the resulting drone operation plans. To support the analysis of DACUS high level objectives and the research challenges identified previously in Figure 4, 5 sub-objectives are included in the task that consider the influence of uncertainty in the planning phase on the demand and capacity modelling, the influence of contingency situations on the demand and capacity modelling, and the effects of adapted trajectories based on the consideration of the weather limitations of the drone types, including the use of a strategic trajectory planner tool to help optimise missions in response to weather constraints.

Using a specifically developed micro-scale weather model, the influence the weather on infrastructure in urban environments and turbulence issues is also analysed.

Validation Objective Id	EXP2-OBJ1
Research Challenge assessed	**RC1 –** *Contingency plans as part of the Collision Risk Model*
Description	Analyse up to what point the inclusion of contingencies in the planning processes could change the overall demand versus capacity situation, and the existing hot spots in the pre-tactical phase.
Success Criteria 1	The changes in the demand vs. capacity situation can be quantitatively measured based on the activation of contingencies per hazard type: • (partial) loss of autonomy level due to degradation in CNS infrastructure/performance; • loss of landing location (meaning zero capacity) due to weather events and using dedicated emergency vertiports;
Success Criteria 2	The impact of the inclusion of contingencies in the planning processes on existing hot spots can be quantitatively measured.
Scenarios	To address this objective, a baseline scenario representing high-level traffic demand (with a set of 5000 operations in a 3-hour timeframe) was changed depending on the activation of large-scale contingency events. To this end, four contingency event scenarios (two modelling GNSS performance disruption and two modelling loss of landing location / vertiport) were modelled. In total, 5 scenarios were used, and the four contingency event scenarios were compared with the baseline in terms of computed hotspot results.

Validation Objective Id	EXP2-OBJ2

Research Challenge assessed	**RC8 –** *Operation Plan as up-to-date information for the entire DCB process*
Description	Analyse up to what point the uncertainty or lack of information provided by the drone operator in the initial submission of the Operation Plans could change the overall demand versus capacity situation, and the existing hot spots.
Success Criteria 1	The changes in the demand vs. capacity situation can be quantitatively measured Definition of baseline demand & capacity situation for the experimental scenario.
Success Criteria 2	Implementation of uncertainties to the experiment and definition of the minimum required information input needed by the operator to be able to create a reliable DCB analysis.
Scenarios	To address this objective, a baseline scenario representing high-level traffic demand (with a set of 5000 operations in a 3-hour timeframe) was modified and an uncertainty component in the temporal domain was included. The uncertainty component models the operational uncertainty in operator preparations at the pre-tactical. In total, 2 scenarios were used, and the uncertainty-based scenario was compared with the baseline in terms of computed hotspot results

Validation Objective Id	**EXP2-OBJ4**
Research Challenge assessed	**RC12 –** *Impact of weather conditions in the DCB process*
Description	Analyse up to what point weather conditions affect the infrastructure in urban environments and therefore the capacity. Especially, the impact of weather forecasts will be assessed.
Success Criteria 1	The quality of the weather forecast allows to characterize the availability of the take-off and landing locations (vertiports) in urban areas.
Success Criteria 2	The changes in the demand vs. capacity situation can be quantitatively measured.
Scenarios	To address this objective, a baseline scenario representing high-level traffic demand (with a set of 5000 operations in a 3-hour timeframe) was modified and the trajectories were re-calculated. For the re-calculation, wind limitations of the vehicle type were considered and two direction of wind flows were taken on board. In total, 2 scenarios were used and the adapted scenario was compared with the baseline in terms of computed hotspot results.

Validation Objective Id	**EXP2-OBJ5**

Research Challenge assessed	**RC12 –** *Impact of weather conditions in the DCB process*
Description	Analyse up to what point high turbulences / high winds affect low weight drones, in order to identify the areas to be avoided by this type of drones.
Success Criteria 1	The weather forecast allows to mark high turbulences / high wind areas for all relevant airspace levels in low weight drone operations.
Scenarios	To address this objective, scenarios consisting of wind field simulations were used. To model different wind conditions, two levels of wind speed (5m/s and 10m/s) and two levels of global wind flow direction (Southwind and Westwind). Furthermore, two weather simulations in two types of urban environments (urban and suburban) were assessed. In total, 9 scenarios were used and the available layers/volumes were assessed based on performance model of 3 different drone types.

Validation Objective Id	**EXP2-OBJ6**
Research Challenge assessed	**RC2 –** *Consistency of the Collision Risk and Societal Impact Models*
Description	Assess the consistency of the process to identify social impact hot-spots and risk-related hot-spots in terms of consistent timeframes and portions of airspace.
Success Criteria 1	The hotspots from the Social Impact and Risk model are consistent regarding their spatial resolution (e.g. matching grids) and their temporal resolution (similar time scale).
Scenarios	To address this objective, the baseline scenario representing high-level traffic demand (with a set of 5000 operations in a 3-hour timeframe) was used.

Validation Objective Id	**EXP2-OBJ7**
Research Challenge assessed	**RC12 –** *Impact of weather conditions in the DCB process*
Description	Assess the relevance of weather information as part of the DCB process in terms of its impact on operations and planning of capacity related measures e.g., scarcity of TOLAs and contingency sites, emergence of new hot spots or weather-related delays, which offset demand.
Success Criteria 1	Reduction of TOLAs as consequence of weather-related closures

	Quantify the improvement of demand forecasts by taking into account weather information.
Success Criteria 2	Reduction of Contingency sites as a consequence of weather-related closures
Success Criteria 3	Flight cancellations appear mostly in the delivery sector
Success Criteria 4	Analysis of affected business sectors shows that not all types of missions can or will be postponed
Success Criteria 5	Analysis of results measuring the average variation on the number of movements per unit of time (capacity) in a vertiport due to weather measures a degradation on the capacity due to weather even for wind values that are within the operating margin considered in 2.7.1
Scenarios	To address this objective, three types of global scenarios were distinguished and are partially connected with scenarios from previous objectives: • Scenarios for assessing the impact on TOLA and contingency sites. Compare with scenarios in **EXP2-OBJ5** • Scenarios for assessing operation cancellations due the impact of wind conditions on the drone wind limitations. Compare with scenarios in **EXP2-OBJ4** Scenarios for the assessing the impact of weather conditions on vertiport capacity.

Validation Objective Id	**EXP2-OBJ8**
Research Challenge assessed	**RC12 –** *Impact of weather conditions in the DCB process*
Description	Analyse up to what point a baseline scenario of high traffic demand can be defined after comparing multiple demand level simulations and using the city of Frankfurt as urban environment.
Success Criteria 1	The defined quantitative metrics enable the analysis of traffic in the spatial and temporal domain.
Success Criteria 2	A baseline scenario of high traffic demand that impacts the demand vs. capacity situation can be identified.
Scenarios	To address this objective, 2 scenarios representing low-level traffic (set of 1000 operations) and high-level traffic (set of 5000 operations) were used and the resulting total hotspot view (integrated risk and social hotspots)

2.3.3.3 Experiment #3

Experiment 3 analyses different scenarios in the Strategic Phase, to test the effect of considering different CNS performances and defining different airspace structures on the maximum acceptable capacity in a certain scenario, comparing the collision risk calculated for each scenario with a certain Target Level of Safety (defined for DACUS purposes as 1E-6 fatalities/flight hour, as per the SORA methodology - *noting that on-going research projects such as BUBBLES [15] are looking at possibly more stringent constraints on this TLS*)

Validation Objective Id	**EXP3-OBJ1**
Research Challenge assessed	**RC2 –** *Consistency of the Collision Risk and Societal Impact Models*
Description	Assure that **overall flight safety and the safety of third parties remains acceptably high** by comparing the Collision Risk model to a certain TLS.
Success Criteria 1	The collision risk calculated in different simulations, increasing sequentially the number of drones, remains below the TLS of 1e-6, per SORA methodology [7], if the capacity (drone density) is limited to a certain threshold (maximum density of drones).
Scenarios	Exp3 Scenario 3 considers different environments (Madrid, Toulouse, Toledo) and different areas in the cities with different population densities and sheltering factors to assess the applicability and consistency of the collision risk analysis approach.

Validation Objective Id	**EXP3-OBJ2**
Research Challenge assessed	**RC3 –** *Consolidation of metrics to determine the max number of UAS operations* **RC4 –** *Applicable DCB measures and their effectiveness*
Description	Introduce in the Collision Risk model different CNS performances assumptions **to analyse the impact on the collision risk** and the different business models that will coexist in the cities.
Success Criteria 1	Estimate different acceptable capacity thresholds depending on Navigation accuracy, communications update rate and tracking integrity.
Success Criteria 2	Estimate the collision risks in a certain scenario depending on Navigation accuracy, communications update rate and tracking integrity.
Scenarios	This scenario will compare the collision risk and, especially, the risk of non-avoidable collisions with a U-space Tactical Deconfliction service in place, for a reference case and several variations of different CNS performances: navigation accuracy, navigation integrity errors, communications update rate and probability of surveillance detection

Validation Objective Id	**EXP3-OBJ3**

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Research Challenge assessed	**RC3 –** *Consolidation of metrics to determine the max number of UAS operations* **RC4 –** *Applicable DCB measures and their effectiveness*
Description	Estimate collision risk and maximum capacity considering **different airspace structures** (free route, layers, etc.).
Success Criteria 1	Estimate different acceptable capacity thresholds depending on the airspace structure restrictions.
Success Criteria 2	Estimate the collision risks in a certain scenario depending on the airspace structure restrictions.
Scenarios	Different techniques to reduce the collision risk have been considered in Exp3 Scenarios 4&5, including separation minima criteria by means of strategic deconfliction and airspace structures (layers and sectors)

Validation Objective Id	**EXP3-OBJ4**
Research Challenge assessed	**RC2 –** *Consistency of the Collision Risk and Societal Impact Models*
Description	Estimate the **effect on false conflict alert rate of the safety margin** to minimise the collisions risk.
Success Criteria 1	Calculate the number of undetected collisions and false conflicts as a function of the safety margin.
Scenarios	Exp3 Scenario 2 analyses the impact of different conflict margins in the overall collisions detected and the impact of the navigation accuracy on the optimum conflict margin.

2.3.3.4 Experiment #4

Experiment 4 considers the use of DCM services supporting collision risk and social impact measures when deployed in the Madrid region during the pre-tactical and execution phases.

The scenarios use DCM services in conjunction with other U-Space services in an integrated operational environment then introduces a variety of Demand Capacity Balancing actions to help evaluate the effectiveness and impacts of the DCM/DCB process.

A fast-time simulation tool is used to quantify the DCB experiments using measurable metrics/KPI (Key Performance Indicators). A reference/baseline scenario was designed and validated to represent and measure baseline operations and performance metrics.

Thereafter, alternative solution scenarios are designed using the baseline scenario with DCB measures applied to hotspot polygon cells that were identified by the DCM tools which were previously validated in experiments #1 and #3.

KPA performance metrics that are aligned with the DACUS performance framework [2] are used to compare the alternatives against the baseline scenario to determine if an alternative scenario performs better or worse than the baseline scenario.

For additional details on the various experiment #4 scenarios, and results obtained, please refer to Annex D of this report.

The following experimental objectives have been considered to help understand how DCM services combined with other U-Space services and functions and the implementation of DCB measures can help identify and mitigate different hotspot situations and respond to key research challenges considered in experiment #4.

Validation Objective Id	**EXP4-OBJ1**
Research Challenge assessed	**RC4 –** *Applicable DCB measures and their effectiveness*
Description	Assess the effectiveness of DCB measures when unexpected events take place in the tactical phase.
Success Criteria 1	Analyse the time to recover from degraded to nominal conditions, in scenarios #1 (Reference) and #2 to #N (all DCB variants). The recovery time from periods with extended hotspots and degraded operations to nominal hotspot free conditions should be lower in the DCB scenarios (#2 to #N)
Success Criteria 2	Analyse the number of tactical conflicts. The number of tactical conflicts is expected to be lower in the DCB variant scenarios (#2 to #N)
Scenarios	Scenario #1 is the ***Reference scenario*** for the Madrid region from which initial filed DOP are extracted and analysed using the DCM services to determine Collision Risk (CR), Noise, and Visual Impact (SOC) hotspots in the traffic baseline. Hotspot cells identified in the *Reference scenario* are added to the ***DCB variant scenarios*** – each of which has specific mitigation strategies assigned to groups of flights in cells that have been identified as either a CR or SOC hotspot. The traffic demand and initial DOP *are the same in all scenarios*, where DCB actions may modify requested mission profiles in accordance with the strategy assigned for Hotspot mitigation actions **Note:** unexpected event scenarios were not considered in the scope of DACUS due to time constraints.

Validation Objective Id	**EXP4-OBJ2**
Research Challenge assessed	**OBJ4 - find the optimal balance between on-board separation intelligence and U-space separation service intelligence in tactical separation** depending on the type of airspace (with or without conflict resolution in strategic and/or tactical phases), type of separation (drone-drone or drone-manned aviation),

	CNS performances and the separation process that applies in each type of airspace area
Description	Optimise decision making between on-board capabilities and U-space separation services.
Success Criteria 1	The program establishes separation rules based on the hierarchy set.
Scenarios	A comparison of the number and complexity of tactical conflicts arising in the reference scenario and those found in the DCB variant scenarios is performed.

Validation Objective Id	**EXP4-OBJ3**
Research Challenge assessed	**RC3 –** *Consolidation of metrics to determine the max number of UAS operations*
Description	Evaluate and consolidate metrics in terms of capacity to determine the maximum number of UAS operations.
Success Criteria 1	Run the baseline ***Reference scenario*** and all the different ***DCB variant scenarios*** and analyse variations in capacity metrics.
Success Criteria 2	Analyse the *drone base* (vertiport/origin) and "*en-route*" throughput in challenging airspace areas (hotspot). This one has to be higher in scenario #1.
Scenarios	The Reference scenario (#1) is executed using the baseline traffic demand and no DCB actions to determine the number of operations in each of the reference grid cells (aligned with the DCM cells). The scenario is executed in conflict detection only mode (to analyse the planned track interactions) and with the Tactical Conflict Resolution active (to evaluate the final counts including resolution actions that were required when drones plans were executed in the region). Each DCB variant scenario (#2 to #N) is executed with the hotspot cells and associated DCB strategy being applied to sets of flights. These scenarios are also executed in detection only mode and with the Tactical Conflict Resolution service active to allow ***capacity KPI comparisons*** against the Reference Scenario.

Validation Objective Id	**EXP4-OBJ4**
Research Challenge assessed	**RC3 –** *Consolidation of metrics to determine the max number of UAS operations*
Description	Evaluate and consolidate metrics in terms of efficiency to determine the maximum number of UAS operations.
Success Criteria 1	Run different scenarios and analyse variations in efficiency metrics.

Scenarios	The Reference scenario (#1) is executed using the baseline traffic demand and no DCB actions to determine the number of operations in each of the reference grid cells (aligned with the DCM cells). The scenario is executed in conflict detection only mode (to analyse the track interactions) and with the Tactical Conflict Resolution active (to evaluate the final counts including resolution actions that were required). Each DCB variant scenario (#2 to #N) is executed with the hotspot cells and associated DCB strategy being applied to sets of flights. These scenarios are also executed in detection only mode and with the Tactical Conflict Resolution service active to allow ***efficiency KPI comparisons*** against the Reference Scenario.

Validation Objective Id	**EXP4-OBJ5**
Research Challenge assessed	**RC3 –** *Consolidation of metrics to determine the max number of UAS operations*
Description	Evaluate and consolidate metrics in terms of resilience and flexibility to determine the maximum number of UAS operations.
Success Criteria 1	Analyse the number of re-scheduled, delayed, and cancelled flights in each of the defined scenarios.
Success Criteria 2	Analyse the drone base and “enroute” throughput.
Success Criteria 3	Analyse the time to recover. This one should be higher in scenario #1.
Success Criteria 4	Run different scenarios and analyse variations in resilience metrics
Scenarios	The Reference scenario (#1) is executed using the baseline traffic demand and no DCB actions to determine the number of operations in each of the reference grid cells (aligned with the DCM cells). The scenario is executed in conflict detection only mode (to analyse the track interactions) and with the Tactical Conflict Resolution active (to evaluate the final counts including resolution actions that were required). Each DCB variant scenario (#2 to #N) is executed with the hotspot cells and associated DCB strategy being applied to sets of flights. These scenarios are also executed in detection only mode and with the Tactical Conflict Resolution service active to allow ***resilience and flexibility KPI comparisons*** against the Reference Scenario. **Note** that in the scope of the DACUS analysis, time to recover was not assessed.

Validation Objective Id	**EXP4-OBJ6**

Research Challenge assessed	**RC4 –** *Applicable DCB measures and their effectiveness*
Description	Evaluate how DCB measures act in scenarios #2 to #N
Success Criteria 1	Run scenarios #1 and #2 to #N and analyse variations in all the metrics.
Success Criteria 2	Estimate the loss of capacity in airspace avoided. This one has to be higher in scenario #2 to #N
Scenarios	The Reference scenario (#1) is executed using the baseline traffic demand and no DCB actions to determine the number of operations in each of the reference grid cells (aligned with the DCM cells). The scenario is executed in conflict detection only mode (to analyse the track interactions) and with the Tactical Conflict Resolution active (to evaluate the final counts including resolution actions that were required). Each DCB variant scenario (#2 to #N) is executed with the hotspot cells and associated DCB strategy being applied to sets of flights. These scenarios are also executed in detection only mode and with the Tactical Conflict Resolution service active to allow evaluation of the ***effectiveness of each DCB strategy*** compared to the Reference Scenario and to each other. An *additional DCB scenario* using a combination of DCB solutions is also included to determine if it delivers better performance KPI than single strategy solution(s).

Validation Objective Id	**EXP4-OBJ7**
Research Challenge assessed	**RC4 –** *Applicable DCB measures and their effectiveness*
Description	Evaluate the effectiveness of the DCB measures in scenario #2
Success Criteria 1	Run scenarios #1 and #2 to #N and analyse variations in metrics. These values have to be higher than a "threshold value" to determine if they are effective or not
Success Criteria 2	Estimate the loss of capacity in airspace avoided. This one has to be higher in scenario #2.
Scenarios	The Reference scenario (#1) is executed using the baseline traffic demand and no DCB actions to determine the number of operations in each of the reference grid cells (aligned with the DCM cells). The scenario is executed in conflict detection only mode (to analyse the track interactions) and with the Tactical Conflict Resolution active (to evaluate the final counts including resolution actions that were required). Each DCB variant scenario (#2 to #N) is executed with the hotspot cells and associated DCB strategy being applied to sets of flights. These scenarios are also executed in detection only mode and with the Tactical Conflict Resolution

	service active to allow ***evaluation of the effectiveness of each strategy*** compared to the Reference Scenario and to each other. An *additional DCB scenario* using a combination of DCB solutions is also included to determine if it delivers better performance KPI than single strategy solution(s). All of the scenarios are used to evaluate the ***effectiveness of different measures either in isolation or mixed to determine how much traffic can operate in various cells across the region with those strategies in place***. The analysis also determines if the strategies can reduce hotspots and maintain the risk-based measures within the desired thresholds.

Validation Objective Id	**EXP4-OBJ8**
Research Challenge assessed	**RC4 –** *Applicable DCB measures and their effectiveness*
Description	Determine which DCB measures are better in scenario #2 to #N
Success Criteria 1	Run scenarios #1 and #2 to #N plus the additional 'mixed' DCB scenario and analyse variations in metrics
Success Criteria 2	Design a matrix that assigns a value to each of the DCB measures in terms of their effectiveness in each simulated scenario. Then, the measures which present the best values will be selected.
Scenarios	The Reference scenario (#1) is executed using the baseline traffic demand and no DCB actions to determine the number of operations in each of the reference grid cells (aligned with the DCM cells). The scenario is executed in conflict detection only mode (to analyse the track interactions) and with the Tactical Conflict Resolution active (to evaluate the final counts including resolution actions that were required). Each DCB variant scenario (#2 to #N) is executed with the hotspot cells and associated DCB strategy being applied to sets of flights. These scenarios are also executed in detection only mode and with the Tactical Conflict Resolution service active to allow ***evaluation of the effectiveness of each strategy*** compared to the Reference Scenario and to each other. Using the generated comparison matrix, an evaluation of how solutions could be combined for use in the *additional DCB scenario* is performed. Promising combinations are then executed to determine if the deliver better performance KPI than single strategy solution(s).

Validation Objective Id	**EXP4-OBJ9**
Research Challenge assessed	**RC7 –** *Prioritization of drone operations within the DCB process*

Description	Evaluate the possibility to assign "virtue points" to specific drones in order to prioritize their operations within the DCB process
Success Criteria 1	Run scenarios #1, #5 and #8 and analyse variations in metrics
Success Criteria 2	Analyse the number of re-scheduled, delayed, and cancelled flights in each of the defined scenarios.
Success Criteria 3	Estimate the loss of capacity in airspace avoided
Scenarios	However, using the RAMS 'flight set' feature and hotspot polygon attributes can allow the DCB variant scenarios to systematically 'exclude' some operations from the set of flights that were 'impacted' by the DCB constraint and to fly through hotspot cells 'as planned' – this could be a suitable initial proxy to represent the 'effect of allowing flights that have sufficient '*virtue points*' to pass through the hotspot areas unimpeded and can certainly help to evaluate the effect of the RC7 challenge. **Note:** in practice only a limited set of mission types were exempted from the DCB measures and no comparison of the impact of those exemptions was performed during the final analysis.

Validation Objective Id	**EXP4-OBJ10**
Research Challenge assessed	**RC7 –** *Prioritization of drone operations within the DCB process*
Description	Evaluate the impact of assigning virtue points in the DCB process in terms of capacity, effectiveness and resilience.
Success Criteria 1	Estimate the loss of capacity in airspace avoided.
Success Criteria 2	Run scenarios #1, #5 and #8 and analyse variations in metrics.
Scenarios	However, using the RAMS 'flight set' feature and hotspot polygon attributes can allow the DCB variant scenarios to systematically 'exclude' some operations from the set of flights that were 'impacted' by the DCB constraint and to fly through hotspot cells 'as planned' – this could be a suitable initial proxy to represent the 'effect of allowing flights that have sufficient '*virtue points*' to pass through the hotspot areas unimpeded and can certainly help to evaluate the effect of the RC7 challenge. **Note:** in practice only a limited set of mission types were exempted from the DCB measures and no comparison of the impact of those exemptions was performed during the final analysis.

Validation Objective Id	**EXP4-OBJ11**

Research Challenge assessed	**RC12 –** *Impact of weather conditions in the DCB process*
Description	Evaluate the impact of meteorology (strong wind gusts) in drone trajectories in terms of capacity, resilience and efficiency.
Success Criteria 1	Run scenarios #1, #7 and #8 and analyse variations in metrics.
Success Criteria 2	Assess DCB measures in bad weather condition scenarios.
Scenarios	All of the scenarios used in the previous experimental scenarios (#1 reference and #2 to #N + combined DCB scenarios) can have a wind grid introduced. Re-executing them with wind grid active will allow for some comparisons to be made (nominal weather vs winds) but no features exist at this stage to allow operations to be diverted away from areas where wind it 'too high' (unless we use restricted areas or another polygon with an avoid strategy for low wind resistant types). Therefore, a wind impacted set of scenarios can be modelled but maybe review once other scenarios are complete. Additionally, vertiport capacity reduction/closure due to weather is not included in the RAMS model at this point. **Note:** Due to time constraints, local winds that had been included in the analysis scenarios were not activated during the simulations so this objective was not assessed.

2.3.4 Validation Assumptions

The validation assumptions that were listed in the WP4 D4.1 – Scenarios for validation experiments document [1] have been applied for each of the four validation exercises performed as part of the research project. In the interest of completeness, these assumptions are included in the various Annexes that provide a detailed description of each set of experiments and the results obtained.

In addition to those assumptions, a new assumption is included in experiment #2 which relates to DOPS that are filed to the U-Space service which also include a suitably encoded contingency plan – which allows a defined action or actions to be implemented if a contingency situation occurs during a scenario (e.g. loss of Vertiport).

2.4 Deviations

2.4.1 Deviations with respect to the Experiment Plan

In **experiment #1**, the following deviations with respect to DACUS D4.1 Validation Plan were identified:

- Number of scenarios has changed: Two load of traffic was expected initially, nominal, and high traffic. We decided to start with the highest possible volume of traffic, based on assumptions, and decrease it progressively: This resulted in 6 scenarios ranging from the highest to the lowest traffic load.

- No distinction between operating conditions were made. However, we decided to change the traffic mix, especially by allowing only some kinds of operation in different scenarios: 2 specific scenarios with either no package delivery or no food delivery.

The reported deviations have no impact on the results.

In **experiment #2**, the following deviations with respect to DACUS D4.1 Validation Plan were identified:

General deviations from Validation Plan:

- Scenarios have been extended to also include weather along with contingency plans and operational uncertainty to support a more accurate impact analysis. There is no variation of airspace restrictions due to ad-hoc constraints.

- In objective 2.4 we expected to look into the impacts of weather forecast. In fact, since the experiments are taking place in the strategic phase, the implemented weather scenarios are per se forecast. But we will not investigate the different uncertainty attached to forecasts depending on the timeframe before the assessment. Instead, uncertainty will be covered in general in objective 2.2.

- The infrastructure component has been moved from 2.4 to objective 2.7. The consequence is that the objective is refocused on the overall effect on the whole traffic picture. Vehicle specific effects are moved to objective 2.5.

- Although the construct for publishing Drone Operation Plans incorporates the capability to include uncertainty using probabilistic 4D positions, in practice probabilistic trajectories were not considered as part of the DOP submitted to the DCM processes. Instead, time uncertainties were incorporated into the Collision Risk modelling service to capture uncertainty in mission trajectories of up to 5-minutes on any 4D point.

- Additional modifications to trajectories, referred to a 'adapted' trajectories were also included in the analysis, where these adaptations were provided by the prototype Trajectory Planner tool in response to adverse weather conditions which missions must avoid.

The reported deviations have the impact that only certain parameter levels are assessed and compared against the baseline scenario. However, in making these changes, a more accurate assessment of their impact can be performed.

Deviations in specific objectives

- Objective 2.1.- The contingency event scenario dealing with the reduction of vertiport capacity based on weather event was not examined in the scope of this objective experiments. However, the impact of weather events on the vertiport capacity was addressed in Objective 2.7.

- Objective 2.2.- Only one level of operational uncertainty was examined, namely time uncertainty. The other aspects (combined time and vertical uncertainty, and combined time, vertical, horizontal uncertainty) were not examined in the experiments

- Objective 2.3 (Analyse the effects of CNS performances such as navigation accuracy and communication update rate): This objective was not addressed in the scope of the experiments. However, the impact of CNS performances was extensively analysed in Experiment 3.

- Objective 2.4.- It was not mentioned in the Validation Plan that for this objective also a comparison analysis (baseline vs. modified scenario) was carried out. This allowed to measure the impact of the adapted trajectories. The weather impact assessment in relation to different vehicle types and performances was examined in Objective 2.5.

- Objective 2.5.- The success criteria regarding the availability to plan the avoidance of high wind areas without overloading the neighbouring areas / zones was not addressed in the scope of this experiment. However, it was tackled as part of Objective 2.4 since the adapted trajectories could avoid high wind areas.

- Objective 2.6.- The assessment of hotspot sizes with regard to the suitability to use them for DCB measures was not addressed in this objective, but in Experiment 4. This objective focused on the consistency of social and risk-based hotspots in order to produce a total hotspot view.

- Objective 2.7: Additional assessments were included in the scope of this objective, as within the development and implementation phases it became clear that the impact of weather conditions are manifold.

- Objective 2.8: This is an additional objective that was not reflected in the Validation Plan, but it was necessary to represent a high-level demand of drone operations covering multiple mission types (transport, surveillance, and inspection).

In the **experiment 4**, the following deviations with respect to DACUS D4.1 Validation Plan were identified:

- Use of the DCM services through an interoperable process and with a '*single source of truth*' – in the initial planning for experiment #4, DCM services were intended to be used in a real-time, interoperable manner.
  The initial prototype implementation was able to achieve this interconnection, through the publication of DOP from the *droneZone* fast time simulation tool to the U-Space Common Information System (U-CIS). Once published, DCM processes for noise and visual impact assessment can be triggered, however due to computational performance constraints that required significantly longer processing times to analyse large numbers of active DOP for noise/visual hotspots, it was decided to employ an offline connection for the analysis process. Nevertheless, work on testing the initial interoperable prototype with UCIS and connected DCM services is continuing to provide a demonstrator platform and this provides an interesting opportunity for future enhancement/development and research into the service-based deployment of the DACUS DCM processes.

- Due to the change in the methods used to consult DCM services, it was not possible to include scenarios where the concept of 'virtue points' could be evaluated. This remains an interesting research topic that can be further assessed in the future now that the fundamental approach using risk and societal based metrics to manage demand has been validated.

- Impact of weather conditions on the DCB process – the impacts of weather on DCB during the execution phase were not able to be included in the scope of the FTS simulations.

However, additional experiments performed as part of **experiment #2** were able to investigate weather impact on drone operation in the urban environment and on the capacity/accessibility of vertiports.

The reported deviations for experiment #4 did not impact the assessment of DCM actions in the pre-tactical and tactical execution phases under nominal conditions. However, sub-nominal scenarios with adverse weather effects were not able to be considered as part of the experiment. Instead, additional experiments were performed as part of experiment #2 which included detailed impact analysis of micro weather effects in the urban environment and capacity reduction/closures of vertiports due to weather.

DCB scenarios in experiment #4 were able to systematically exclude key traffic (e.g. medical emergency missions or traffic surveillance) from hotspot mitigation actions. However, no comparisons were performed to determine how such exemptions impacted other planned missions and the concept of ‘virtue points’ was not expanded in the scenarios.

Real-time consultation of the DCM services via the U-CIS platform was replaced by static publication and consultation in both experiment #2 and #4. Nevertheless, the U-CIS platform was used as the common information source for DOP and the social risk services consumed the data published in U-CIS to carry out the Noise and Visual impact analysis. Results were then manually injected into the FTS analysis platform to declare hotspots and include DCB measures in the various analysis scenarios.

3 Experimental Results

3.1 Summary of experimental results

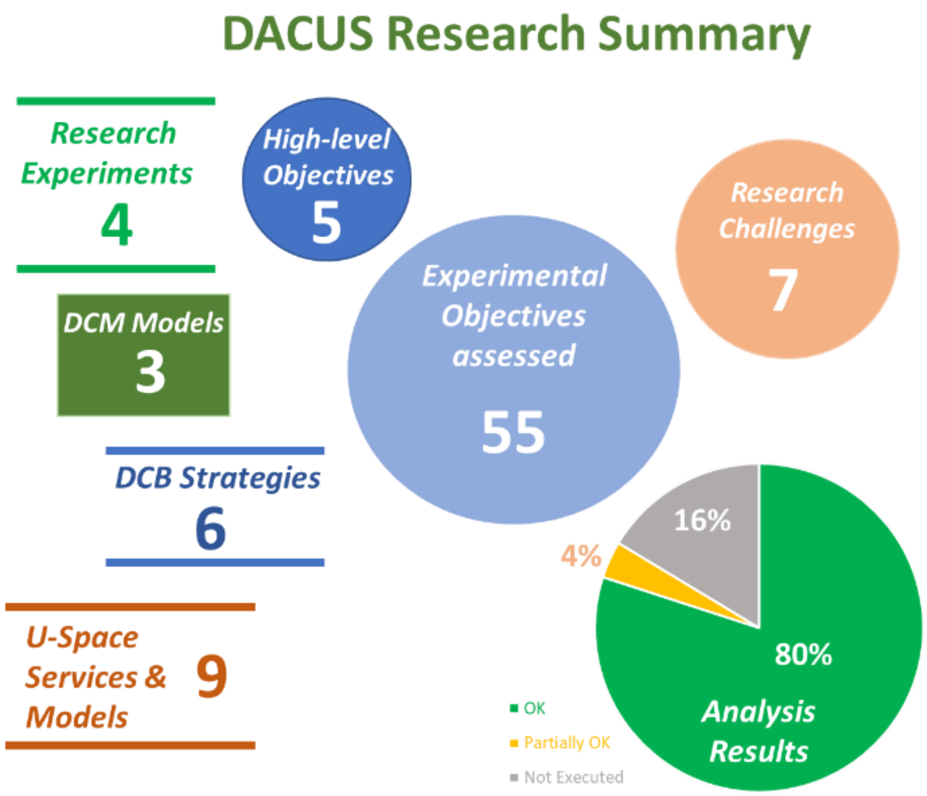

Figure 5: Summary of Validation Exercises & Results

The four research experiments described previously and detailed in *Annexes A through D* of this document, considered the 5 high-level DACUS objectives using 55 specific experimental objectives and the 3 DCM service prototypes.

These were supported by up to 9 different models of U-Space services, ranging from mission planning to execution and including micro-weather and a wind-impacted vertiport capacity model. Exercises carried out in the various analysis exercises focused on the 7 main research challenges and 6 different DCB mitigation strategies were considered in different experimental scenarios.

Overall results for all experiments showed that around ***80% of the success criteria identified in the analysis were achieved successfully***, with a further ***4% being partially achieved*** as detailed in the next section.

Due to time constraints and other technical issues, around 16% of the original objectives that were identified during the experimental design were unable to be executed during the validation phases.

3.2 Results per experimental objectives

This section provides a summary of the results for each of the experiments based on the objectives and success criteria being considered. Detailed results are provided for each of the experiments in the corresponding appendix.

3.2.1 Experiment #1 Results

3.2.1.1 Experiment #1 - Objective 1.1 assessment results

Experiment #1 objective 1.1 aims to **assess the feasibility of using metrics related to the noise and visual impact of drone operations (RC3)** to determine urban areas in which the demand should potentially be limited to maintain noise or visual impacts within a determine maximum level for the population in that area, i.e. using metrics for the identification of social impact hotspots.

Three main analysis/assessments techniques were used to measure the level of success for this objective:

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
Focus on location of hotspot.	Proposed metrics (parameters selected) allow the identification of hotspot locations based on the 4D trajectories.	OK
Focus on duration of hotspot.	Proposed metrics (parameters selected) allow the identification of hotspot duration based on the 4D trajectories.	OK
Impact threshold variation and hotspot parameters correlation.	Impact threshold and parameters allow to identify hotspot.	OK

Table 3. DACUS Experiment #1 - OBJ1.1 assessment result

The selected social impact indicators allow for the identification of hotspots in both space and time.

Two important parameters to characterize hotspots were evaluated as part of the analysis: length and frequency:

- Length of hotspot is the duration in minutes.
- Frequency is defined as the total number of minutes a region is subject to a hotspot during a given timeframe – where this last parameter aims to capture the frequency as well as the duration of hotspots for the different indicators.

  The experiments showed that cells of 1 kilometre square provide a good mapping of hotspot localisations. It allows to precisely distinguish the origins of hotspots like logistics warehouses or city centre restaurants for instance. It is also a trade-off with calculation time as the more cells depict a city, the longer is the calculation.

  The model provides duration of hotspots in minutes in each cell as well as the duration of the whole hotspots that occurred in the same cell.

The different thresholds defined revealed hotpots as soon as reached. The results show for instance that noise annoyance critical threshold would be 3000 for 3000 operations in two hours.

3.2.1.2 Experiment #1 - Objective 1.2 assessment results

Objective 1.2 aims to **assess the consistency of the process to identify social impact hotspots in terms of consistent timeframes and portions of airspace (RC2)**. This is also compared with the hotspot timeframes and airspace cell dimensions used by the collision risk assessment model (experiment #3).

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
DCB measure based on hotspot	The size of cells for noise and visual impact allows us to propose DCB measures with regards to the hotspots identified.	OK
Measurements cadence	Measurements cadence is relevant to capture all the hotspots (e.g., every minute, every 5 minutes).	OK

Table 4. Experiment #1 - OBJ1.2 assessment result

The size of the analysis cells that were used for the noise and visual impact assessment (1km x 1km) and the cadence of those measurements allow the model to identify, explain and take DCB measures on triggered hotspots.

Automatic DCB measures such as altitude variations and departure delays on flights, applied one-by-one on a theoretical basis resulted in a decrease the number of hotspots, with up to 60% of the hotspots being reduced in some situations.

3.2.1.3 Experiment #1 - Objective 1.3 assessment results

Objective 1.3 considers **the applicability of DCB measures and their effectiveness (RC4)** and looks to identify those DCB measures which are more effective from the perspective of the reduction of noise and visual impact of drone operations, i.e. to assess the applicability of DCB measures for the resolution of social impact hotspots.

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
Hotspot behaviour after application of global DCB measures	Application of automatic global DCB measures (drone flight height modification or departure delay) reduces the number of hotspots or moves them.	OK
DCB measures ranking	Being able to propose a ranking in the DCB measures efficiency. At long term, the chosen DCB measure always reduce the number of hotspots.	OK

Table 5. DACUS Experiment #1 - OBJ1.3 assessment result

Automatic DCB measures such as altitude variation and departure delay on flights were able to decrease the number of hotspots, with up to 60% reduction of the hotspots in some situations.

A DCB measures ranking based on scores can decrease the number of hotspots even further, up to 80%. In some situations, but in general, DCB measure ranking seems comparable to randomly selecting

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DCB measures, in terms of number of hotspots. However, the number of tests needed to select a measure always decreases when using a ranking approach compared to a random one.

The number of tests required to decrease the hotspots number with the scored approach has been divided up by 2 compared to the random approach for a number of hotspots decrease of 78% without DCB measure.

Even when the gain is quite similar compared with the random approach, scored approach requires less tests (almost 30%).

3.2.2 Experiment #2 Results

3.2.2.1 Experiment #2 - Objective 2.1 assessment results

Experiment #2 objective 2.1 considers the **use of contingency plans as part of the DCM process (RC1)** and aims to analyse up to what point weather conditions affect the infrastructure in urban environments and therefore the capacity and how pre-defined contingency actions can help maintain a balanced demand in response to the reduced capacity.

For this assessment, two simulation analysis techniques applied in a realistic operational environment were used:

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
Simulation of contingency scenario: loss of landing location	The changes in the demand vs. capacity situation can be quantitatively measured	OK
Simulation of contingency scenario: degradation in CNS infrastructure performance	The changes in the demand vs. capacity situation can be quantitatively measured	OK

Table 6. DACUS Experiment #2 – OBJ2.1 assessment result

Using the success criteria shown above, it is concluded that through the calculation of Collision Risk and Social Impact hotspot values, it is possible to measure changes in the demand vs. capacity situation

In the contingency scenarios representing a loss of landing locations, the peak of maximum airborne flights is 108% higher than compared to the baseline scenario, because the delayed flights are randomly scheduled after the contingency situation is over and these delayed flights happen at the same time as regularly planned flights.

In the CNS degradation scenarios, the maximum value of simultaneously airborne drones increases by 111 % due to the same reason as in the first contingency scenario.

Regarding the development of collision risk, it can be stated that in all four contingency scenarios, the maximum average and the maximum instantaneous collision risk increase by several orders of magnitude compared to the baseline scenario. Besides it is evident that the event of degradation of CNS infrastructure performance has a much more severe impact on the collision risk values than the loss of landing locations.

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3.2.2.2 Experiment #2 - Objective 2.2 assessment results

Experimental objective 2.2 considers how **the operation plan can provide the most up-to-date information for the entire DCB process (RC8)** and analyses up to what point the **uncertainty** or lack of information provided by the drone operator in the initial submission of the drone Operation Plans can impact the overall demand versus capacity situation, and the hotspots that are identified by the DCM services.

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
Simulation of time uncertainty	The changes in the demand vs. capacity situation can be quantitatively measured	OK
Simulation of time and vertical uncertainty	The changes in the demand vs. capacity situation can be quantitatively measured	Not Performed

Table 7. Experiment #2 - OBJ2.2 assessment result

The verdict of the first success criterion is that through the calculation of Collision Risk hotspot values, it is possible to measure changes in the demand vs. capacity situation. Basing the modelling of time uncertainty on the operational uncertainty originated from expected drone operator preparation and planning uncertainty.

Increasing the time uncertainty in the calculation of Collision Risk for the scenario, leads to higher values for the instantaneous and average Collision Risk values. While in the baseline scenario, the highest average Collision Risk detected is 4.98e-7, after increasing the time uncertainty, the highest average Collision Risk is 2.59e-6, which is an increase of 420%. At the same time, the highest instantaneous Collision Risk value detected increases by a factor of 100 (6700%). Moreover, the number of areas where an instantaneous collision risk is detected is twice as high in the scenario considering uncertainty.

3.2.2.3 Experiment #2 - Objective 2.3 assessment results

For objective 2.3, an assessment of the **consistency of the collision risk and societal impact models (RC2)** in an operational context is performed during the strategic planning phase. Use of consistent hotspot analysis cells from both dimensional and temporal aspects is reviewed when supporting the hotspot assessment for DOP in the Frankfurt region.

Analysis of the effects of different CNS performances such as navigation accuracy and communication update rate in the risk (both in air and ground) was carried out for the given scenario considering the 4D nominal trajectories provided by the demand model.

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
Analysis of navigation accuracy and communications update rate	Estimate the collision risks for the given scenario (considering 4D nominal trajectories from demand model) depending on Navigation accuracy and communications update rate	Not performed
Effect on false conflict alert rate	Estimate the effect on false conflict alert rate of the safety margin to minimise the collisions risk, which	Not performed

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
	would be set based on navigation accuracy	

Table 8. Experiment #2 - OBJ2.3 assessment result

This objective was not addressed in the scope of the experiments.

However, the impact of CNS performances was extensively analysed in Experiment #3.

3.2.2.4 Experiment #2 - Objective 2.4 assessment results

The fourth experimental objective looks at **the impact of weather conditions on the DCB process (RC12)** and analyses how varying weather conditions may affect the infrastructure in urban environments and therefore the capacity.

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
2.4 Effect of weather information on local hotspots appearance.	Analysis of hotspots location data indicates that activated weather information intensifies hotspots in certain areas.	Partially OK

Table 9. Experiment #2 - OBJ2.4 assessment result

To test the impact of weather scenarios on hotspot appearance, the experiments were conducted with and without weather information, and with different levels of adverse conditions. It can be confirmed that the reduction of flyable areas intensifies [or relocates] hotspots.

In detail, the results show that especially the rerouting of flights around areas with high wind speeds lead to higher social impact and collision risk values as the areas with acceptable wind speeds get more congested. Specifically, in the grid cell with the most severe impact, the average collision risk increases by three orders of magnitude (from ~1e-7 to ~ 1e-4).

Moreover, the number of areas where an instantaneous collision risk is detected is twice as high in the scenario considering weather impact.

As the effect of weather on vertiports capacity is expected to be a key capacity constraining factor, to evaluate it in further detail, a separate set of simulations were performed. As this additional analysis extends the assessment beyond simply the capacity availability status based on some per platform threshold and studies the finer effects of weather on infrastructure capacity, ***more detailed results are provided in objective 2.7***, which specifically addresses the weather effect on the capacity demand balancing process.

3.2.2.5 Experiment #2 - Objective 2.5 assessment results

For objective 2.5, an analysis of the i**mpact of how high turbulences/high winds may affect low weight drones (RC12)** is performed, to identify areas that may need to be avoided by this type of drone.

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
2.5.1 Effect of turbulences on certain drone types	Analysis of integrated weather scenarios shows that light weight drones are mostly affected by turbulences.	Partially OK

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
2.5.2 Effect of high winds on certain drone types	Analysis of integrated weather scenarios shows that light weight drones are mostly affected by winds at 50-meter altitude.	OK

Table 10. Experiment #2 - OBJ2.5 assessment result

Due to different robustness levels of drone types, the effect of weather conditions is not homogenous on the traffic mix. The verdict of the second success criterion is that especially low weight drones, such as lightweight multi-copters, are affected by slightly and strongly non-nominal wind speeds.

Regarding the first success criterion, it was discovered that turbulence conditions can be simulated with the techniques presented in Annex B. However, the resulting effect of that turbulence on drone types ***cannot be reliably simulated at this stage, as no suitable performance data from drone manufacturers are available*** (e.g. disturbance/rejection capabilities).

3.2.2.6 Experiment #2 - Objective 2.6 assessment results

Objective 2.6 considers the **consistency of the process to identify social impact hot-spots and risk-related hot-spots (RC2)** in terms of consistent timeframes and portions of airspace.

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
Capturing of social impact hotspots and risk-related hotspots	The hotspots from the Social Impact and Risk model are consistent regarding their spatial resolution (e.g. matching grids) and their temporal resolution (similar time scale)	OK

Table 11. Experiment #2 - OBJ2.6 assessment result

Experimental results confirm that the identified hotspots from both the Social Impact and the Collision Risk models can be aligned in both dimensional and temporal resolution. Although the hotspots have different spatial resolution, the spatial resolution of the Social Impact model is exactly half as high as the resolution of the Collision Risk model, it still permits the evaluations to be consistently aligned to portions of the airspace being managed.

3.2.2.7 Experiment #2 - Objective 2.7 assessment results

Objective 2.7 assesses the **relevance of weather information as part of the DCB process (RC12)** in terms of its impact on operations and planning of capacity related measures e.g., scarcity of TOLAs and contingency sites, emergence of new hot spots or weather-related delays, which offsetting demand.

These experiments were further enhanced through the development and use of a vertiport capacity and availability simulation tool which was developed in addition to the originally planned analysis techniques.

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
2.7.1 Availability of TOLAs based on weather impact level	Reduction of TOLAs as consequence of weather-related closures	Partially OK
2.7.2 Availability of Contingency sites based on weather impact level	Reduction of Contingency sites as a consequence of weather-related closures	OK

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
2.7.3 Impact of weather conditions on specific mission types	Flight cancellations appear mostly in the delivery sector	OK
2.7.4 Weather related delays by business sector	Analysis of affected business sectors shows that not all types of missions can or will be postponed.	OK
2.7.5 Weather related capacity variation at Vertiports	Analysis of results measuring the average variation on the number of movements per unit of time (capacity) in a vertiport due to weather measures a degradation on the capacity due to weather even for wind values that are within the operating margin considered in 2.7.1.	OK

Table 12. Experiment #2 - OBJ2.7 assessment result

The first two success criteria reflect the impact of weather conditions on the availability of TOLAs and contingency sites. Iterations of weather scenarios prove that adverse conditions create a scarcity of such infrastructure although the volume of drone traffic is decreased. The third and fourth success criteria asses the effects on cancellations and potential delays of mission types. It is shown that delivery missions are especially sensitive to such effects, but these tend to be cancelled rather than postponed.

The fifth success criteria reflects that, provided detailed performance models that through the modelling of weather effects on drones it is possible to estimate the time required for vertiports movement to occur under the predicted weather conditions and therefore, measure the effects of the vertiport capacity. This approach shows that the effect on capacity is relevant and that this effect should be considered especially in high demand scenarios, where demand is very close to maximum capacity.

An analysis of the wind impact on different types of drone configurations showed, that in the case of 10m/s south wind, the complete airspace above 100-meter altitude is not flyable for multirotor UAV, while for fixed wing configurations the conditions even at 150-meter altitude allow hindered flight in more than 10 % of the airspace. Close to the ground (10-meter altitude), the impact is much smaller. Here, 70 % of airspace is available for multirotor configurations, while the weather conditions don't prevent any fixed wing flights at all.

In general, objective 2.7 shows that the capacity of both, urban airspace and ground infrastructure is very relevant and that its estimation based on weather predictions in order to estimate capacity should be an essential part of the DCB process in order to be able to operate in off-nominal weather conditions. As this allows us to measure the expected reduction in capacity, this ability becomes increasingly important in scenarios where the expected demand is higher.

3.2.2.8 Experiment #2 - Objective 2.8 assessment results

The final experimental objective, 2.8 also considers the **relevance of weather information as part of the DCB process (RC12)** at the strategic level and aims to analyse up to what point a baseline scenario of high traffic demand can be defined after comparing multiple demand level simulations and using the city of Frankfurt as urban environment.

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
Definition of metrics to analyse traffic scenarios with different demand levels	The defined quantitative metrics enable the analysis of traffic in the spatial and temporal domain.	OK
Simulation of different levels of traffic demand including delivery, surveillance and inspection mission types	A baseline scenario of high traffic demand that impacts the demand vs. capacity situation can be identified	OK

Table 13. Experiment #2 - OBJ2.8 assessment result

The results from testing different traffic demand levels indicate that it is possible to simulate demand scenarios (based on available forecasts and educated assumptions) that stress the capacity situation and lead to a significant appearance of hotspots from both models.

3.2.3 Experiment #3 Results

Experiment #3 performs isolated testing and verification of the methodology that was selected to evaluate the Collision Risk modelling process and how it can be used to support the DCM process by identifying high risk hotspots in an urban region based on planned operations and the population density and sheltering factor for the people above which operations take place.

3.2.3.1 Experiment #3 – Objective 3.1 assessment results

Experiment #3 objective 3.1 focuses on the analysis of the **consistency of the collision risk method (RC2)** and how it compares to the societal risk model and DCM process in both temporal and dimensional aspects.

The experiment aims to evaluate the maximum acceptable capacity in different locations, with different population densities and sheltering factors. Increasing drone densities have been analysed in different areas of Madrid, Toulouse, and Toledo, identifying the maximum acceptable capacity, considering free flight and without any strategic deconfliction.

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
3.1 Assure that overall flight safety and the safety of third parties remains acceptably high by comparing the Collision Risk model to a certain TLS.	The collision risk calculated in different simulations, increasing sequentially the number of drones, remains below the TLS of 1e-6, per SORA, if the capacity (drone density) is limited to a certain threshold (maximum density of drones)	OK

Table 14. DACUS Experiment #3 – OBJ3.1 assessment result

Conclusion related to the first success criterion are that the maximum capacity for different airspaces can be identified to maintain the level of risk of fatalities to third parties on the ground below the desired Target Level of Safety. Annex C, Scenario 3, presents the calculated fatality risk in different environment, and the associated maximum capacity linked to the population density and sheltering factor.

3.2.3.2 Experiment #3 - Objective 3.2 assessment results

Experiment #3 objective 3.2 considers two research challenges – firstly how to **consolidate metrics to help determine the maximum number of UAS operations in different parts of the urban environment (RC3)** and **how applicable potential measures could be, and their theoretical effectiveness (RC4).** In particular, the analysis aims to evaluate the *impact of CNS performances on the collision risk* and the associated maximum capacity.

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
3.2 Introduce in the Collision Risk model different CNS performances assumptions to analyse the impact on the collision risk and the different business models that will coexist in the cities.	Estimate the collision risks in a certain scenario depending on Navigation accuracy, communications update rate and tracking integrity.	OK
	Estimate different acceptable capacity thresholds depending on Navigation accuracy, communications update rate and tracking integrity.	OK

Table 15. Experiment #3 - OBJ3.2 assessment result

The first success criterion tested how the collision risk increases when navigation accuracy decreases; how the collision risk decreases when the communication update rate increases (the lower the update frequency, the lower the collision risk); and how an integrity error in the tracking data increases the collision risk. Annex C, Scenario 1, presents the results for different update rates.

For the second success criterion for objective 3.2, a maximum capacity level was set based on the results of the impact on the collision risk of the navigation accuracy, communications update rate and tracking integrity, to keep the risk on ground below the target level of safety. Annex C, Scenario 3, presents the results of the maximum capacity in different environments, depending on the navigation accuracy.

3.2.3.3 Experiment #3 – Objective 3.3 assessment results

Experiment #3 objective 3.3 also considers the two research challenges that were assessed in experiment #2, namely, how to **consolidate metrics to help determine the maximum number of UAS operations in different parts of the urban environment (RC3)** and **how applicable potential measures could be, and their theoretical effectiveness (RC4).** However, this experiment aims to evaluate the capacity increase that may be obtained when strategic conflict management actions including separation minima or dynamic airspace structures are introduced in comparison to free flight – where drone operators are able to fly their own preferred profiles. Experiment #3 does not consider how any remaining tactical conflicts might be resolved, however as it focuses on how strategic actions may help reduce conflict risk to help increase the capacity in the planning phase.

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
3.3 Estimate collision risk and maximum capacity considering different airspace structures (free route, layers, etc.).	Estimate the collision risks in a certain scenario depending on the airspace structure restrictions.	OK

Table 16. DACUS Experiment #3 – OBJ3.3 assessment result

The results have shown that the introduction of adequate structures (layers, sectors) can reduce the collision risk and, therefore, the fatality risk, with regard to the free flight case. Also, that initial separations, introduced by means of *strategic deconfliction techniques*, allow to increase the capacity.

Annex C, Scenario 4 & 5, present the results of the collision risk comparison for free flight with regard to scenarios in which separation minima and layers were introduced.

3.2.3.4 Experiment #3 – Objective 3.4 assessment results

Experiment #3 objective 3.4 also investigates the **consistency of the collision risk assessment (RC2)** using an analysis of the optimum conflict margin that can be used to detect the majority of potential collisions, as a function of the navigation accuracy.

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
3.4 Estimate the effect on false conflict alert rate of the safety margin to minimise the collisions risk	Calculate the number of undetected collisions and false conflicts as a function of the safety margin.	OK

Table 17. DACUS Experiment #3 – OBJ3.4 assessment result

It has been tested that, although increasing the safety margin reduces the number of undetected collisions, it also increases drastically the number of false conflicts per flight hour. Annex C, Scenario 2, presents the percentage of undetected collisions for different conflict margins and navigation accuracies as well as the number of false conflicts per flight hour.

3.2.4 Experiment #4 Results

Experiment #4 is designed to provide an analysis platform that can be used to submit pre-tactical drone Operation Plans that can be assessed using the validated DCM models from experiments #1 (social) and #3 (collision risk) to analyse if hotspots can be identified based on the proposed operational missions. Hotspot analysis uses both the collision risk and social impact models with a common grid of 1km square cells positioned over the Madrid city region and returns results using the same temporal scale as the previous experiments.

A baseline scenario is created in which no actions are taken in response to hotspots that have been identified. Thereafter, several variant scenarios are executed in which selected DCB strategies are tested to determine how effective they can be in mitigating collision risk, noise, and visual hotspots (or all three).

All the DCB actions are applied as *pre-tactical modifications* to the requested DOP, using the *droneZone* fast-time simulator tool combined with the DCM models. Mitigation actions are applied to profiles before the drones are allowed to operate in accordance with the rules associated with any hotspot cell or cells that the drone may cross. Once processed, the mission is executed using either the original or the DCB modified trajectory according to the hotspots that each operation may encounter.

Scenarios are also executed with and without the Tactical Conflict Resolution service (modelled in the *droneZone* simulator as described in Annex D) to evaluate how strategic management of hotspots can combine with tactical conflict management to support operational demand.

3.2.4.1 Experiment #4 - Objective 4.1 assessment results

Experiment 4, objective #1 considers how **applicable DCB measures are (in an operational context) and their effectiveness (RC4).**

In this experiment, different DCB actions are assigned to sets of drone traffic in response to hotspot cells that they are predicted to encounter, based on initial planned trajectories/drone Operation Plans (DOP). DCB strategies are assigned for each hotspot cell and are applied to the initial requested mission profile. The requested DOP are adapted in accordance with the DCB rules for any flight that crosses a hotspot that is contained in the candidate set of operations that mitigation actions should be applied to. Actions for each cell are based on the associated mitigation rule (for example adaptation of the operating altitude when crossing the cell for different flight directions through the hotspot regions).

Analysis of the impact on various KPI is carried out using comparisons against the unimpeded reference scenario.

Traffic demand is unchanged for initial profiles to ensure that the same demand set is used prior to DCB actions being applied for all the variant scenarios.

Note that due to time and technical constraints when creating and executing the pre-tactical and FTS scenarios, the introduction of unexpected events was unable to be considered as part of the experiment #4 scenarios.

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
4.1 Assess the effectiveness of DCB measures and response when unexpected events take place in the tactical phase	Analyse the time to recover from degraded to nominal conditions, in scenarios #1 (Reference) and #2 to #N (all DCB variants).	Not performed
	Analyse the number of tactical conflicts. The number of tactical conflicts is expected to be lower in the DCB variant scenarios (#2 to #N)	OK

Table 18. DACUS Experiment #4 – OBJ4.1 assessment result

Regarding the ***effectiveness of DCB measures***, general results indicate that for all the DCB solution scenarios, the number of collision risk hotspots is greatly reduced through the application of the DCB actions. However, for noise and visual impacts, only the scenario with an increase in the operational ceiling produced any reduction in social hotspots.

The use of directional layers produced the best reductions in collision risk hotspots with a 72% reduction. This was followed by the scenario with an increase in the operational ceiling (53% reduction), introduction of routes or departure delays (40% and 42% reductions) and speed constraints provided the least improvement (21% reduction).

Increasing the operational ceiling provided a 32% reduction in noise/visual impact hotspots – since allowing drones to operate at higher altitudes reduces both their noise and visual impact for the population living below. However, other strategies that were applied had little effect in terms of social impact:

The use of departure delays resulted in little change (1% *increase* in social impact hotspots - not surprising since the delays were calculated to solve operations with high risk of collisions). Directional flight layers and the route grid solutions increased noise and visual hotspots (by around 8-9%). Reducing the speed for drones crossing hotspot areas had the largest negative impact on noise/visual impacts with an increase of 26% compared to the baseline (again, this result is not surprising since reducing the speed simply means that the vehicles remain in hotspot areas for longer, which would imply more noise or visual impact).

The number of tactical conflicts identified using the DOP that had been modified to implement the different DCB actions, compared to those found in the original planned operations in the reference scenario also show significant reductions for most of the variant scenarios:

Increasing the operational ceiling (44% reduction), application of directional flight layers (27% reduction) and delays (5% reduction) provided the best results in terms of remaining tactical conflicts following application of strategic DCB measures. However, speed management (12% increase) and surprisingly the use of a gridded route structure (54% increase) resulted in higher initial conflict counts than those found using the reference DOPs. Additional analysis (see annex D section D.3) suggests that the introduction of route structures reduces the degrees of freedom for drone operation which in turn increases the number of conflicts. However, the additional room that is available allows those conflicts to be solved in a much more efficient manner with lower risk of other induced conflicts.

When running with the tactical conflict resolution service active, all variant scenarios saw a decrease in the number of conflicts that were induced by a previous resolution action with large improvements ranging from 70-94% reductions. This would imply that the complexity of the traffic has been reduced due to the application of DCB measures and clearly helps the tactical resolution service.

3.2.4.2 Experiment #4 - Objective 4.2 assessment results

Experiment #4 objective 2 was intended to consider how **decision making between on-board drone capabilities and U-Space separation/DCM management services might impact the DCB situation (Obj4)**.

However, in the absence of suitable data regarding on-board *Detect and Avoid* capabilities for different drone vehicle types, and due to time constraints on the design and execution of the exercises this analysis was not performed as part of the DACUS project.

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
4.2 Optimise decision making between on-board capabilities and U-space separation services.	The program establishes separation rules based on the hierarchy set.	**Not Performed**

Table 19. Experiment #4 - OBJ4.2 assessment result

3.2.4.3 Experiment #4 - Objective 4.3 assessment results

Experiment #4 objective 3 considers the **consolidation of metrics to determine the maximum number of UAS operations (RC3)** that may be manageable in different parts of the urban airspace. **Objective 4.3 focuses on the *capacity* of the region**, with, and without, DCB measures being applied.

For this analysis, the reference scenario is executed using the unmodified baseline traffic demand with no DCB or tactical conflict management actions being applied to provide baseline KPI related to the unconstrained demand and capacity for the Madrid region. The same scenario is also executed with Tactical Conflict management active to measure how the unconstrained traffic might be managed if not subjected to strategic DCB or strategic conflict management measures.

Variant scenarios with specific DCB mitigation actions applied to the candidate set of operations in each of the identified hotspot regions are executed to allow analysis of the same capacity KPI with DCB actions applied. Comparisons against the baseline metrics (with and without tactical conflict resolution active) and between variant scenarios provide indicators on how effective each strategy may be in terms of capacity for the analysis region.

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
4.3 Evaluate and consolidate metrics in terms of capacity to determine the maximum number of UAS operations.	Run the baseline Reference scenario and all the different DCB variant scenarios and analyse variations in capacity metrics.	OK
	Analyse the drone base (vertiport/origin) and "en-route" throughput. This one has to be lower in scenario #1.	OK

Table 20. Experiment #4 - OBJ4.3 assessment result

Capacity metrics indicate that the majority of the DCB scenarios result in improvements in the number of drones operating in challenging airspace and a slight increase in most cases for peak arrivals and peak departures at the drone bases.

As it is presented in Annex D, all DCB measures that are applied reduce the number of Collision Risk hotspots. However, only the increase of the operational ceiling achieves better results than the reference scenario for the Social Impact results (but in case of visual impact, the organization per routes and delays on ground also improves this value).

Most of the scenarios present better results in conflict-related metrics (total number of conflicts in airspace and conflicts derived from other conflicts' resolution). In contrast, metrics related to delays get worse in solution scenarios.

Metrics show variations in the number of requirements respected (from a 60,39% in the route-based scenario to a 88,61% with the increase of the operational ceiling with respect to the 71,30% in the reference scenario) , in the number of close aircraft (from 21% with the increase of the operational ceiling to a 57% in the route-based scenario with respect to the 37% in the reference scenario) and the number of severe intrusions (from 2% in the speed-controlled scenario to a 10% in the route-based scenario with respect to the 6% in the reference scenario).

These variations in metrics and the consistency of the results with the proposed solution scenarios demonstrate that this set of metrics is appropriate to measure deviations in the capacity of the system.

However, it is necessary to establish thresholds for these values to determine up to what point the total number of missions is feasible and these values are acceptable or not.

3.2.4.4 Experiment #4 - Objective 4.4 assessment results

Objective 4 also considers the **consolidation of metrics to determine the maximum number of UAS operations (RC3)** in different parts of the urban airspace. **Objective 4.4 focuses on *efficiency* in the region**, and how those metrics vary when DCB measures are applied.

As previously, the analysis is executed using the unmodified baseline traffic demand with no DCB or tactical conflict management actions being applied to provide a series of baseline KPI related to the unconstrained demand for the Madrid region. The same scenario is also executed with Tactical Conflict management active to measure how the unconstrained traffic can be managed if not subjected to strategic DCB or strategic conflict management measures.

DCB variant scenarios with specific mitigation actions applied to the candidate set of operations in each of the identified hotspot regions are executed to allow analysis of the *efficiency* KPI with DCB actions applied, and comparisons against the baseline metrics (with and without tactical conflict resolution active) provide indicators on how effective each strategy may be in terms of *efficiency* for the analysis region.

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
4.4 Evaluate and consolidate metrics in terms of efficiency to determine the maximum number of UAS operations.	Run the baseline Reference scenario and all the different DCB variant scenarios and analyse variations in efficiency metrics.	OK
	Analyse the drone base (vertiport/origin) and "en-route" throughput to assess how DCB measures impact/affect efficiency of operations	OK

Table 21. Experiment #4 - OBJ4.4 assessment result

KPI Metrics provided in annex D consider both horizontal and vertical operational efficiency as well as arrival times, delays to operations and overall elapsed airborne operating times.

Results confirm ***a general loss of efficiency when DCB measures are applied***, but in terms of horizontal efficiency (track distance) only the route-based solution has a significant impact with up to 18% increase in track distances flown. All the other solutions have little or no impact on the horizontal track distance as the actions focus on other aspects of the trajectory (i.e. altitude/time).

Vertical efficiency is directly impacted by the application of directional layers (46%) and the increase of the operating ceiling (363%) which is not surprising.

Airborne times are significantly impacted by the route-based solution (57% increase) and in scenarios with significant changes in altitudes (increased ceiling showing a 6% increase and directional layers almost 4%). Use of speed constraints in hotspot cells also increases the overall airborne times.

In terms of drone/vehicle efficiency, since the model accepts any modification without considering the maximum fuel range/battery life, all solutions apart from the use of ground delay actions exhibit a theoretical increase in battery/energy use when DCB actions are applied in the different variant scenarios. Speed and directional layers show small increases of only a few percent in battery needs (ranging from 1.5% to 3.5%) but the route scenario shows a very large increase (83%). Similar results are seen in the energy requirement, however the increase in operational ceiling also requires significantly more energy (an increase of just over 21%) and gridded route needs an additional 61%.

3.2.4.5 Experiment #4 - Objective 4.5 assessment results

Experiment #4 objective 5 also considers the **consolidation of metrics to determine the maximum number of UAS operations (RC3)** in different parts of the urban airspace. **Objective 4.5 focuses on the *resilience and flexibility* in the region**, with, and without, DCB measures being applied.

As previously, the analysis is executed using the unmodified baseline traffic demand with no DCB or tactical conflict management actions being applied to provide a series of baseline KPI related to the unconstrained demand for the Madrid region. The same scenario is also executed with Tactical Conflict management active to measure how the unconstrained traffic might be managed if not subjected to strategic DCB or strategic conflict management measures.

DCB variant scenarios with specific mitigation actions applied to the candidate set of operations in each of the identified hotspot regions are executed to allow analysis of the same KPI with DCB actions applied. Comparisons with baseline metrics (with and without tactical conflict resolution active) provide indicators on how effective each strategy may be in terms of ***resilience and flexibility*** for the analysis region.

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
4.5 Evaluate and consolidate metrics in terms of resilience and flexibility to determine the maximum number of UAS operations.	Run the baseline Reference scenario and all the different DCB variant scenarios and analyse variations in resilience and flexibility metrics.	OK
	Analyse the number of re-scheduled, delayed, and cancelled flights in each of the defined scenarios	OK
	Analyse the drone-base/vertiport and "enroute" throughput.	OK
	Analyse the time to recover. This one has to be higher in scenario #1.	Not performed
	Run different scenarios and analyse variations in resilience metrics	OK

Table 22. Experiment #4 - OBJ4.5 assessment result

Following the execution of each of the DCB scenarios, analysis of metrics relating to the resilience and flexibility of each type of solutions was performed. KPI for the percentage of missions that were successfully concluded, those where operations were delayed for more than 3-minutes and assessments of the loss of capacity in airspace or vertiport/drone bases that could be avoided were calculated.

All the DCB scenarios showed small improvements in missions that were successfully completed with those not completed ranging from 0.5% (increased operational ceiling) to 2.28% (delay) in the DCB scenarios, compared to a rate of 4.3% in the baseline reference scenario with no DCB applied.

Little or no change to flights with a delay greater than 3-minutes was seen in the speed, increase ceiling and directional layer scenarios when compared to the reference (0.02%). However, ground delay increased the flights with more than 3-min delay to 0.4% and the gridded route solution showed an increase in >3min delay for 3.1% of the planned operations.

All DCB scenarios showed improvements in system resilience and airspace capacity with significant proportions of airspace capacity loss being avoided due to the actions (up to 80% when using the directional layers solution). However, as DCB actions were mainly focused on airborne solutions for traffic operating in hotspot cells, little or no changes to vertiport throughput/capacity were identified.

Since technical and time related issues did not allow for unanticipated events to be introduced in the analysis scenarios, analysis of the time to recover was not able to be performed as part of the experiment #4 analysis.

3.2.4.6 Experiment #4 - Objective 4.6 assessment results

Experiment #4 objective 6 considers the **applicability of DCB measures and their effectiveness (RC4)** for different types of DCB strategy in response to hotspots.

As previously, the baseline analysis using the unmodified baseline traffic demand, with no DCB or tactical conflict management actions applied, is used to determine a baseline set of KPI related to the unconstrained demand for the Madrid region. The same scenario is also executed with Tactical Conflict management active to measure how the unconstrained traffic might be managed if not subjected to strategic DCB or conflict management measures.

DCB variant scenarios with specific mitigation actions applied to the filtered set of operations in each of the identified hotspot regions are executed to allow analysis of the same KPI with DCB actions applied, and comparisons the impact of the DCB measures is determined using a variety of KPI.

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
4.6 Evaluate how DCB measures act in scenario #2 to #N	Run scenarios #1 and #2 to #N and analyse variations in all the metrics	OK
	Estimate the loss of capacity in airspace avoided. This one has to be higher in scenario #2 to #N	OK

Table 23. Experiment #4 - OBJ4.6 assessment result

As indicated in section 3.2.4.1 previously, general results indicate that all the DCB solution scenarios are successful in reducing the number of collision risk hotspots through the application of the DCB actions. Speed constraints in hotspot cells reduced collision risk hotspots by just over 20%, with routes/departure delays reducing them by around 40%, an increased ceiling by 53% and the introduction of directional altitude layers achieving up to 72% reduction of hotspots when used as a DCB measure – this is consistent with the results for the application of directional layers seen during experiment #3 which performed validation of the collision risk modelling approach and considered a series of potential mitigation actions that could help mitigate risk.

However, for noise and visual impacts, only the scenario with an increase in the operational ceiling produced any reduction in social hotspots and additional research will be needed to help determine how other DCB actions could be adapted to respond to noise and visual issues in an urban operating environment.

3.2.4.7 Experiment #4 - Objective 4.7 assessment results

Objective 7 also considers the **applicability of DCB measures and their effectiveness (RC4)** for different types of DCB strategy in response to hotspots.

As previously, the baseline analysis using the unmodified baseline traffic demand with no DCB or tactical conflict management actions is used to determine a set of baseline KPIs related to the unconstrained demand for the Madrid region. The same scenario is also executed with Tactical Conflict management active to measure how the unconstrained traffic might be managed if not subjected to strategic DCB or strategic conflict management measures.

DCB variant scenarios with specific mitigation actions applied to the filtered set of operations in each of the identified hotspot regions are executed to allow analysis of the same KPI with DCB actions applied, and comparisons the impact of the DCB measures is determined using a variety of KPI.

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
4.7 Evaluate the effectiveness of DCB measures in scenario #2 to #N	Run scenarios #1 and #2 to #N and analyse variations in all the metrics	OK

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
	Estimate the loss of capacity in airspace avoided. This one has to be higher in scenario #2 to #N	OK

Table 24. Experiment #4 - OBJ4.7 assessment result

Generally, the DCB actions used in the various scenarios proved to be effective in responding to situations where risk exceeded the Target Level of Safety, and overall, results from experiment #4 showed similar reductions in risk to those performed in experiment #2. Actions were less effective when responding to noise and visual impact issues, suggesting that additional research may be required to help identify or refine DCB actions from the societal aspect.

3.2.4.8 Experiment #4 - Objective 4.8 assessment results

Experiment #4 objective 8 provides a third scenario that considers the **applicability of DCB measures and their effectiveness (RC4)** for different types of DCB strategy in response to hotspots.

As previously, the baseline analysis using the unmodified baseline traffic demand with no DCB or tactical conflict management actions is used to determine a set of baseline KPIs related to the unconstrained demand for the Madrid region. The same scenario is also executed with Tactical Conflict management active to measure how the unconstrained traffic might be managed if not subjected to strategic DCB or conflict management measures.

DCB variant scenarios with specific mitigation actions applied to the filtered set of operations in each of the identified hotspot regions are executed to allow analysis of the same KPI with DCB actions applied, and comparisons the impact of the DCB measures is determined using a variety of KPI.

Using the comparison results (a matrix) a suitable mixture of solutions for different hotspots across the operating region can be determined and tested.

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
4.8 Evaluate the effectiveness of DCB measures in scenario #2 to #N	Run scenarios #1 and #2 to #N and analyse variations in all the metrics	OK
	Design a matrix that assigns a value to each of the DCB measures in terms of their effectiveness in each simulated scenario. Then, the measures which present the best values will be selected	Partially OK

Table 25. Experiment #4 - OBJ4.8 assessment result

Results presented in Annex D provide a matrix-like set of results for a variety of metrics relating to each of the research challenges and experimental sub-objectives identified in experiment #4. These matrices illustrate how each of the solutions impact different indicators and how the measured results compare to the original baseline metrics.

However, due to time constraints, it has not been possible to assess the different solution metrics against one another or to produce a suitable combination of solutions that may help to create an optimal 'mixed' solution using a combination of DCB actions – hence the conclusion that the success criterion is only partially achieved. Nevertheless, the foundation has been built to support the analysis of such combined scenarios in future DCB research in the urban environment.

3.2.4.9 Experiment #4 - Objective 4.9 assessment results

Experiment #4 objective 9 considers the **prioritization of drone operations within the DCB process (RC7)** for different types of DCB strategy in response to hotspots.

A system of '*virtue points*' was intended to be considered to help to determine how systematic exclusion of certain privileged operations may impact other operations in the region. However due to time constraints on the analysis, a scenario using realistic 'virtue points' was not able to be completed in the scope of the project.

Nevertheless, using the hotspot candidate flight filters provided in the *droneZone* model, certain types of flight operation (e.g. medical delivery operations, emergency missions and traffic surveillance missions) were excluded from DCB measure and these missions were able to be executed as planned if they passed through hotspot cells. However, no comparison has been performed for equivalent scenarios where those flights were not excluded from hotspot DCB actions so in the current results it is not possible to measure the impact of excluding these missions on the other traffic.

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
4.9 Evaluate the possibility to assign "virtue points" to specific drones in order to prioritize their operations within the DCB process	Run scenarios #1 and #2 to #N and analyse variations in all the metrics	OK
	Analyse the number of re-scheduled, delayed and cancelled flights in each of the defined scenarios	Not performed
	Estimate the loss of capacity in airspace avoided	Not performed

Table 26. Experiment #4 - OBJ4.9 assessment result

Despite being unable to produce and execute scenarios where a system of *virtue points* was put in place to optionally exclude key operations from DCB actions, using the *droneZone* DCB strategy filters that are available in the hotspot polygon structures, certain types of drone operation were excluded from mitigation actions when operating in a hotspot cell.

Those missions that were in the excluded category were allowed to operate as planned, thereby forcing actions onto operations in the remaining set. However, execution of scenarios where those operations were not excluded, to help determine the difference to all operations when sub-sets are systematically excluded from actions was not performed as part of experiment #4 and would be subject to follow up research activities.

3.2.4.10 Experiment #4 - Objective 4.10 assessment results

Experiment #4 objective 10 also aims at the analysis of the **prioritization of drone operations within the DCB process (RC7)** for different types of DCB strategy in response to hotspots.

As mentioned previously in section 3.2.4.9, while some key operations (medical, emergency, traffic surveillance/security) were excluded from DCB measures, no specific comparisons have been made to help measure the impact of such exclusions on the remaining impacted traffic.

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Type of analysis/assessment	Success Criterion	Success Criterion Verdict
4.10 Evaluate the impact of assigning virtue points in the DCB process in terms of capacity, effectiveness and resilience	Run scenarios #1 and #2 to #N and analyse variations in all the metrics	OK
	Estimate the loss of capacity in airspace avoided	Not performed
	Run scenarios #1, #5 and #8 and analyse variations in metrics.	Not performed

Table 27. Experiment #4 - OBJ4.10 assessment result

Excluding/prioritising given operations was modelled in the experiment #4 DCB scenarios, but due to time constraints it was not possible to measure the impact on other traffic due to the systematic exclusion/prioritisation of sub-sets of operations. This should be assessed in more detail in future research.

3.2.4.11 Experiment #4 - Objective 4.11 assessment results

Experiment #4 objective11 looks to assess the **impact of weather conditions in the DCB service (RC12)** for different types of DCB strategy in response to hotspots.

The experiment aims to repeat previous scenarios with different wind grids and wind impact modelling on drone performance included in the experiments.

DCB variant scenarios with specific mitigation actions applied to the filtered set of operations in each of the identified hotspot regions are executed to allow analysis of the same KPI with DCB actions applied, and comparisons the impact of the DCB measures is determined using a variety of KPI.

Using the comparison results (a matrix) the potential impact of wind and weather effects on different hotspots and DCB actions across the operating region can be determined and tested.

Type of analysis/assessment	Success Criterion	Success Criterion Verdict
4.11 Evaluate the impact of meteorology (strong wind gusts) in drone trajectories in terms of capacity, resilience and efficiency	Run scenarios #1, #7 and #8 with wind grids included and analyse variations in metrics.	Not performed
	Assess DCB measures in bad weather condition scenarios	Not performed

Table 28. Experiment #4 - OBJ4.11 assessment result

The experiment #4 scenarios were able to include wind grids for the simulation regions however, due to time constraints, an analysis of the impact/effect of local wind conditions on drone operations and DCB measures was not carried out as part of experiment #4. Nevertheless, experiment #2 included analysis scenarios relating to weather and wind impacts on drone mission planning during the strategic planning phase and considered potential contingency actions and the effects on vertiport capacity due to adverse weather. Nevertheless, additional analysis of weather/wind impacts during the pre-tactical/execution phase would be of interest in future research.

3.3 Confidence in Validation Results

Using multiple validation experiments, the DACUS research has been able to investigate novel capacity demand management metrics based on societal indicators such as Noise and Visual impacts as well as

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risk-based metrics that consider the consequences of collisions between two or more drones or vehicle failures in terms of the risk of injury to the population below.

Experiments #1 and #3 considered each of the models in isolation and performed several simulation exercises to help verify the behaviour of the Noise, Visual and Collision Risk prototypes for varying levels of drone operation and mission types. Results were produced based on the population density for different operating regions, as well as sheltering factors. By varying input parameters and configuration settings the models were able to be calibrated for use in an operational setting, and target operating thresholds were identified to allow the prototypes to be used in other simulation scenarios.

Adaptation and calibration of the analysis grid sizes was performed to identify suitable sizes and temporal limits that allow the services to perform hotspot analysis in an optimal manner using consistent (and where feasible common) grid sizes and locations for different cities. Furthermore, the introduction and initial assessment of potential DCB strategies as part of the isolated experiments allowed DCB measures that had the potential to help mitigate hotspots to be identified for further analysis in the subsequent operational scenarios.

By applying the DCM prototypes in a more operational context, a series of focused results were able to be obtained which also brought operational and mission uncertainties into play, particularly during the strategic planning phase.

The introduction of micro weather effects and impact of winds on vertiport capacity also supported an assessment of how contingency can be incorporated into the validation scenarios and the impacts that uncertainty may have when operating in the urban environment. Using simulated 4D trajectories based on more detailed performance data and the simulation of drone-drone interactions and tactical resolution services during the execution phase, additional performance metrics and indicators were able to be analysed and comparisons of the impact of different DCB strategies in terms of capacity, efficiency, flexibility, and resilience were able to be performed.

3.3.1 Limitations of Validation Results

As DACUS was an exploratory research project with a low TRL, the initial objective was to create DCM service prototypes that use novel capacity metrics, namely Noise, Visual impact, and Collision Risk indicators. Once the prototypes were available, they could be validated and calibrated in isolation before being applied in realistic simulation scenarios to assess the effectiveness/limitations of the DCM approach.

DCM indicators and the hotspots that are identified depend heavily on the projected mission plans (DOP) and on the population density for areas above which the drones are planned to operate.

In the DACUS prototypes, the ***population figures that were available tended to be static*** and, apart from of some limited experiments performed during experiment #1, they ***did not account for the changes at different times of day*** (for example, when people are at work or when they are at home).

Additionally, as very little forecast data is available for use in generating DOP the types of missions that may be flown in the different cities that were assessed in the DACUS experiments, other methods to create demand forecasts and the mixture of missions had to be identified:

The ***use of road traffic data***, ***taxi flows***, existing ***ground-based delivery statistics*** and ***food orders based on population and restaurant locations*** combined with the application of some AI-based forecasting techniques from WP2 [8] enabled the project to produce a series of missions that can be considered representative for future operations. Nevertheless, ***a focused and common set of drone mission forecasts (potentially by city/region) would be helpful for future analysis*** and would bring added value to future research projects.

Similarly, the ***choice of vehicle types that may be used for different missions*** is also a significant factor when generating drone operations for a given region. For the DACUS project, ***generic drone types were mainly used*** to represent the type of vehicles that would operate the different kinds of mission. In reality, many 100's or 1000's of different vehicles are already on the market (the *droneZone* FTS simulator contains performance and vehicle characteristics data for more than 2000 different vehicles for example) and future research would benefit from the availability of enhanced vehicle information – not least when considering wind/weather effects, operating altitudes and speeds, operating ranges etc.

Nevertheless, through careful verification and calibration of the DCM prototypes, operating limits were able to be set and areas of the target cities where hotspots were likely to occur could be easily identified and appropriate actions to help mitigate those issues could be evaluated.

Due to limited time, and a very ambitious scope for the DACUS experiments, some of the ***more complex scenarios were unable to be considered*** in the available timeframe. This included the introduction of ***constrained airspace regions*** and concepts such as ***virtue-points***, which require significantly more analysis before creating an operational scenario.

Similarly, enhanced modelling and understanding of ***mission operating characteristics, particularly relating to altitude profiles*** would be of significant benefit for future research activities. Similarly, the introduction of ***restricted operating areas*** (e.g. above schools or hospitals) and ***environmentally (green) based indicators within the DCM*** process would be of additional research interest.

3.3.1.1 Quality of Validation Results

Considerable effort was made during the verification and validation of the DCM prototypes during experiments #1 and #3 to ensure that when the prototypes were subsequently deployed in an operational context in experiments #2 and #4, confidence in the hotspot results being identified was high.

Careful assessment regarding the location and size of the analysis grids for use in an urban environment also helped to improve the quality of results, where a trade-off between grid/cell sizes and temporality that could optimise both the collision risk prototype and the noise/visual impact assessment processes was also achieved.

The introduction of detailed 4-dimensional micro weather models to capture urban wind effects, particularly for light weight drone operations, allowed high quality wind impact modelling to be included in support of uncertainty and contingency actions during the strategic phase in experiment #2.

The use of performance metrics related to capacity, efficiency, flexibility, and resilience in the operational phase following the pre-tactical application of DCB strategies to selected missions passing through hotspot cells also added to the overall quality and utility of the validation analysis results.

3.3.1.2 Significance of Validation Results

During the testing and verification experiments that were performed for each of the DCM prototype models several simulation exercises were executed to stress the models with varying levels of mission demand and mixtures of traffic types. In experiment #1 a total of 9 exercises with 2-hour mission counts ranging from 12048 operations down to 81 for the Toulouse region have been performed to help test and calibrate both the Noise and Visual impact prototypes using a grid of 1KM x 1KM analysis cells and metrics calculated at 1-minute intervals.

Four different threshold values are computed for each of the 754 cells in the 2-hour analysis period for each scenario resulting in more than 360,000 measures for each traffic scenario considered during the experiments. For additional information regarding the analysis please refer to appendix A.

Similar numbers of assessments were carried out during experiment #3 when validating the collision risk model which considered large quantities of drone mission in three regions, Madrid, Toledo, and Toulouse. In addition to reference scenarios that were used to verify and calibrate the prototype, 5 'solution' scenarios were also executed with initial estimation for the impact/benefit of DCB strategies including flight layers, sectorisation and routes/flight tubes.

Different scenario runs were performed with variation of independent variables relating to CNS performance (accuracy/update rate), conflict margins (ranging from 3-10 meters), urban population exposure (low to high density ranging from 60 inhabitants/km2 to more than 5000) and sheltering factors. (See appendix C for more details).

When deployed in the operational scenarios, several scenarios with mission demand ranging from 1151 to 5668 were executed with DCM services for Noise, Visual impact and Collision Risk analysis being consulted using a grid of 1km x 1km cells for the societal impact model and 500m x 500m (aligned with the other grid to ensure no overlaps) for the collision risk analysis. Operations are simulated in a highly realistic operating environment using the available simulation tools using a mixture of mission and vehicle types. Time-based mission uncertainty combined with the effects of weather on drone operations and vertiport capacity/availability and the use of different types of contingency action increase the operational significance of the scenarios that were considered. (See Appendix B for more details).

Finally in the experiment #4 scenarios, a series of 6 different simulation scenarios with more than 6500 drone operations in a 24-hour period for the Madrid region were executed. Each scenario was performed both with and without the tactical conflict resolution service active, resulting in a total of 12 scenarios (>78,000 flights). Noise, Visual impact and Collision Risk indicators were calculated for a set of 3600m 1km x 1km grid cells on a minute-by-minute basis over the 24-hour analysis period for all of the operations performed in the simulation exercises.

4 Conclusions and recommendations

4.1 Conclusions

Conclusions are detailed by experiment and place special emphasis on the research questions to be answered by each of them.

4.1.1 Conclusions from Experiment #1

The aim of Experiment #1 was foremost the analysis of the efficiency of social impact indicators that can be used to identify hotspots on a grid of 1km² cells. Following this identification, the goal was to establish if DCB measures can be proposed automatically by the DCM service to decrease social impact. These questions were analysed for traffic in a 2-hours timeframe, mainly focusing on package and food deliveries.

To support the **consolidation of social impact indicators to determine the maximum number of UAS operations**, the proposed indicators –based on Noise and Visual annoyance and exposure – were used to determine a pseudo-maximum number of UAS operations per measurement cell. This number is not fixed, as it may vary slightly depending on actual operating characteristics, altitude of the drone being the most significant one.

The distinction between noise and visual impacts remains important as they behave in a slightly different way, even if they are highly correlated to the number of drones and the population density in a cell. However, the distinction between annoyance and exposure is more complex. For noise impact, annoyance, and exposure are highly correlated and could be merged as one indicator. For visual impact, annoyance, and exposure these are also highly correlated for areas with a high population density, but they exhibit more complex patterns at low population density.

We identified the need to **consolidate the notion of social impact hotspot**, as an area where the drone traffic demand generates noise and visual exposure or annoyance above acceptable thresholds for a pre-defined duration, or pre-defined frequency in a given period. In some situations, one or two-minutes duration of the hotspot can be acceptable whereas a twenty-minutes duration is not.

On the other hand, the need to **consolidate acceptable thresholds** was also identified. It should be taken into account that the diverse business models for drone missions are impacted differently by the social impact thresholds due to the different distribution of operations in the city. For example, package delivery comes from few, but moderately inhabited regions to highly populated areas. But food delivery comes from and typically goes to highly populated areas. Consequently, package deliveries impact more areas with moderate impact, and food deliveries impact less areas but with high impact. Hence, high noise and visual impact restrictions in the urban areas are detrimental for the food deliveries business models, whereas package deliveries are not so constrained.

The use of a **1km² cells grid enables to identify and comprehend source of hotspots**, and cells of this size are also appropriate to implement local DCB measures. This grid was consistently integrated in several cities with the one proposed by the collision risk model, which displayed a 0.5km² cells-grid. Despite this spatial difference, the two models were consistently combined in EXP2 and EXP4.

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Concerning **the identification of DCB measures to solve social imbalances,** two DCB measures are proposed to reduce the number of social hotspots: later or earlier departure time, and modifications of the flight height. DACUS tested the feasibility of applying these measures *automatically* as soon as a new drone operation plan is submitted, and it is causing a social hotspot. Two different strategies for the automatic implementation of a solution were tested:

1. U-space proposing solutions based on the quantification of their effectiveness for the previously executed operations, e.g. changing the flight level to 10 meters above/below.
2. drone operators sending changes in their operation plans randomly, taking into account the constraints received.

Hotspot identification enables the DCM service to select automatic DCB measures with a significant efficiency. Experiments showed that the first strategy is more effective than the second, i.e., less iterations to find a suitable change in the operation plan to remove the hotspots, and a smaller number of unresolved cases. However, the second strategy resolves a significant number of cases, providing more freedom to the drone operators to look for suitable alternatives according to their own business needs.

In general, the process is sensitive to the distribution of the demand in the city, which at the same time is determined by the type of business models in place. It is easier to take automatic DCB measure when some specific locations, like vertiports, are part of the context. This is typically the case when there is high demand of package delivery missions. In this case, the 1st strategy of scoring the DCB measures is even more efficient. When flights are not concentrated in specific departure and arrival locations, such as in food deliveries, the process of searching for measures is more unpredictable.

In conclusion, the process is more effective in the case of package deliveries (high distribution of moderate social hotspots in a wider area) than in the case of food deliveries (concentration of critical hotspots in the city centre).

With regards to the **effectiveness of the proposed DCB measures**, as expected, increasing flight height decreases the social impact, but the high concentration of operations in the city centre for food deliveries makes it necessary to impose higher variations in the flight height to solve hotspots, and more iterations to find a suitable solution. Changing the departure time also reduces the social impact, but this measure implies to move some drones out of the peak hours.

4.1.2 Conclusions from Experiment #2

The aim of Experiment #2 was the analysis of the sources of uncertainty of the drone demand, and how this demand uncertainty may impact the identification of collision risk and social hotspots in Frankfurt. Three different sources of uncertainty were studied: impact of contingency actions, impact of changes in the departure time of +/- 5 minutes, and the influence of micro-weather. In the scope of the analysis, two different contingencies were considered: unavailability (or closure) of landing locations simultaneously, and degradation of the navigation performance with several strategies to recover the situation (return to base, divert to alternative location, land immediately).

Considering various sources of uncertainty during the creation of trajectories indicated a high variation of actual traffic patterns. Depending on the intensity of the changed parameters and scenarios, routes were altered to a different extent and had downstream influences on the collision risk and social impact hotspots.

The **integration of contingency plans**, such as the redirection to emergency landing sites, impacts the localization of collision risk hotspots, as well as the areas where social impact hotspot are located. In addition, the displacement of operations due to the delays caused by the contingency event leads to a higher appearance of hotspots. There are some contingencies that change the overall set of social and collision risk hotspots more critically than others - In particular, the closure of a vertiport for 1 hour and GNSS disruptions such as those related to misleading satellite information for 1 hour. As a conclusion, contingency plans and related outcomes, need to be considered not only for a safe conduct of the single flight but also considering the effects on the overall network.

Adverse weather conditions, which lead to a limited availability of emergency landing sites for example, amplify the effect related to contingency plans. This is related to the accumulation of flight operations in low impact zones and a higher assignment of flights to a reduced number of emergency landing sites.

The experiments showed that **5 minutes of uncertainty in the departure time** leads to an observable change in the risk hotspot appearance. This level of uncertainty shows that the number of collision risk hotspots are increased almost the double. Collision risk values in each cell are also increased, as well as the number of cells with hotspots. With this in mind, we conclude that additional research on this topic should be carried out, since the assumptions made in this early research were possibly too general. 5 minutes are too short for some missions as well as they are too long for others.

The experiments showed that **weather impact** can increase the intensity and result in relocation of hotspots (mostly affected were collision risk hotspots). The reason for this is a clear reduction of available airspace volume for drones (due to weather constraints) and therefore more frequently used routes. This should be accounted for in DCB measures.

Considerations of how to identify a social hotspot, given the average length of social hotspots in Frankfurt is lower than 3 minutes raises the question whether this poses a relevant disturbance for citizens or not. Besides the average duration of hotspot cells, the time frame in over which those hotspots appear is also of interest. For example, in a 20-minute time frame, there could be five 3-minute hotspots. In this case, the average duration of a hotspot would be 3 minutes, but for the total 20-minute period, 15 minutes can be considered 'hot' (or around 75% of the time).

The distribution of affected drone types and the effects depending on the altitude (wind speeds increase logarithmically with height) were studied. Wind-sensitive drones, such as smaller multi-copters that are used for food delivery, are the most affected, up to a degree where certain layers of the airspace were not available for them. Consequently, risk modelling approaches which are fed back into the DCB and U-space processes certainly need to differentiate among airframe types. DCB measures that are based on assigning, or changing the structures of airspace layers for example, need to consider altitude-based effects indicated through the micro-weather models.

With respect to the assessment of the **reduction of vertiports capacity** due to adverse weather conditions on vertiport infrastructure, the experiments highlighted a reduction in capacity due to the additional time required to depart from the capacity constrained locations. The effect on capacity is relevant and in conclusion, better ways to estimate the available capacity on ground should be investigated. This is especially relevant in high demand scenarios, where demand is very close to maximum capacity. We therefore recommend building more detailed models and in particular models of drone performance with enough detail to be able to predict vertiport capacity, so that this can be reflected in traffic planning and any DCB measures that may be required.

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4.1.3 Conclusions from Experiment #3

The main aim of Experiment #3 was to design a method to determine the maximum number of drones that can be managed in an urban environment to maintain the risk of collision to 3rd parties below an acceptable threshold.

The experiment tested the applicability of the method and associated model during the strategic phase, when the number of drone operation plans already submitted are not enough to have a stable traffic demand. Analysis of the applicability during the pre-tactical phase, with most of the operation plans known, was also performed.

All scenarios assume free-flight operations by default – meaning that Drone operator is able to fly their own preferred profiles without any constraint, and that during the execution phase it is assumed that tactical conflicts would be resolved using on-board or ground-based technology (e.g. DAA).

In conclusion, the proposed approach of using a **collision risk model to determine the maximum number of drones** that can safely operate in a given U-space airspace was proven to be applicable.

The model was demonstrated to be sensitive to variations in the CNS performances, the impact of implementing U-space services, the population density in the cities and the sheltering effect of the buildings to reduce the risk of injury due to collision or vehicle failures.

On one hand, the approach was used to determine the maximum number of drones that can operate in the whole city without exceeding the fatality rate established by SORA (1E-6). This approach would probably be best used in the **strategic phase**, when not enough number of submitted operation plans are available. In this case, the number of drone operations is highly dependent on the density of the population. For example, densities above 20 UAS/km2 can only produce a fatality rate below the TLS (1E-6) if the population density is lower than 900 inhabitants/km2. On the contrary, in dense-populated cities (more than 5000 inhabitants/km2), the drone density must be radically reduced, and should be lower than 5 UAS/km2, if strategic deconfliction of trajectories in a free flight environment is not included.

On the other hand, the analysis approach was used for the identification of local urban areas with air and ground risk above the threshold established by SORA (collision risk hotspots). This was implemented by means of a grid of cells of 0.5km² in 2D and 3D. This approach will probably be implemented in the **pre-tactical phase** when most of the drone operation plans are known. In this phase, collision risk values were highly sensitive to pair-wise interactions among drone operation plans that are in the same cell at the same period. These potential collisions should be solved through strategic conflict resolution actions, without the need of implementing DCB measures. In this aspect, it is considered necessary to perform further work to analyse the size of the cells and the notion of a *collision risk hotspot*. The experiments performed consider that a hotspot exists if the instantaneous collision risk – risk in 1 minute – is above the target threshold. Peaks and duration of the collision risk values are other parameters that are also able to be taken into account to redefine this notion of collision risk hotspot.

By using the collision risk prototype model, the following conclusions can be extracted with regards to the added value of the **U-space services and appropriate CNS technologies to reduce the risk of air and ground collision** in U-space airspace:

- **U-space strategic conflict** service reduces the collision risk significantly (by a factor of ten in the experiments performed as part of experiment #3) compared to a volume without such a service available. It is also shown that for those scenarios considering this deconfliction service, the lower the update rate (greater frequency), the lower the collision risk.

- In a free flight environment (with no airspace structures/routes), the navigation accuracy has no effect on the number of potential collisions. However, it impacts the ability to detect avoidable collisions, with a larger number of undetected collisions when the accuracy worsens. Results show a clear reduction of collision risk for SBAS augmented GPS at lower conflict margins than for GPS L1 only.

- As stated previously, the results show that as the conflict margin increases, the percentage of undetected collisions drastically decreases. However, as the conflict margin increases, the number of false conflicts per flight hour also raises exponentially. Therefore, it is necessary to find a **trade-off between the ability to detect conflicts and efficiency**. Based on the results obtained, this could be GPS + SBAS with a conflict margin of 5m, whereas in cases of drones equipped only with GPS L1, a conflict margin of 10 m would be required, causing therefore many more false conflicts and/or a reduction in operational efficiency/capacity.

- The existence of a **U-space Tactical Conflict resolution service** to deal with pre-defined separation requirements further reduces the collision risk and, therefore, greater drone densities could be accepted safely in more densely populated environments. As the horizontal separation distance increases, the overall collision risk decreases; but, in the conditions assumed in the experiments, the vertical separation must be kept as a fraction of the horizontal separation, otherwise the collision risk will worsen. It should be noted however, that increasing the separation will limit the total capacity, so a trade-off assessment is required.

The benefits of applying **DCB measure by organizing the traffic in layers** reduces the risk compared to the free-flight environment, for the same drones’ density. The results show that a 4 layers’ structure produces a lower collision risk than a 2 layers’ one. They also show that increasing the layer thickness reduces the collision risk, in a linear manner; as the drone density increases, the layers effect improvement decays, at least for small layer thicknesses but is still relevant for wide layers.

4.1.4 Conclusions from Experiment #4

The main aim of Experiment #4 was to assess the integration of the collision risk and social impact capacity management prototypes for drone operations in the city of Madrid and to test the implementation of local DCB measures to reduce the number of hotspots, while minimising the impact on other KPAs such as mission efficiency, resilience, or flexibility. Additionally the effect of strategic DCB measures applied pre-flight is assessed with relation to the Tactical Conflict Resolution service, in particular focusing on the number of tactical conflicts that are identified both with and without DCB actions as well as the complexity of those conflicts – assessed in terms of how many conflicts are induced by tactical resolution actions, as well as the number of missions that require vehicles to either land immediately or return to base due to tactical separation issues.

In the experiments, up to 5 different DCB measures were implemented locally, i.e. in those cells of 1km² were identified as collision risk or social impact hotspots. Mitigation actions that were investigated included: speed-controlled zones of 1 hour to the zones where a hotspot is identified, increase of operational ceiling in peak hours, organization of the traffic using directional flight layers, use of pre-defined routes in the different flight layers, and finally, delays on the ground to reduce the number of critical hotspots.

Both the collision risk and social impact models were proven to be **applicable for the identification of hotspot in Madrid**. The influence of population density is also demonstrated in the results with most hotspots detected over the city centre. It is also assumed that drone movements will be similar to current road traffic movements in the future which contributes further to the location of those hotspots.

Although all the DCB measures reduced the total number of collision risk hotspots – with different effectiveness –, they were not always suitable in reducing the number of social impact hotspots, with the exception of the increase of operational ceiling. Hence, there is a **need to define additional DCB measures, addressing the reduction of the noise and visual impact on citizens**.

As previously stated, only the **increase of the operational ceiling** was able to simultaneously reduce both the collision risk and social impact hotspots. However, this DCB measure makes use of the portion of airspace between Very-Low Level (VLL) airspace, i.e. 400 ft, and the minimum altitude for manned aviation in urban environments, i.e. 1000 ft. Using this airspace in peak hours is beneficial to manage higher drone demand with less safety and social impact, but the safety buffer with manned aviation is not maintained. Consequently, interactions with ATM traffic should be taken into consideration and additional research may be required before implementing/recommending this measure.

Besides the increase of the operational ceiling, the **organization per directional flight layers** that are dynamically activated for operations within one or more hotspot cells during the period that the thresholds are exceeded is the most effective DCB measure in reducing the number of collision risk hotspots. This DCB measure also shows improvements on indicators associated with Flexibility and Resilience KPA and exhibits better behaviour when disruptions such as contingencies take place. In addition, this measure presents lower penalization on the efficiency of the missions than others, although all the DCB measures increase mission inefficiencies in comparison to free-route operations.

Although the use of **speed-controlled zones** is the least effective measure in reducing the number of hotspots, it does reduce the number of severe conflicts however, and therefore improves the overall safety of the scenario. For this reason, it should be applied to those zones where higher number of severe intrusions are predicted.

The use of **delays on the ground** is shown to be effective in deconflicting some trajectories that are in conflict before taking off. By applying this DCB measure for short timeframes (e.g. between 2 and 10 minutes) the overall mission efficiency is improved - i.e. flight duration and number of batteries and energy required. However, in the scenario that was analysed, this measure was only implemented to reduce the number of collision risk hotspots. Nevertheless, it could be a promising measure to delay, re-route or cancel those drone operations that are generating severe social impact on the population as well and this may support mitigating the negative effects on human health (e.g. sleep disturbance, increase of blood pressure, etc.).

Although the **organisation per routes** appears to be the most restrictive measure. (the implementation was based on organization per flight layers and routes in each layer), it does not present the best results in reducing the number of hotspots. On the other hand, this measure is highly penalizing the overall mission efficiency as it can be seen in indicators such as the Elapsed Airborne Time. In conclusion, it is not recommended to implement this measure in urban air mobility scenarios because it reduces the degrees of freedom in drone trajectories and, therefore, in avoidance manoeuvres, without significant improvement in the KPAs with respect to the free route scenario. However, further analysis to identify a more operationally efficient temporary route structure may increase the efficiency of the solution it should not be fully ruled out at this stage and additional research may be of interest.

Regarding the **impact of DCB and strategic management actions that are applied in the pre-flight phase, tactical conflict resolution counts are generally reduced following DCB measures**, with the exception of the speed and route-based solutions. DCB and strategic conflict management actions using altitude-based solutions show large reductions in separation issues (with directional layers by 27% and the increased operational ceiling as much as 44% fewer conflicts).

However, as none of the DCB measures tested manages to resolve all hotspots completely, it will be necessary to be able to **dynamically combine the measures** to optimise DCB actions.

For example, a combination of the flight layers organization combined with a temporary increase of operational ceiling could be tested in future scenarios by taking into consideration not only the directions of the operation plans, but also the drone dimensions, shape and noise and visual impact. drones causing higher impact on population should fly at higher altitudes.

4.2 Recommendations

4.2.1 Recommendations for next phase

The DACUS validation experiments have laid a strong foundation for the use a DCB process and alternative capacity measures in support of drone operations in urban environments, with particular focus on the impact of drones on the population living in those regions.

The use of metrics and indicators based on societal factors and risk to people living in the urban areas has proven to be a very valuable method with which to help manage the demand for drone operation to respect the limits and thresholds defined by the DACUS research. This does not, however, preclude the use of maximum operation counts, or simultaneous operation limits in the different grid cells that have been created to help monitor and manage drone missions, but offers a new perspective on methods through which operations can be planned, using a society-based management approach – which remains important given the low altitudes that are expected to be used for this type of operation.

In general, the research is **fully aligned with the concepts expressed in the CORUS ConOps**, that has been expanded upon where necessary by the DACUS ConOps. DACUS has successfully demonstrated that a continuous and pro-active monitoring and management of the evolving traffic situation is able to identify and provide suitable measures to resolve situations where capacity thresholds are expected to be exceeded.

It is relevant to mention that, although the **notion of Required Time to Act (RTTA)** is described both in the CORUS ConOps and also in DACUS ConOps, there could be differences in its interpretation. DACUS understands RTTA as a certain time before the execution in which the drone traffic demand is stable enough to take decisions with regards to the implementation of DCB measures. For DACUS, this is the transition between the strategic and the pre-tactical phase and it is a notion closely linked to overall management of the drone traffic network. On the other hand, CORUS (and its extension in CORUS-XUAM) is also considering the possibility that RTTA is associated to the time in advance that the drone operator can consolidate its operation plan, providing a stable departure time. These different interpretations make it necessary to further clarify this notion, which is a relevant point in the overall DCB process.

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Other important topic that needs further clarification and research is **the role of each actor when constraints associated to DCB measures are imposed**. Two different approaches can be followed: U-space Capacity Management service provides the best solutions to the drone operators, or the drone operator receives the constraints and decides how to fly. DACUS performed an initial assessment of both approaches, and although the 1st one was more effective to design new operation plans in line with the constraints, the 2nd approach resolved a significant number of cases as well. In addition, this second option provides more freedom to the drone operators to look for suitable alternatives according to their own business needs, which are not necessarily well-known by the U-space Service Providers[1].

The 1st approach could rely on **machine-learning techniques that consider previous acceptability of solutions by drone operators**. One of the most relevant factors to take into account is the specific characteristics of each business model, as it was identified by DACUS.

The implementation of the 2nd approach makes it necessary to provide drone operators with a **detailed view of how the overall drone demand and potential collision risk and social hotspots is evolving**. This information could be included in the U-space Aeronautical Information Management service, but DACUS recommends defining a new U-space service, maintaining separated the aeronautical information and the information associated to the demand picture.

In the scope of the DACUS experiments the prototypes used to implement the models of the Noise, Visual impact and Collision Risk services have been focused on producing reliable and re-useable metrics for grids located in the operating regions (as described in appendix A-D). However, they have not been developed for use in an interoperable, real-time mode, and were consequently consulted in a so-called 'static' mode with the analysis of traffic requiring very high execution times.

One obvious topic for future research would be to refactor these tools so that they can be used as **interactive, real-time, services that consume the most up-to-date information available**, and which can be consulted at any time to provide immediate, on-demand hotspot assessment for all phases of the planning process. Moreover, through the use of a common information system that maintains all of the most up-to-date DOP for the region, any changes to proposed missions at any stage of the process can be immediately investigated and new views on the resulting hotspot issues can be immediately assessed and appropriate action can be applied.

With regard to the dimensions of the cells used to evaluate the different indicators, where a 1km x 1km cell was found to be suitable for the societal impact indicators, it was necessary to reduce the size to 0.5Km x 0.5km when calculating to conflict risk – mainly to reduce the size of the impacted population in each cell and thereby help to achieve the selected Target Level of Safety (TLS). The dimensions were also carefully selected to permit borders to be aligned, however further research would be of value to see if the dimensions could be reduced further or not.

Similarly, the hotspot duration, or length of time that any given cell is above the desired threshold before action is necessary to mitigate the problem, and methods to aggregate across a longer

[1] Examples can be found in section 5.3 of DACUS D5.3 Performance Framework.

timeframe to produce sustained hotspot metrics in addition to instantaneous ones would also be of interest in future analysis.

A considerable level of confidence in the outputs of the DCM prototype models has been attained during the verification and validation experiments, both related to the results that are produced, and their use in an operational context. This suggests that the TRL level for this type of capacity management tool can be considered to be higher than the original target at which the DACUS research was focused. In the view of the partners, the DCM prototypes used to support the Collision Risk and Social Impact measures can be considered to be stable and mature and around the TRL 3 level. For the DCB solution as a whole, the partners consider that the research is reaching TRL 2. This will be further discussed in the Final Project Results Report (D6.3).

However, before progressing to TRL which are significantly higher, it is recommended to consider the aspects that are described in the bullets shown below.

In any case, DACUS has analysed the whole DCB process for U-space in the medium to long-term timeframes. It is recommended to identify those elements that are mature enough to proceed with their implementation at short-term, assuming that an initial DCB will be needed as soon as the new U-space airspace will be in place in Europe.

- **More complex operational scenarios with a variety of additional situations** being considered, particularly for the pre-tactical and tactical execution phases, and additional planning scenarios which extend the initial work using micro-weather effects would be of significant additional value in follow-on research.
  This includes the additional scenarios which consider the original experimental objectives that were targeted in the DACUS experimental plan, but which were unable to be executed in the scope and time that was available for performing those experiments would also be an important element of any future research.

- Consolidation of the **notion of social impact and collision risk hotspots**. DACUS has considered as hotspots all instantaneous values above the thresholds, and other aspects need to be captured as the duration, frequency, or absolute values of the hotspot.

- Research on the definition of **additional DCB measures addressing the reduction of noise and visual impact on citizens**. The effectiveness of two DCB measures was proved by DACUS: modifications of the flight levels and the increase of operational ceiling. However, the rest of DCB measures are focused on the reduction of the collision risk are not beneficial for the social impact.

- Close cooperation with Councils and Authorities to better understand the **acceptable thresholds with regards to noise and visual impact**, taking into consideration the diversity of urban areas and periods of the day.

Considering the high impact that weather, last-minute changes in the departure time and activation of contingency plans has over the uncertainty of the demand, further research is needed to define the recommended **timeframe to take DCB decisions prior to the execution**.

Additional analysis scenarios which consider the original experimental objectives that were targeted in the DACUS experimental plan, but which were unable to be executed in the scope and available time that was available for performing those experiments would also be an important element of any future research.

5 References

5.1 Reference Documents

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[2] DACUS D5.3 – Performance framework, Edition 00.02.00, November 2021

[3] DACUS D1.1 – drone DCB Concept and Process, Edition 01.00.00, March 2021

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[7] JARUS guidelines on Specific Operations Risk Assessment (SORA), Edition 2.0, JAR-doc-06, Jan 2019

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[9] DACUS TASK FORCE – drone Traffic Characterization, Edition 00.00.02, October 2021

[10] DACUS D3.2 – Capacity Models, Edition 00.02.00, August 2021

[11] DACUS D5.2 – Separation Management, Edition 00.03.00, July 2021

[12] Instituto Nacional de Estadística: https://www.ine.es/

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[14] Concept and Requirements for an Integrated Contingency Management Framework in UAS Missions, H. Eduardo Teomitzi and J. R. Schmidt (2021), IEEE Aerospace Conference, 2021, pp. 1-17, doi: 10.1109/AERO50100.2021.9438458

[15]BUBBLES – Defining the Building Basic Blocks for a U-Space Separation management service: https://www.sesarju.eu/projects/bubbles

Appendix A Experiment #1 Detailed Report

A.1 Scenarios

A.1.1 Operation types

For this experiment, we define a reference scenario. This reference scenario represents realistic needs for the operation of drones in an urban environment. It focuses on a context where drones are highly integrated in everyday life and used frequently. This realistic point-of-view comes from the use cases and their volume, not the preference of using drones instead of other means. Additional scenarios are derived from the "nominal" reference one.

For every scenario, we selected drone traffic on a Tuesday between noon and 2pm in Toulouse urban area.

In the operation generator, there are four types of operations (described below):

- Food delivery;
- Package delivery;
- Monitoring;
- Taxi drone.

Food delivery

From *deliverect* website, in France, 74% of food deliveries are concentrated on Friday, Saturday and Sunday. Still from the same website, 3 food orders are submitted every second in France, which is 94,608,000 orders every year.

If we consider that only inhabitants leaving in urban units greater than 10,000 inhabitants have access to food delivery services, it corresponds to 44,207,629. An even spread gives 2.14 orders per inhabitant per year. In Toulouse urban area, where the population is 1,360,514, we get 55,990 orders per week. Considering the day distribution, 41,366 orders (74%) on Friday, Saturday and Sunday, and 14,624 on the other days. In our scenarios, we only consider Tuesday, between 12pm (noon) and 2pm. The total number of food deliveries in these conditions is around 549 for the reference scenario.

Package delivery

From *statista* website, there were 1.215 billion packages delivered in France in 2019. For a population of 67 million, it gives 18.1 per inhabitant. For Toulouse Urban Area: 473,564 per week. From several website, including *statista* and *laposte*, around 35% corresponds to small package, which can be carried per drone. The total estimation for our scenario is around 4967.

Monitoring

The number of monitoring operations is negligible compared to the two previous operation types, but this type of operation lasts longer because the drone is very slow, between 1 and 5m/s, and makes some stops at some points that can range between 30 seconds and 2 minutes. For these reasons, monitoring operation last from 30 minutes to 2 hours.

Taxi drone

We decide to simulate taxi drones with regular taxi lines. The first line connects the main train station to the airport. This line gets around city centre by north and a taxi drone leaves every 20 minutes. The other line connects the major city south of Toulouse (Muret) to the airport. This line follows the Garonne (main Toulouse River) to cross the city to the north and a taxi drone leaves every 40 minutes. These two lines are represented by two blue lines in Figure 7.

A.1.2 Scenario definitions

Based on this estimation, we have generated scenario #1, the reference scenario. We have derived scenario #2, #3, #4, #5, #6 and #7 by progressively decreasing the number of package and food deliveries (most of the operations). It allows us to have scenario with lower impact and help the understanding with lower traffic, closer to what we can expect in drone traffic. Also, we have generated scenario #8 and scenario #9 for which we keep only one of the two operations previously listed, package and food deliveries respectively, with a number of operations comparable to the other operations, especially taxi drones. The nine scenarios are summarized here:

- **Scenario #1**: estimation of all deliveries in Toulouse made by drones. Taxi drone departure every 5 minutes.
- **Scenario #2, #3, #4, #5**: 75%, 50%, 25%, 10% of scenario #1 for package and food deliveries.
- **Scenario #6**: 0,1% of scenario #1 for package deliveries, 1% for food deliveries.
- **Scenario #7**: no package and food delivery.
- **Scenario #8**: 5% of scenario #1 for package deliveries, no food delivery.
- **Scenario #9**: 50% of scenario #1 for food deliveries, no package delivery.
- The distribution of the number of drones is presented in Table 29.

Scenario #	Package delivery	Food delivery	Return	Monitoring	Taxi drone	Total
01	5574	473	5937	0	64	12048
02	4177	357	4467	2	64	9067
03	2764	233	2976	0	65	6038
04	1360	154	1493	1	65	3073
05	589	38	617	1	64	1309
06	7	2	8	0	64	81
07	0	0	0	1	64	65
08	285	0	281	5	64	635
09	0	258	213	6	65	542

Table 29 Number of operation types and total number of operations per scenario.

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The "Return" column shows the return flight for package and food deliveries, but it is not equal to "Package delivery" + "Food delivery" as we allow food delivery to carry more than one order, up to 3. The average number of orders per drone is around 1.25.

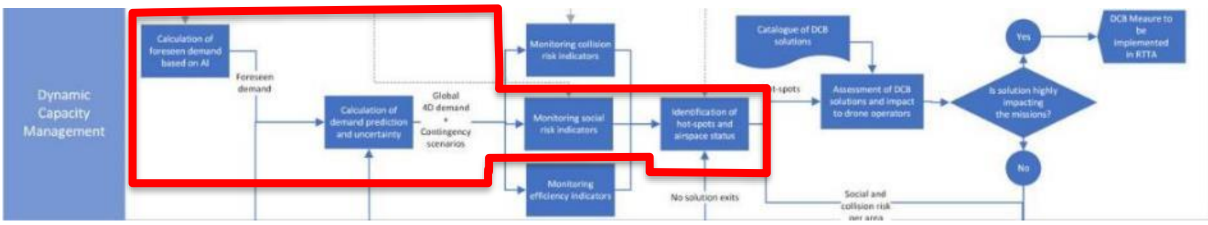
In this table, we emphasize four scenarios with two colours. Scenarios #1 and #2 are not included in this report. Results from other scenarios and preliminary results from these two allowed us to conclude that this number of operations saturates the impact and the number of hotspots, given the threshold used (see below). Proper analysis and conclusion can only be done for all other scenarios. We also emphasize scenarios #8 and #9. Indeed, all scenarios are based on a variation of the reference scenario which is dominated by package deliveries. All but scenario #9. For this last scenario, there is no package delivery, mainly food deliveries, and the total number of operations is similar of scenario #8. In the following results, this comparison will make sense and we will mainly focus on these two scenarios.

A.2 DCM service and social impact model

A.2.1 DCM service

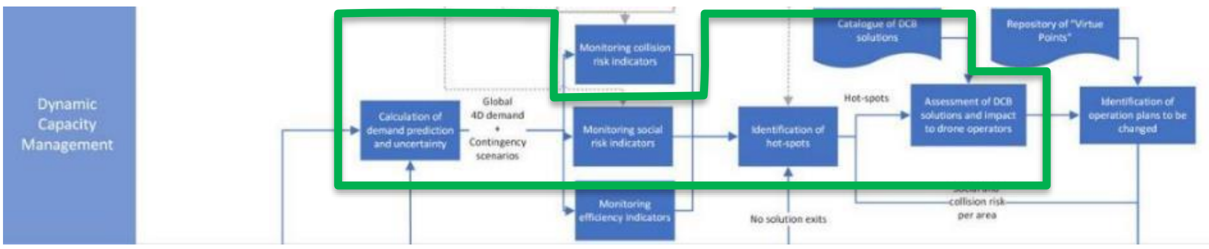
The DCM service for the strategic phase consists of (1) the creation of traffic demand forecasts, (2) use of this demand forecast to assess DCB indicators for impact hotspots, and (3) reporting hotspot forecasted situations such that either additional capacity could be planned, or the demand can be adjusted such that DCB hotspot measures are reduced.

Experiment #1 considered two phases: The first focused on the red box - for the strategic planning phase:



This box is composed of the capacity/demand predictor, the social impact model and the hotspots identifier. The capacity/demand predictor will provide capacity prediction of every cell in a grid that covers the whole city, every minute, to the social impact model. From these previsions, social impact model can compute social impact metrics (noise and visual impacts). Finally, the hotspot identifier saves the predicted hotspots to be used during pre-tactical phase.

The second experiment focused on the green box - for the pre-tactical planning phase:



This box is composed of the 4D trajectory calculator, the social impact model, the hotspots identifier and the DCB measure selector. During pre-tactical phase, flight plans start to be submitted. The 4D trajectory calculator will compute the trajectory based on these plans. Then, the hotspots identifier triggers the DCB measure selector if at least one hotspot is identified from the social impact model. The DCB measure selector will simulate DCB measures on one or more flight and verify that it reduces or deletes hotspot. If all hotspots are deleted, the DCM service can finally propose the measure to the drone operator. In the case where a hotspot has been predicted during strategic phase, the DCB measure selector can have an early trigger, in order to have time to take decision, find the best measure and smooth traffic flow.

A.2.2 Social impact model

The societal impact model aims at providing metrics for the DCM process that allow the identification of both noise and visual impact. It provides such metrics from a single drone or traffic point of view. The drone point of view enables to score an operation as if there is no other operation in the vicinity. This is a cumulative exposure created by a single flight.

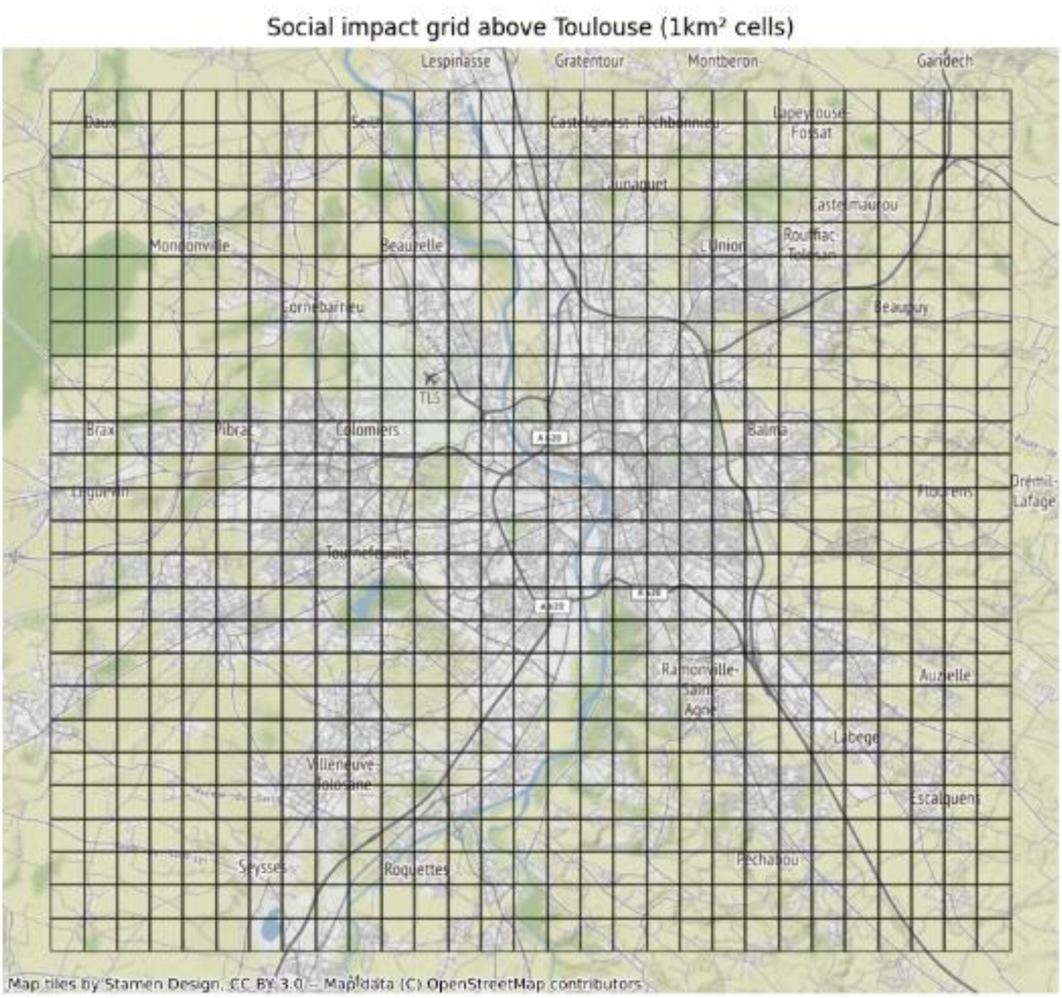


Figure 6 Social impact grid above Toulouse. Each cell is 1km². Total grid size is 754km².

The traffic point of view is the core of the model and enables the detection, and localization, of hotspots. This is an area-wide effect calculated over a specific period. Hotspots can be triggered using a specific threshold. The model can provide all the cells where the noise and/or visual impact exceed the threshold at a given time. In order to estimate the impact, we firstly create areas to localize those impacts. In this exercise, we made a grid over the city of Toulouse (France). This grid is made of 1km-side squares (see Figure 6). It covers a large region, above Toulouse urban area, of 754km².

The DACUS D5.3 Performance Framework [2] presents all metrics description. Based on telecom network data, we derived a population density map (see Figure 7). This map shows a very high population density cell, in the city centre, and some surrounding cells. This observation will be important for the analysis.

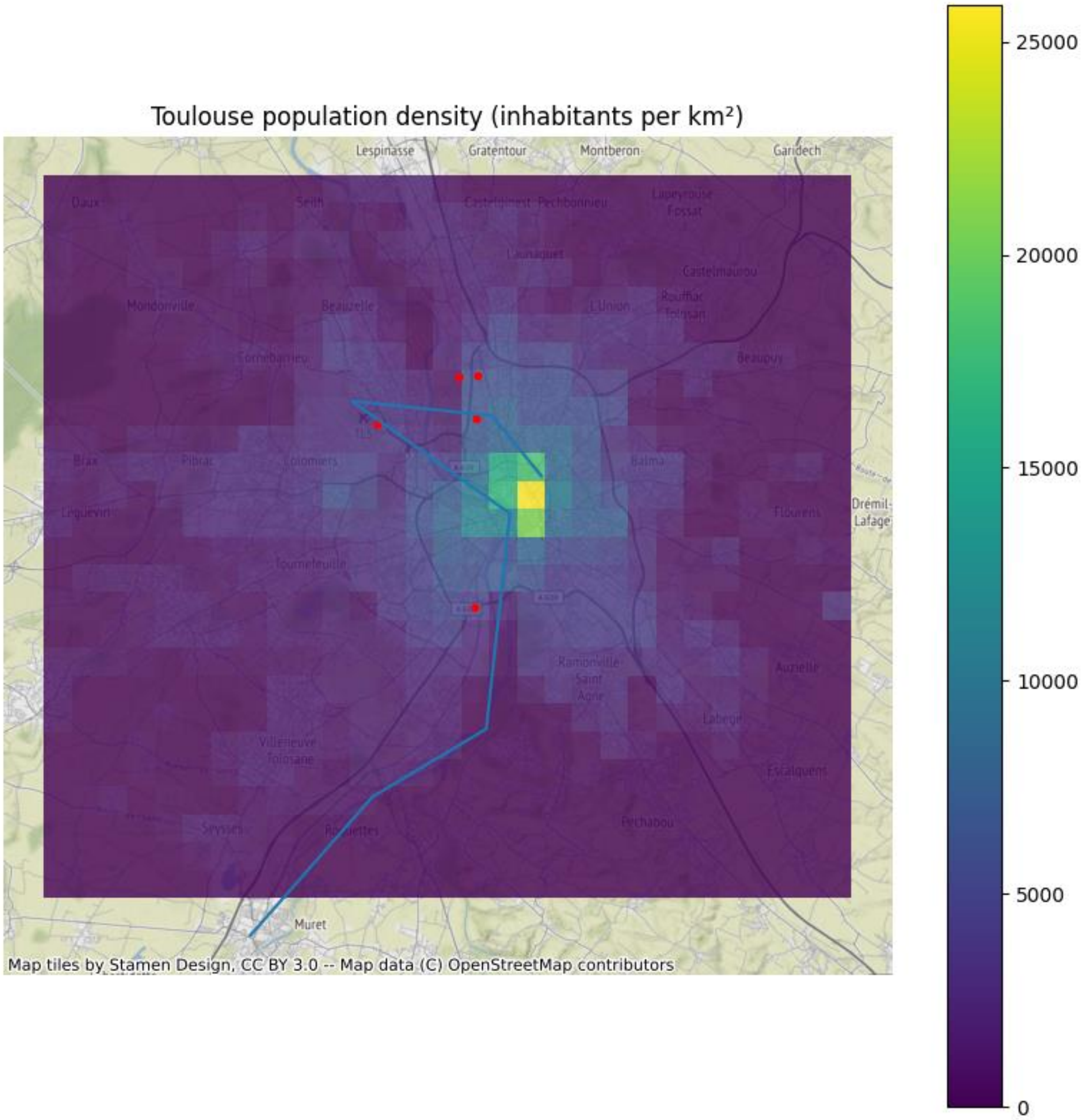


Figure 7 Toulouse urban area population density in inhabitants per km².

Red points are warehouses of Toulouse main delivery companies. The two blue lines are the taxi drone lines. One connects the Muret main train station (largest city in the south) to the airport, and the other one connects the Toulouse main train station to the airport.

A.3 Hotspot identification

A.3.1 Threshold variation

To evaluate the effectiveness of the hotspot identification, we evaluate the effectiveness of the threshold. The purpose of this study is not to find the value of the thresholds but their behaviour and their consistency. The appropriate value of the thresholds should be discussed in accordance with UTM rules and laws.

In the social impact model, there are four different thresholds, one for each impact type:

- Noise Annoyance (NA);
- Noise Exposure (NE);
- Visual Annoyance (VA);
- Visual Exposure (VE).

The threshold is the impact value for which the DCM service triggers a hotspot, at a precise time and location. By varying this threshold, we can emphasize some behaviour of the hotspots. Obviously, the number of hotspots increases while the threshold lowers. In Figure 8, we plot the number of hotspots versus a threshold coefficient. This threshold allows us to vary all the thresholds with only one parameter. All four thresholds are multiplied by this coefficient and the reference thresholds are:

- Threshold NA: 500;
- Threshold NE: 12000;
- Threshold VA: 500;
- Threshold VE: 1000.

We chose a common parameter because one-by-one impact study shows a similar behaviour, when varying the threshold, for every kind of impact. Typically, the number of hotspots is proportional to $\exp\left(-\sqrt{threshold}\right)$.

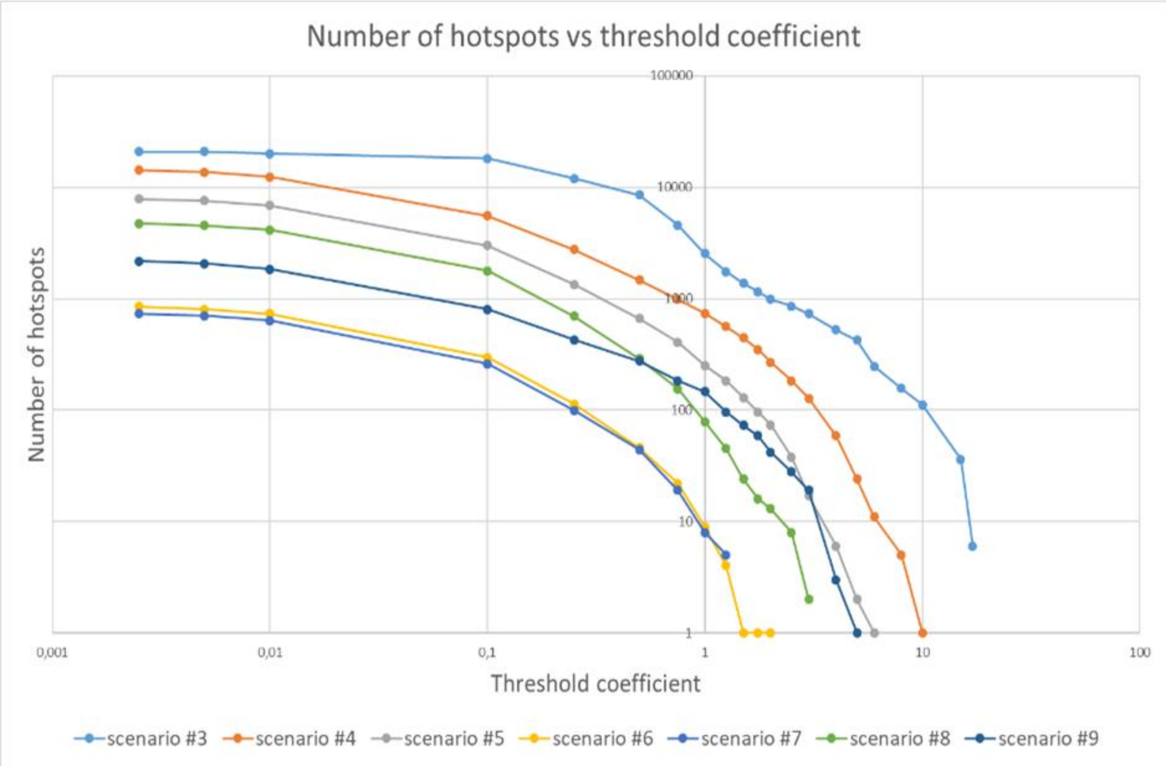


Figure 8: Number of hotspots per scenario versus threshold coefficient

We observe two interesting behaviours: a crossing of scenario #8 and #9 around a coefficient of 0.5 and a critical value on the threshold, for every scenario, for which there is no hotspot.

As mentioned in chapter A.1.2, if we consider all scenarios, they are all dominated by package deliveries but scenario #9. This last one is dominated by food deliveries and has no package delivery. In Figure 8, we can see that all the curves have the same shape, except for one shift related to the number of drones during the scenario. Only scenario #9 is flattened compared to the others. This flattening leads to a crossing point with the scenario #8, comparable in terms of number of drones. **Differences in food and package delivery shapes are the reason of the different behaviours**. Package deliveries (scenario #8) take off from few precise locations, where the population density is low or at most moderated. Then, the “target location” is more likely a highly populated region. In comparison, food deliveries (scenario #9) take off from restaurants. The probability of take-off location is proportional to restaurant density and this restaurant density is highly correlated to population density. Then, like package delivery, the “target location” is more likely a high-density region. To summarize, package delivery comes from few but moderately inhabited to highly populated region and food delivery comes from and to highly populated region. In Figure 9, the number of drones flying over each cell is represented. We see that more cells are impacted in scenario #8 but in regions with less inhabitants, whereas in scenario #9, most drones are concentrated in the city centre, where the population density is the highest.

To conclude this observation, package deliveries impact more cells with a moderate impact, favourable with high thresholds, and food deliveries impact less cells with high impact, favourable with low thresholds.

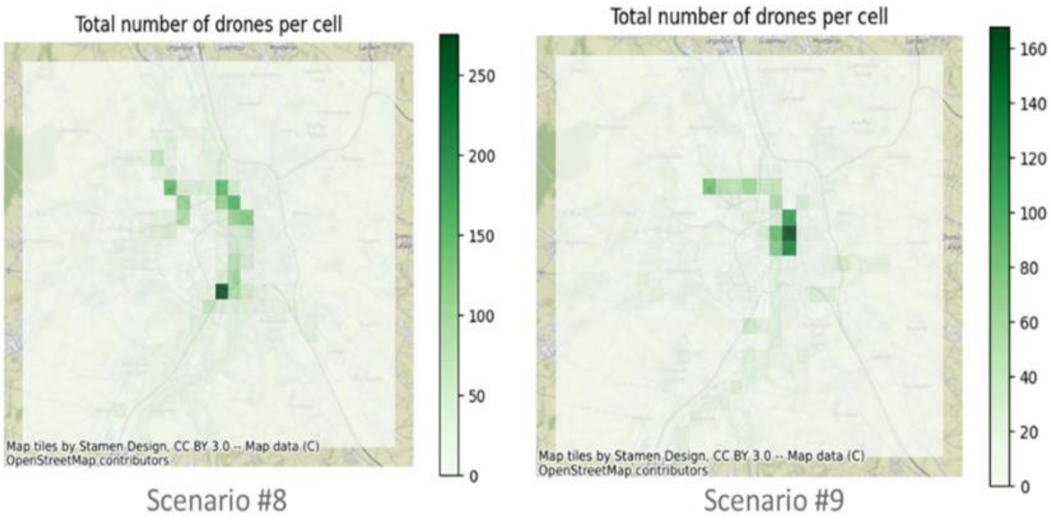


Figure 9: Number of drones overflying by cell during entire scenario (2 hours).

Defining hotspots is made by threshold. Once an impact value gets above this threshold, the corresponding cell and the time of impact define a hotspot. At some threshold level, no impact goes above the threshold, meaning there is no hotspot at all. This point is called a “critical threshold”. It varies depending on the maximum impact reached for every scenario. In Figure 10, the critical thresholds are plotted, based on values from Figure 8. We can see relation between the number of drones for 2 hours and the critical threshold. This relation is $\propto \sqrt{number\ of\ drones}$. This behavior may help getting early results when we fix thresholds, knowing if the expected traffic of drones may raise or not hotspots. Similar early analysis can be done from Figure 8 to estimate the number of hotspots which can be triggered.

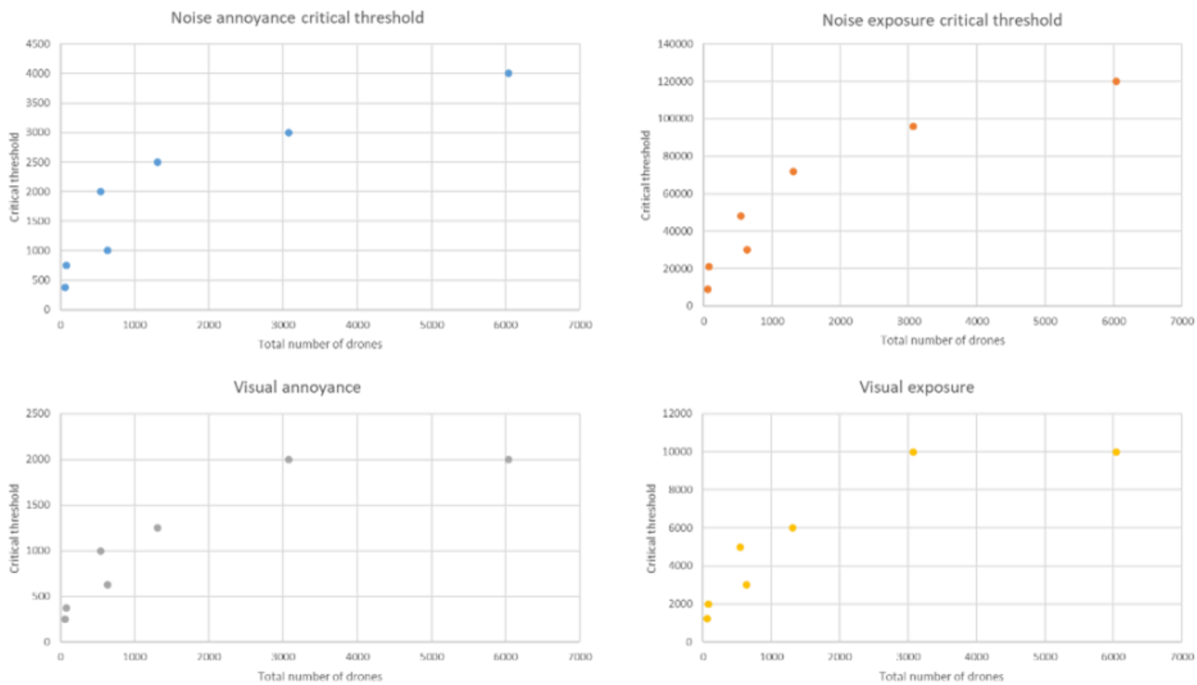


Figure 10: Critical thresholds for every impact type versus the number of drones per 2 hours

A.3.2 Social impact correlation

We have studied correlations between the four social impacts: noise and visual, both annoyance and exposure. This study allows us to determine if the four social impact types are relevant, independently one with the others.

Because the impacts get higher as the number of drones increases, we can see a clear linear correlation (see Figure 11). To better understand this correlation, we have to look at the dispersion around this linear correlation. To do so, we calculate the ratio between impacts:

- $r_{E\backslash A}^{noise} = \frac{I_{exposure}^{noise}}{I_{annoyance}^{noise}}$ - (see Figure 11 graph 1 below).
- $r_{E\backslash A}^{visual} = \frac{I_{exposure}^{visual}}{I_{annoyance}^{visual}}$ - (see Figure 11 graph 6 below).
- $r_{V\backslash N}^{exposure} = \frac{I_{exposure}^{visual}}{I_{exposure}^{noise}}$ - (see Figure 11 graph 5 below).
- $r_{V\backslash N}^{annoyance} = \frac{I_{annoyance}^{visual}}{I_{annoyance}^{noise}}$ - (see Figure 11 graph 2 below).

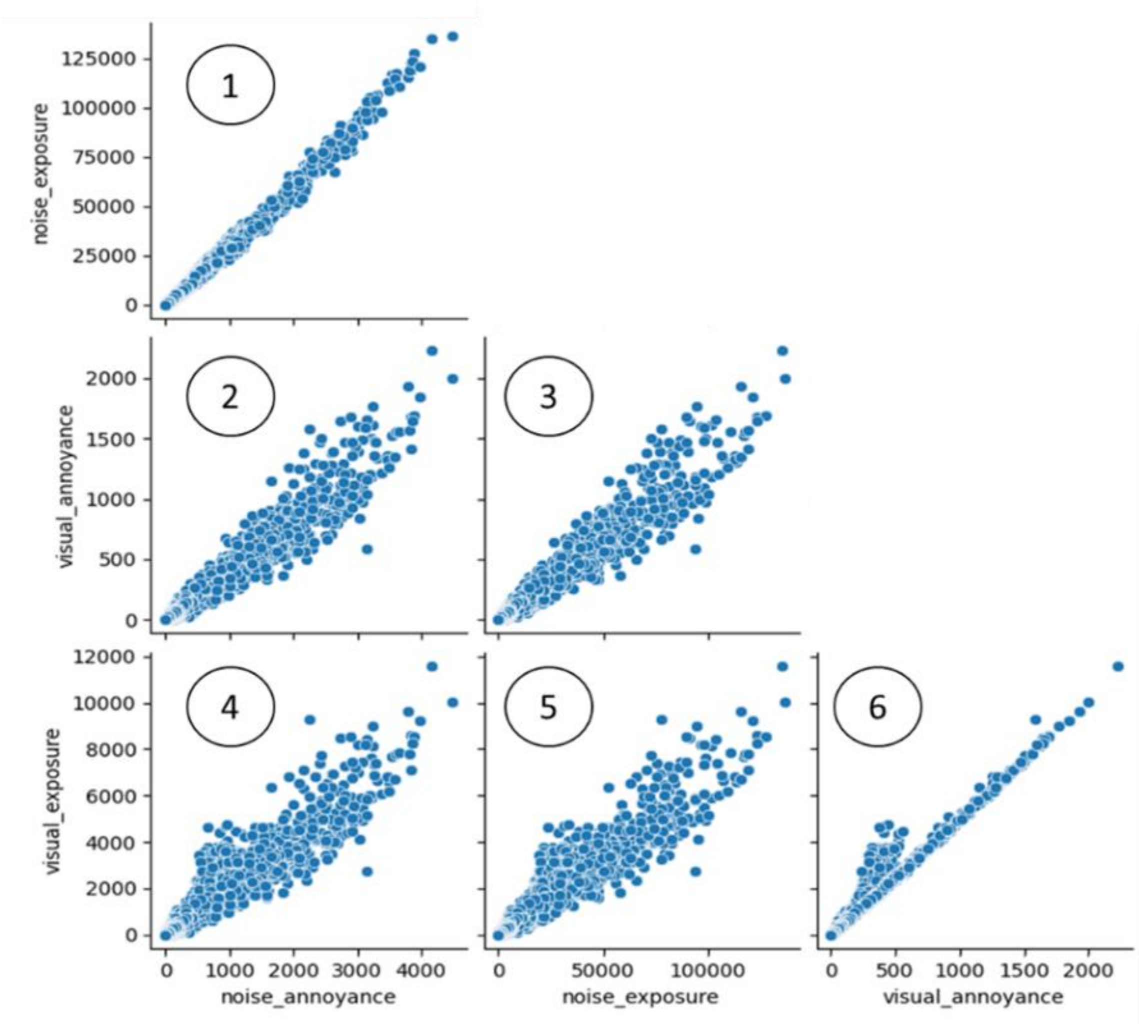


Figure 11: Correlation between each social impact for scenario #3.

Note: the graphs shown above illustrate the correlation between each social impact for scenario #3 where every point shown in each graph is data for a given cell and time.

For correlation between noise impacts (annoyance and exposure) (Figure 11.1), we see a nice linear correlation. The ratio $r_{E\backslash A}^{noise} = \frac{I_{exposure}^{noise}}{I_{annoyance}^{noise}}$ is plotted for every point in Figure 12. On the left plot, with every data, we see the majority of data with the same ratio ~22.84.

This value corresponds to an impact where only the lowest impact area is present, for drones flying high enough

We can see that most drones have this impact on the ground. On the right plot, the number of remaining values decrease as the ratio increase.

For correlation between visual impacts (annoyance and exposure) (Figure 11.6), we see a nice linear correlation but also a small cluster for small values of impact, disappearing at visual annoyance impact greater than 500.

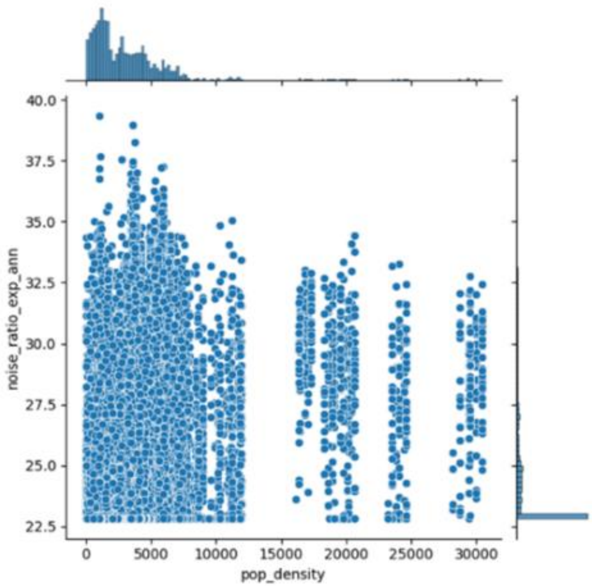


Figure 12: Ratio $r_{E\backslash A}^{noise}$ for every point versus population density.

Note in the figure above, the chart on the left shows every data point, while the one on the right is without the main value at 22.84.

The ratio $r_{E\backslash A}^{visual} = \frac{I_{exposure}^{visual}}{I_{annoyance}^{visual}}$ is plotted for every point in Figure 13 below.

So far, the cause of the small cluster is not yet determined. But plotting the ratio shows that it has a negligible effect compared to the main line.

As for noise impact, we see the majority of data with the same ratio ~4.55. This value corresponds to an impact where only the lowest impact area is present, for drones flying high enough.

We can see that most drones have this impact on the ground. On the right plot, the remaining values have another density peak around the value 5. Even if the behaviour of visual impacts is mostly the same as noise impacts, it seems to show more complex structure and might need further investigations.

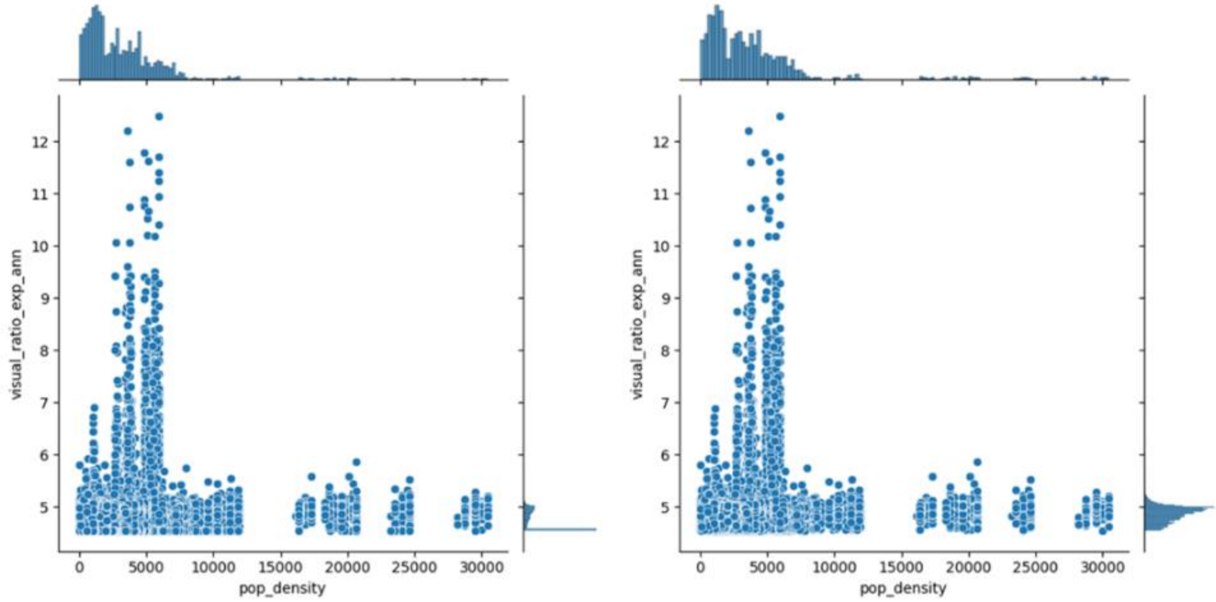


Figure 13: Ratio $\mathrm{r}_{E\backslash A}^{visual}$ for every point versus population density

Figure 13, above, shows all data points on the left, and without the main value at 4.55 on the right.

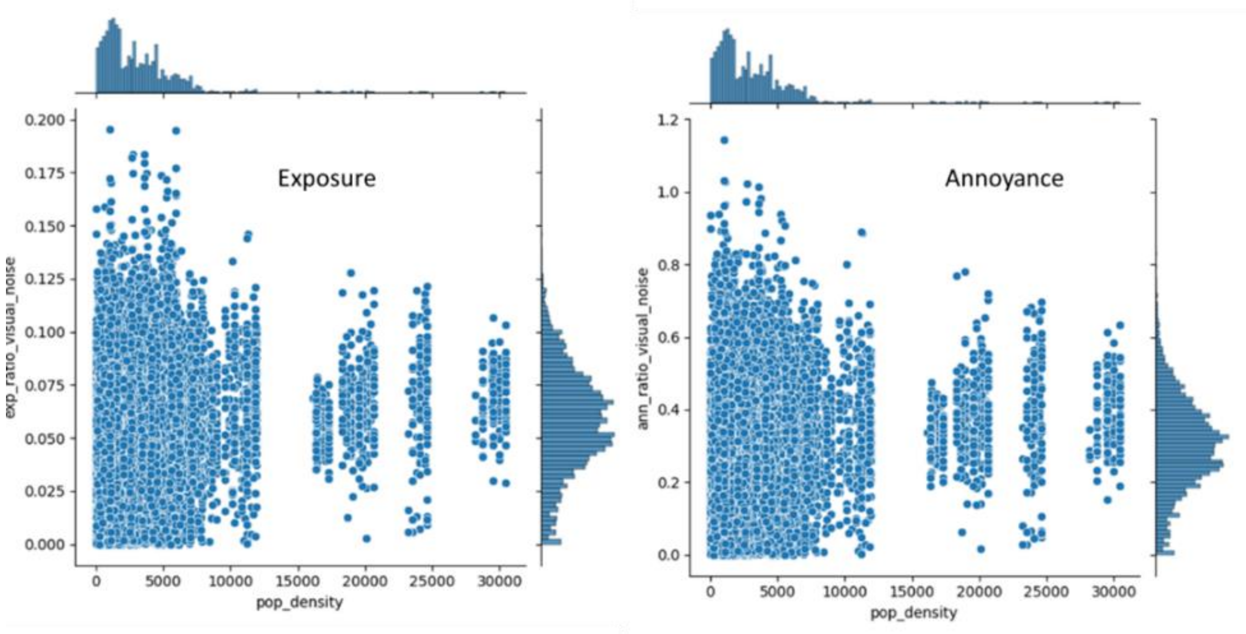


Figure 14: Left: ratio $\mathrm{r}_{V\backslash N}^{exposure}$. Right: ratio $\mathrm{r}_{V\backslash N}^{annoyance}$

Finally, correlations between noise and visual impacts (Figure 11.5 and Figure 11.2) also show linear correlation but with a higher dispersion of the values. Ratios $r_{V\backslash N}^{exposure} = \frac{I_{exposure}^{visual}}{I_{exposure}^{noise}}$ and $r_{V\backslash N}^{annoyance} = \frac{I_{annoyance}^{visual}}{I_{annoyance}^{noise}}$ are shown Figure 12. The ratio distributions indicate high correlation between noise and visual social impact, but the high dispersions highlight the necessity to have both indicators, as one can increase when the other decreases.

A.3.3 Hotspot location in space and time

So far, a "hotspot" is defined by a location (cell) and a time (with a frequency of one minute). However, consecutive hotspots in one cell can be seen as one hotspot with a third parameter which is the time length. In some situation, one or two-minutes hotspot can be acceptable whereas a twenty-minutes hotspot is not. In this section, we discuss if the definition of hotspots in 1km² cells-grid allows us to identify hotspots and take appropriate measures.

In scenario #3, the most representative one in terms of hotspots, we analyse the number of "one-minute hotspots" and the average number of consecutive "one-minute hotspots". These two indicators tell us how long, during a timeframe of 2 hours, people are exposed or annoyed, and how long it lasts on average, independently of the timeframe. In Figure 15, the left panel presents the average hotspot length for every cell. We can see two cells where a hotspot is constantly present. The two-hours hotspot in the south of the map is in a cell containing a delivery warehouse close to residential area. The other cell with a constant hotspot is surrounded by three delivery warehouses in the northwest and the city centre in the southeast. The high impact is due to a high traffic of drones above this area. We can see that, even with a drop in the hotspot length (around 40 minutes), the other most impacting cells are in a NW-SE axis around this cell. About this axis, right panel on Figure 15 indicates that most of the time during the scenario, there are one or several hotspot(s) located here. It means that only in few times, there is no hotspots. We can conclude, especially in the north, that **hotspot length is not the only parameter to take into account but also the frequency of hotspot**, as some regions show a short average length but a high total of minutes with high social impact during the 2-hours timeframe.

This level of granularity, 1km² per cell, is small enough to allow us to determine the hotspot causes and identify with precision location in time and space.

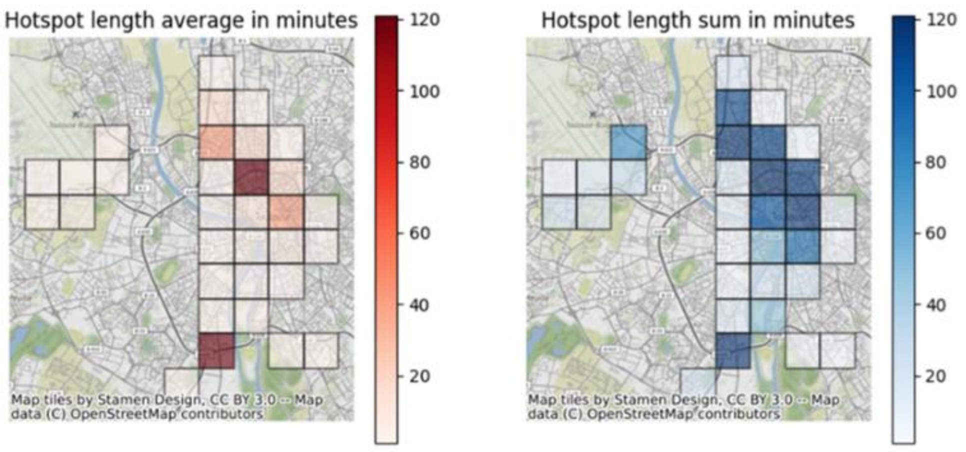


Figure 15: Hotspots length for scenario #3.

Figure 15 above shows the average length of hotspots on the left chart, and the total number of minutes with a hotspot (over a 2-hour period) on the right.

A.3.4 Automatic DCB measures

Automatic Demand and Capacity Balancing (DCB) measures can be calculated and proposed by the DCM service. The tested DCB measures are the simplest possible and applied to the whole flight. Two automatic DCB measures are tested: **delay on the departure and modification of flight height**. For the delay, the measure is parametrized by the number of minutes before or after the scheduled time of departure and can be -15, -10, -5, 5, 10, 15, 20, 25 and 30 minutes. We allow negative value because the DCM service aims to suggest a potential measure which reduces the number of hotspots. If the drone operator considers that the measure can be applied, it is worth it to probe all possibilities, even an early take-off. For flight height modification, the parameter is the number of meters below or above scheduled flight height and can be -40, -30, -20, -10, 10, 20, 30, 40, 50, 60, 70 and 80m. Because of negative value, if the resulting altitude is lower than 20m, the measure is considered as not applicable.

We have tested two approaches on how to apply DCB measures. For both approaches, each time a drone operation triggers hotspots, the **DCM service searches for a DCB measure which decreases the number of triggered hotspots**. If such a measure is found, it is automatically applied to the operation.

The first approach is to pick a random measure and to check the number of hotspots variation. If the number of hotspots has decreased, we apply the measure. If the number of hotspots has increased or remains the same, we pick another DCB measure and repeat the process. The maximum number of tests is set to 5. When this maximum number is reached, the DCB measure search process is stopped without applying a measure. The other approach is the same as before, but the picking is based on a score. Each DCB measure has a score between 0 and 1, where 1 is the most successful, starting with 0.5 for every measure. The probability of picking a measure is based on this score. After each test, we update the DCB measure score regarding the number of hotspots variation. The update is defined to ensure to keep the score between 0 and 1 and is as follow:

- Relative variation is computed $\widetilde{\Delta} = \frac{\Delta}{\overline{\#_{hotspots}}}$, where $\Delta = \#_{hotspots\_after} - \#_{hotspots\_before}$ and $\overline{\#_{hotspots}} = \frac{\#_{hotspots\_after} + \#_{hotspots\_before}}{2}$
- New score s_k is computed based on the relative variation:
    - If variation is negative: $s_k = -(1 - s_{k-1}) \tanh \widetilde{\Delta} + s_{k-1}$
    - If variation is positive: $s_k = s_{k-1} - s_{k-1} \tanh \widetilde{\Delta}$
    - If DCB measure is not applicable: $s_k = 0.9 s_{k-1}$

We focused on scenario #8 and #9 to compare if the scenario type has an effect on automatic DCB measure application. The results are shown in Table 30.Table 1 We see an improvement in the number of hotspots when applying automatic DCB measures. For scenario #8, the number of hotspots decreased by 60% with random picking and 78% with score-based picking. The reduction is less significant for scenario #9 with 31% decrease with random picking and 25% with score-based picking. Even with a less significant reduction with the scored measure, difference between the two reductions is not large enough to conclude that score is less efficient than random picking in this situation. Regarding the number of tests will help decide between the two picking procedures.

Scenario #	Automatic DCB measure	Number of hotspots	Number of DCB measures tests
08	None	83	/
08	Random	33	192
08	Scored	18	152

Scenario #	Automatic DCB measure	Number of hotspots	Number of DCB measures tests
09	None	148	/
09	Random	102	372
09	Scored	110	298

Table 30: Number of hotspots and DCB measure tests for scenario #8 and #9 for run with no, random and scored automatic DCB measures

Considering the total number of tests for every run, there is 20% less tests when using a scored picking. For scenario #8, it is faster to find DCB measures with scored measures with an improvement of 46% in the number of resulting hotspots. For scenario #9, it is also faster for a comparable number of resulting hotspots (only 8% more with scored DCB measures compared to random ones).

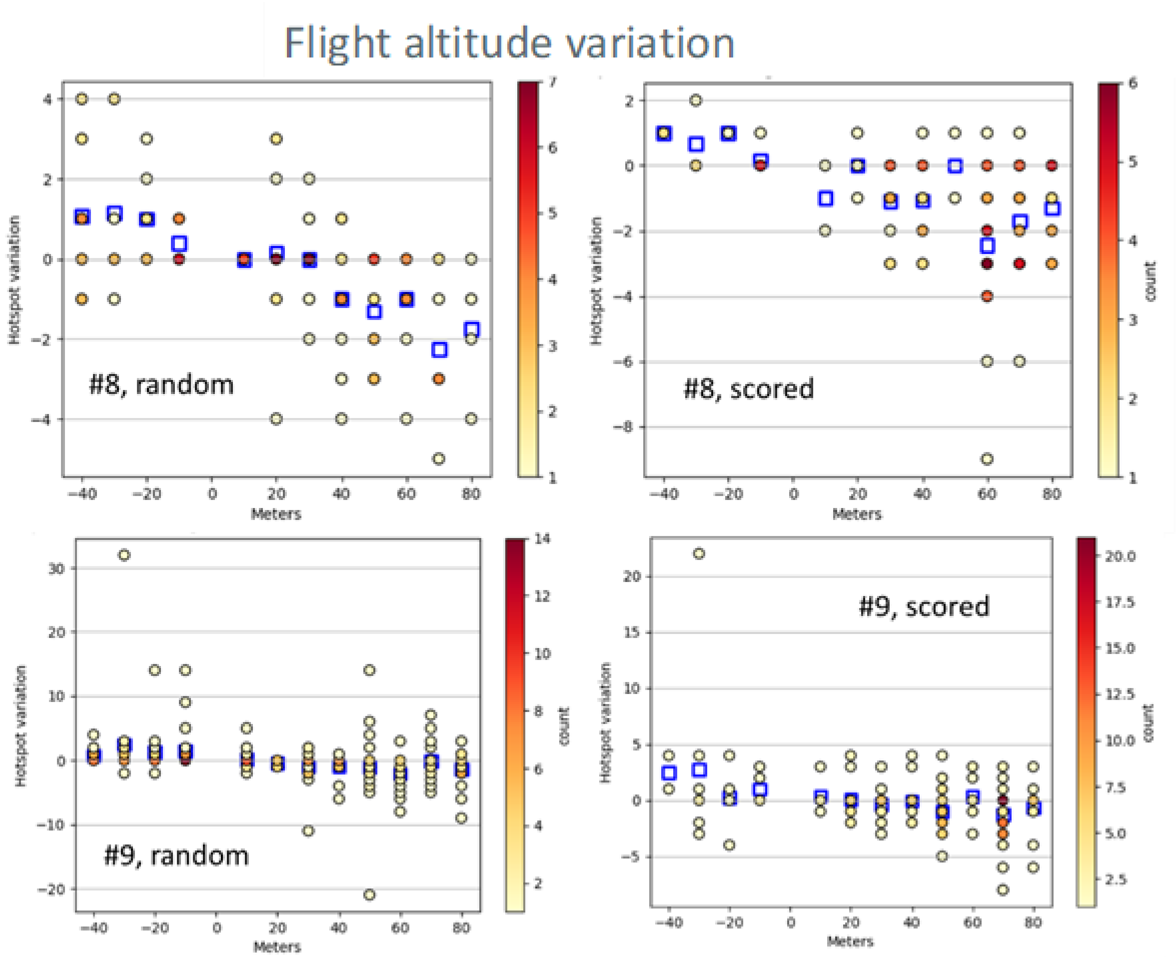


Figure 16: Hotspots variation versus "altitude variation" measure

In Figure 16 above the top row of graphs show results from scenario #8 and bottom row from scenario #9. The graph on the left is *random* selection and on the right is *scored*. The colour legend counts the number of tests for each point and blue squares are the average height variation and departure delay, respectively. Circle presence implies that at least one test of the corresponding DCB measure leads to the corresponding hotspots variations. The colour scale indicates the number of tests leading to the same situation. Finally, mean variation per DCB measure is plotted as blue squares. We can see a clear difference in the variation dispersion between scenario #8 and #9. Considering the overall tests, altitude, and delay, random and scored, scenario #8 has a potential variation between -9 and +4, whereas scenario #9 has a potential variation between -28 and +32.

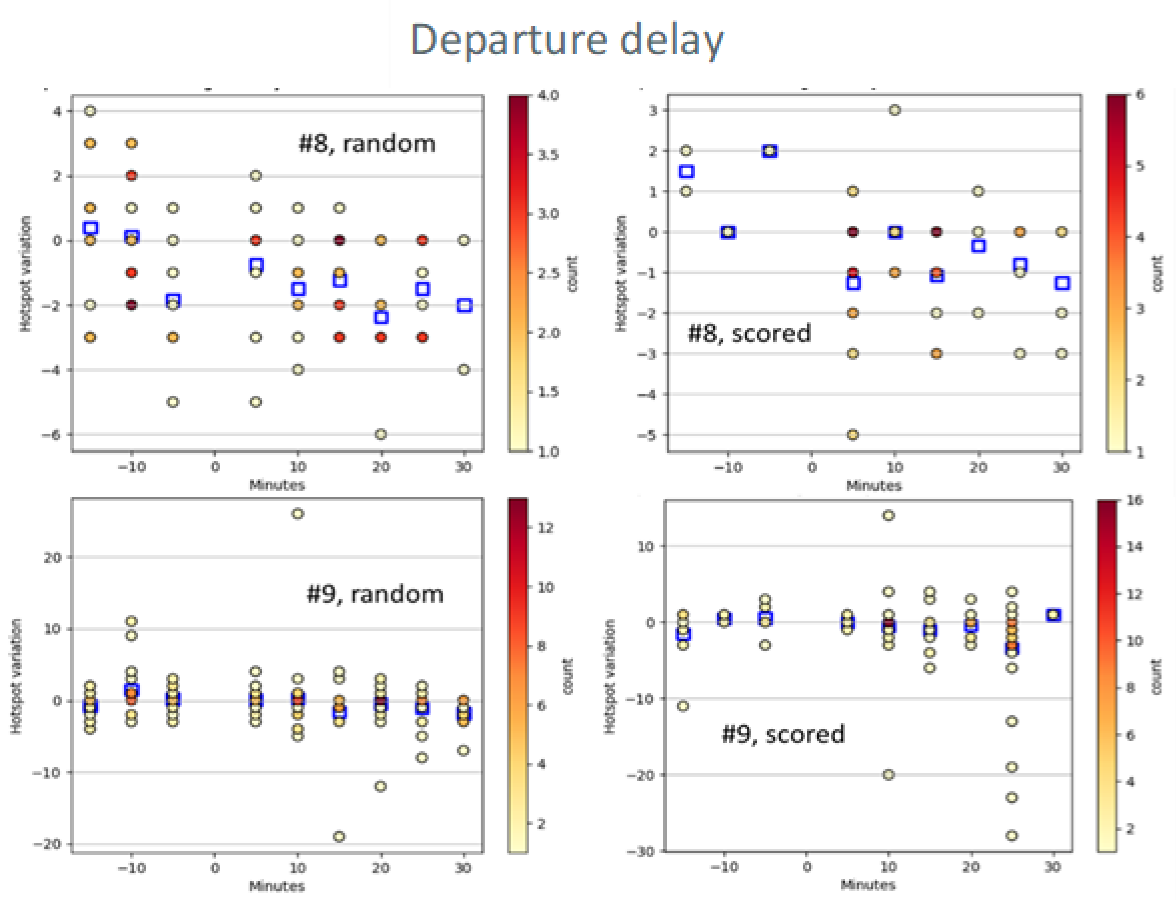


Figure 17: Hotspots variation versus "delay" measure

Figure 17 shows scenario * on the top row and scenario 9 on the bottom, with the left chart showing random selections and the right using scored. The coloured legend shows the counts for the number of tests for each point and blue squares the average variation for each metric.

This high dispersion makes the measure selection less predictable, explaining why "scored" version of the process is less efficient in this case. However, for both scenario, trend of efficiencies tends to be same. For flight height variation, as expected, lowering drone altitude increases noise and visual impacts. On the contrary, increasing drone altitude decreases social impacts, and so the number of hotspots. Situation is not as clear for departure delay. For scenario #8, take off earlier increases the number of hotspots and take off later decreases it. It makes sense as there are already drones taking off from the same position prior to the operation, whereas there is no flight planned later at the time of operation. submission. For scenario #9, the situation is the same but with a global effect, so the result is less significant. Prior to the operation, there are already drones scheduled and probability to interact with this traffic is high. There are less drone operations planned minutes later, therefore probability of interaction is lower.

Final scores computed for each DCB measures is plotted in Figure 18. For scenario #8, because of low dispersion, scores seem to tend towards 1 and stabilizes at this value for positive delay and altitude variation. Other scores have decreased. Because the process is continuous and scores can highly vary for each test, scores for scenario #9 does not seem to stabilize.

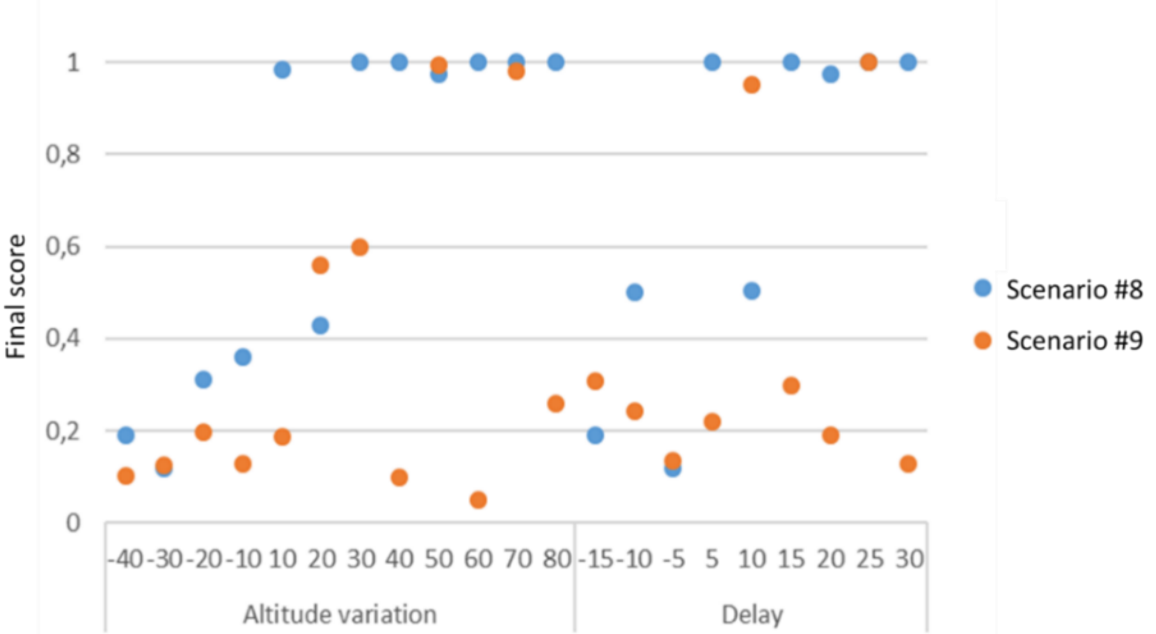


Figure 18: Final score for each DCB measure for scenario #8 (blue) and scenario #9 (orange).

In the figure above, altitude variations are shown on the left with delays on the right.

Some DCB measures have very low score, below 0.1 (e.g. altitude variation of 40 and 60m), whereas their average hotspots variation is negative. To better understand this result, further investigation on the dynamic of the score update should be done with more data.

Appendix B Experiment #2 Detailed Report

This appendix provides detailed information about the architecture and the platform with the underlying technology used for the simulation of flight planning functionalities in the DCM process. Furthermore, the modelling techniques employed in the respective sub-experiments will be presented. Finally, the results obtained in the experiments are also explained.

B.1 Experiment Description

B.1.1 High-level service and capability component architecture

The technical framework for this experiment encompasses the drone Trajectory Management framework to produce drone operation plans (DOPs) from a foreseen traffic demand. Furthermore, the Social Impact and Collision Risk models are integrated for the assessment of the demand and capacity situation of the simulated traffic load scenario. The interaction of these components is shown in the following high-level architecture diagram.

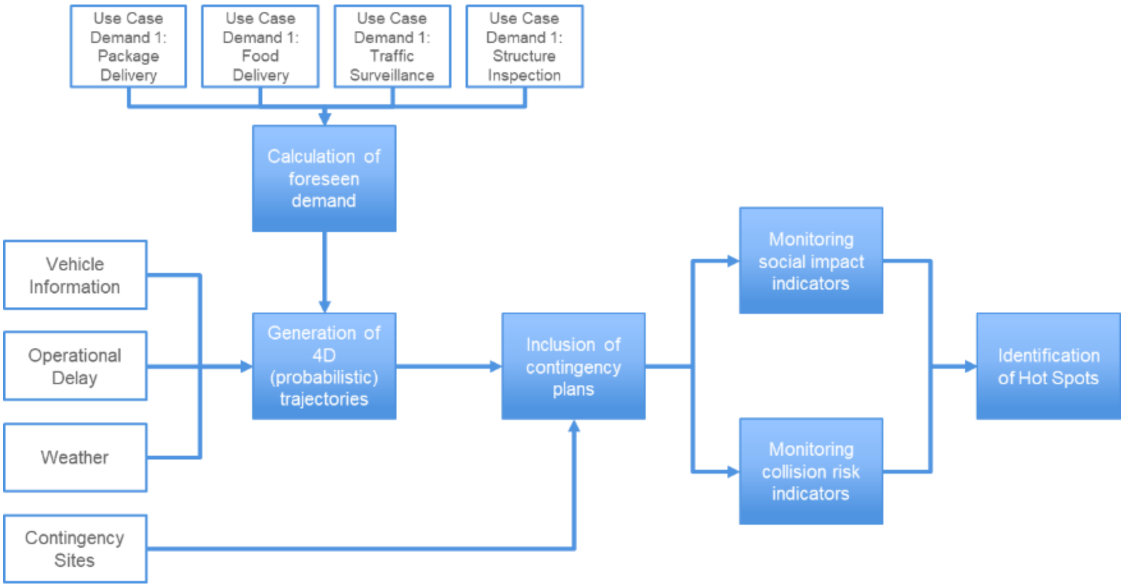


Figure 19: Component architecture in Experiment 2

Experiment platform

The platform is built in a way that DOPs with different level of information can be modelled. The main input for the Trajectory Planner are the mission profiles from the Traffic Demand Generator. The trajectories can either only be modelled under consideration of city buildings or additionally considering the wind limitations of the vehicle. Moreover, strategies to treat contingency events can be added through the Contingency Planner. Finally, the consolidated set of DOPs is transmitted to the DCM service for the assessment of the demand-capacity situation through the resulting hotspots.

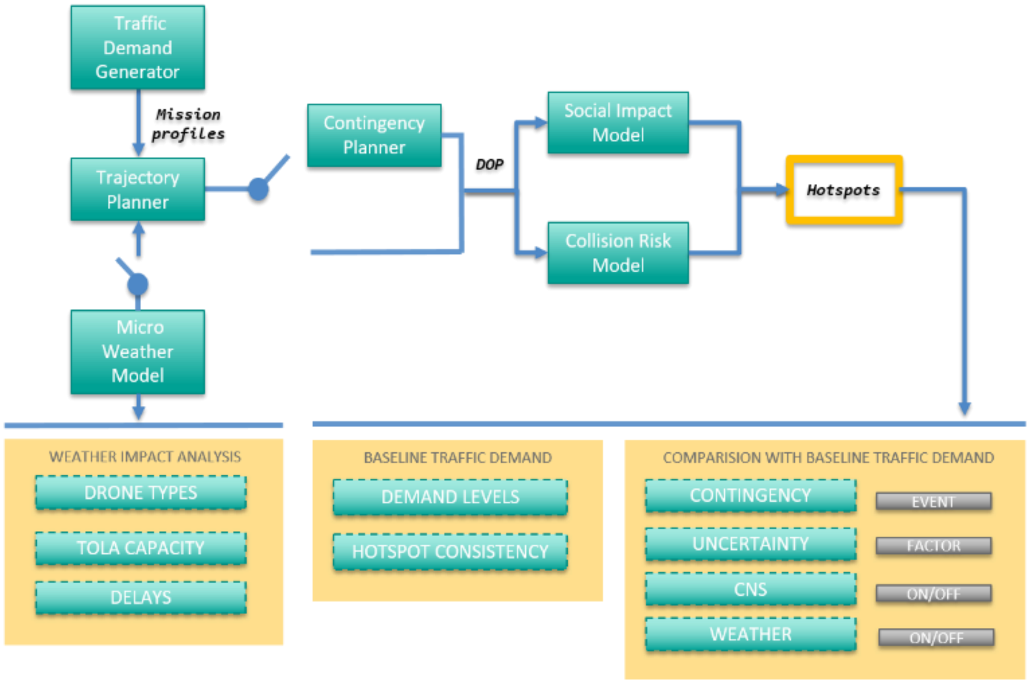


Figure 20: Experiment 2 platform

Drone Operation Plan

The drone operation plan (DOP) is an angular element of the flight plan processing processes and the intended capacity and demand analysis. Throughout the project, the DACUS consortium developed an extended data model for DOP to incorporate information related to operational uncertainty, contingency planning and weather limitations of the vehicle. All DOP elements are formalized using the *JSON* standard to ensure interoperability. The relevant elements of the DOP that have been used in this experiment are the following:

DOP aspect	Field name	Data representation
drone	Weight	[kg]
	drone class	Name of class
	drone type	Name of type
	Wind speed restriction	[m/s]
Operation	Expected start	[datetime]
	Expected end	[datetime]
	Operation type	Name of type
	Operation domain	Name of domain
	Crossing datetime	[datetime]

DOP aspect	Field name	Data representation
Geospatial occupancy	Point 3D	[lon,lat,height]
	Uncertainty	[meters,seconds]
Contingency plan	Phase	[initial coord., end coord.]
	Contingency type	Name of type
	Contingency strategy	Array of procedures and measures

Table 31: DOP information relevant for Experiment 2

B.1.2 Traffic scenarios

The baseline scenario only includes nominal 4D trajectories and shall represent a significant traffic demand, meaning that a considerable number of hotspots are expected from the analysis of the resulting demand and **capacity situation. Furthermore, within the scope of the experiments only a 3-hour timeframe (4pm – 7pm) was** examined. This timeframe is aligned with one of two high overall traffic demand timeframes identified in the DACUS drone Traffic Characterization report [9]. For every application type a specific rationale was followed and assumptions were met to come up with an initial traffic estimation in the city of Frankfurt. The figure below summarizes the assumptions and resulting operations per application type.

In order to scale up the number of operations, one main assumption was made: instead of the initial assumption that only around 10% of the food and package orders would be delivered by drones, it was assumed that approximately **50% of the orders** were delivered by drones. For the other two application types it was however complicated to scale up the initial values since too little forecast information could be found. The resulting number of operations from the scale up estimation is also given in the last column of the table.

Application type	Annual baseline demand	Rationale of demand estimation	Daily operations in 3h timeframe (initial estimation)	Daily operations in 3h timeframe (scaled up estimation)
Food delivery	3,25 Orders/person/year	Statistics on online food orders, payload capacity, profitability.	260	1408
Package delivery	B2B: 27750 packages/km^2/year B2C: 4,5 packages/person/year	Statistics on B2B/B2C deliveries, payload capacity, profitability for express deliveries	835	4180
Traffic surveillance	-	Assumptions on surveillance of highways	50	50
Inspection	2 inspections/site/year for 1h	Online information about bridge inspection intervals Bridges + high-rise buildings in Frankfurt: ca. 600	6	30

Co-funded by the European Union

Application type	Annual baseline demand	Rationale of demand estimation	Daily operations in 3h timeframe (initial estimation)	Daily operations in 3h timeframe (scaled up estimation)
Total			**1151**	**5668**

Table 32: Number of operations and rationale

The Social Impact and the Risk Model prototypes have different grid cell resolutions (in the spatial scale) implemented due to the requirements and limitations of the models. Nevertheless, it has been assured that the cells are fully aligned, allowing to consider the same social impact and risk hotspots for the same ground areas. Furthermore, the shape of the grids was defined as a *square* shape. For the temporal resolution, both DCM model prototypes provide hotspot results with a 1-minute rate. The table below summarizes the characteristics of the grids used for the hot-spot identification:

Hot-spot grid characteristics	Social Impact Model prototype	Risk Model prototype
Spatial resolution (grid cell size)	1000 x 1000m	500 x 500m
Temporal resolution (rate of hot-spot calculation)	1min	1min

Table 33: Characteristics of Social Impact and Collision Risk models

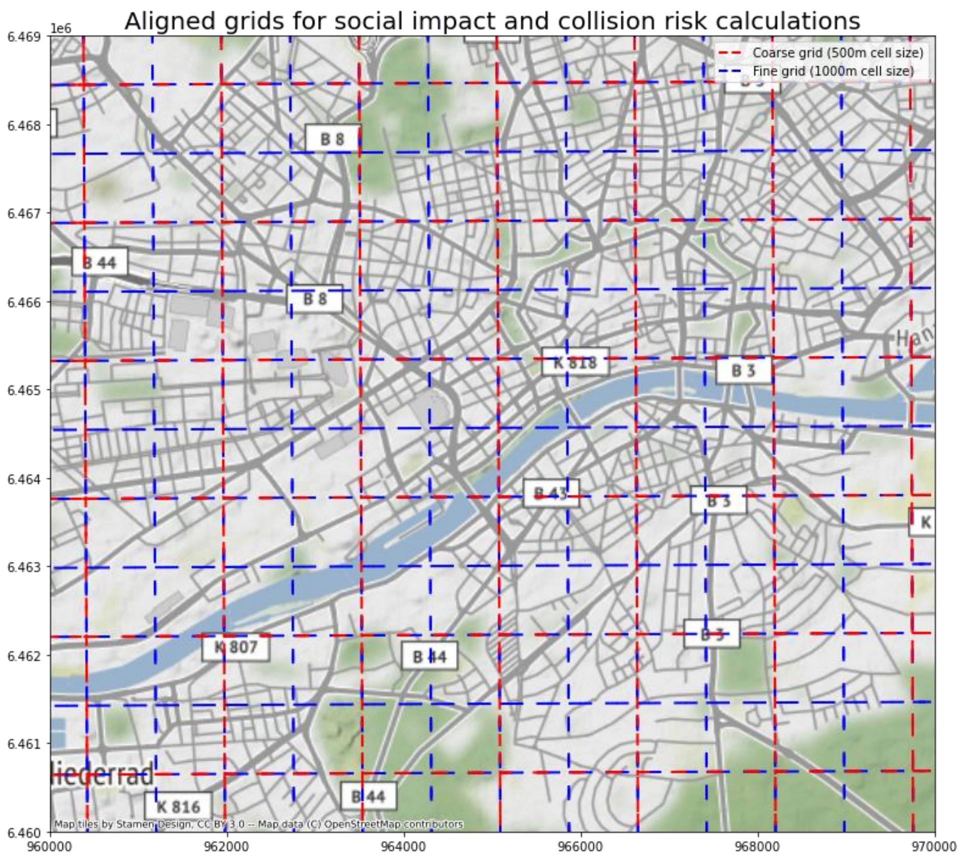


Figure 21: Aligned grids for Social Impact and Collision Risk hotspots

B.2 Experiment Results

For the two traffic scenarios, the traffic information was submitted to the Social Impact model and the resulting noise and visual hot spots were analysed. The following table summarizes the results of the two simulated traffic demand scenarios and the metrics used to assess the hot spot picture.

Metric	Low-level demand (initial estimation)	High-level demand (scaled-up estimation)
Number of operations	1151	5668
Aircraft airborne	Max: 122, Average: 64	Max: 534, Average: 314
Overall number of cells with *Social Impact* hotspots	125	140
Number of cells with *Social Impact* hotspots: Noise (exposure / annoyance)	111/78	107/94
Number of cells with *Social Impact* hotspots: Visual (exposure / annoyance)	114/114	140/66
Overall duration of *Social Impact* hotspots	69min	84min
Duration of *Social Impact* hotspots: Noise (exposure / annoyance)	65/47	80/77
Duration of *Social Impact* hotspots: Visual (exposure / annoyance)	65/65	84/70
Number of cells for the time with the highest number of *Social Impact* hotspots	16:44: 6 cells	16:50: 40 cells
Airborne aircraft for the time with highest number	16:44: 108 airborne aircraft	16:50: 466 airborne aircraft
Aircraft involved in *Social Impact* hotspots	9	123
Overall number of cells with *Collision Risk* hotspots	137	411
Overall duration of *Collision Risk* hotspots	89min	127min
Number of cells for the time with the highest number of *Collision Risk* hotspots	17:21: 8 cells	16:19: 8 cells 17:05: 8 cells 17:38: 8 cells 17:59: 8 cells

Table 34: Results of simulation of traffic demand levels

From the table above it can be extracted that in the low-level demand simulation only very few hotspot cells emerge, even at the time with the highest number of hotspots. Here the number of aircraft involved is also relatively low. Opposed to this, the number of hot spots and aircraft involved is much higher for the high-level demand. In addition to this analysis, the number of hotspot duration appearances was also examined. The results for the high-level demand simulation are shown in the figure below.

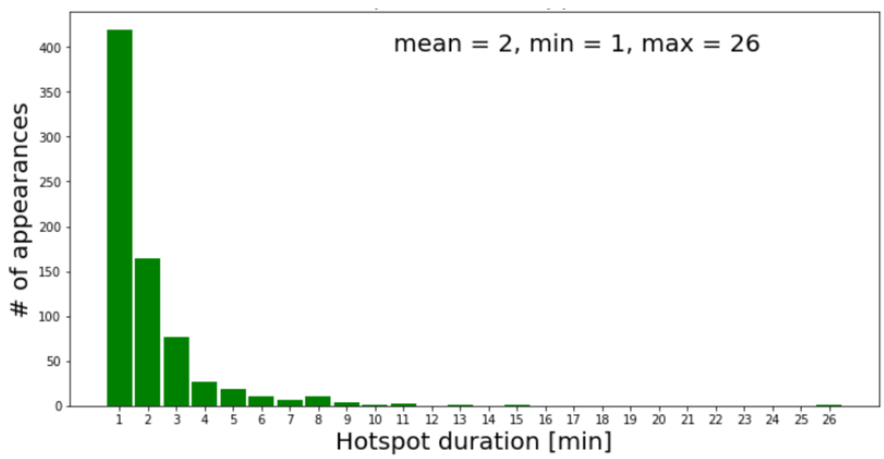


Figure 22: Distribution of Social Impact hotspot duration for a high-level demand simulation

Furthermore, two metrics regarding the hotspot length have been used for assessing the impact of computed hotspots. The figure below visualizes both metrics and also depicts the spatial distribution of overall social impact hotspots for the **high-level demand simulation**. On the left side, the length average is shown and it can be seen that for all social impact hotspots the **average length is lower than 3 minutes**. One the right side, the cumulated sum length is depicted. Here it can be extracted that the **maximum sum length is around 50min for a 3-hour timeframe**.

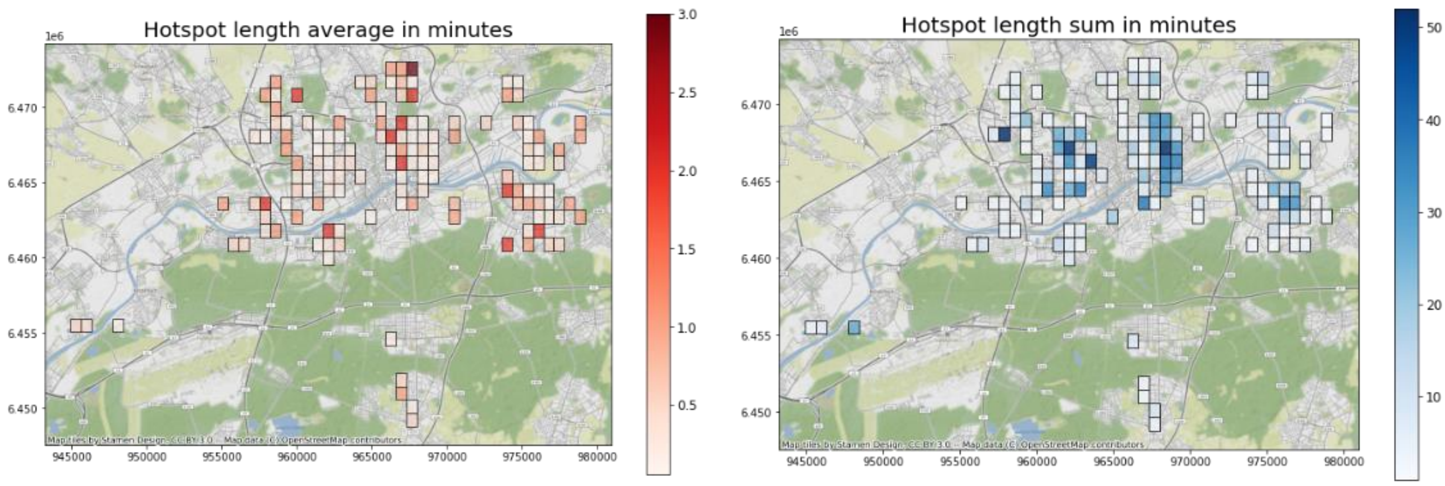


Figure 23: Spatial distribution of hot-spot appearances from the Social Impact Model

Lastly, the following diagram shows the distribution of application types for the baseline scenario to be used for the remaining experiments. In general, it can be summarized that only when assuming a high percentage of delivery orders using drones, a significant number of hotspots emerge in the Frankfurt scenario.

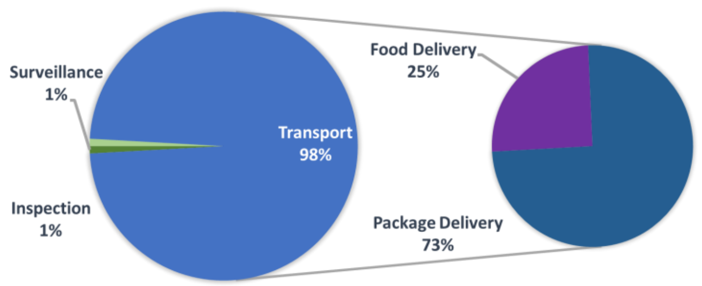


Figure 24: Distribution of application types

B.2.1 Impact of contingency events

For simulating the impact of contingency events, a model for contingency planning was developed and used for certain contingency scenarios that have a large-scale impact character. The Contingency Planner model is capable to produce strategies that treat various contingency events, and it expands the drone operation plans with these strategies in the form of alternate procedures and commands. The strategies for contingency can then be activated at any time during the mission and might be valid for one or more mission phases. In the scope of this experiment, certain contingency events are simulated for a span of time and the drone 4D trajectories are modified according to the procedures declared in the contingency plan.

Two types of contingency events with large-scale character have been simulated in this experiment: **unavailable (or closure) of landing locations simultaneously** and **degradation of the navigation performance**. For each type of events and each type of application type, a series of strategies have been defined:

Unavailability / Closure of landing location	Package delivery	Food delivery	Traffic surveillance	Infrastructure inspection
Strategy 1: return to base using nominal waypoints			X	
Strategy 2: divert to alternate location and activate conflict management procedure	X	X		
Strategy 3: land immediately and activate contingency volume				X

Table 35: Strategies for Contingency Event 1

To define strategies for multiple contingency events and integrate these in the DOP without adding too much complexity, a list of general procedures and measures has been used:

Procedure or measure	Code in DOP
Alternate Landing Coordinate	alc

Procedure or measure	Code in DOP
Containment Volume	ca
Execution Timeout	et
Contingency Flight Procedure	FP
Contingency Landing Procedure	LP
Containment Procedure	CP
...	...

Table 36: List of procedures and measures

Each procedure/measure has been assigned a code that is used in the DOP. To implement a certain strategy, the correspondent codes are detailed in the DOP in a serial form. To illustrate the result of this process, the implementation of three strategies for the same contingency event is given in the next figure.

The final selection and implementation of the contingency strategies is dependent on the characteristics of the operation (e.g. contingency sites available) and the vehicle itself (e.g. advanced sensors or autonomy systems on-board [14]).

Event	Closure of vertiport
Treatment Strategy	Land immediately and activate contingency volume
Code in DOP	phase1+ LP3+CP1+cv1+et1

Event	Closure of vertiport
Treatment Strategy	Return to base
Code in DOP	phase2+ FP1+LP1+et1

Event	Closure of vertiport
Treatment Strategy	Divert to alternate
Code in DOP	phase3+ FP3+LP2+alc1+et1

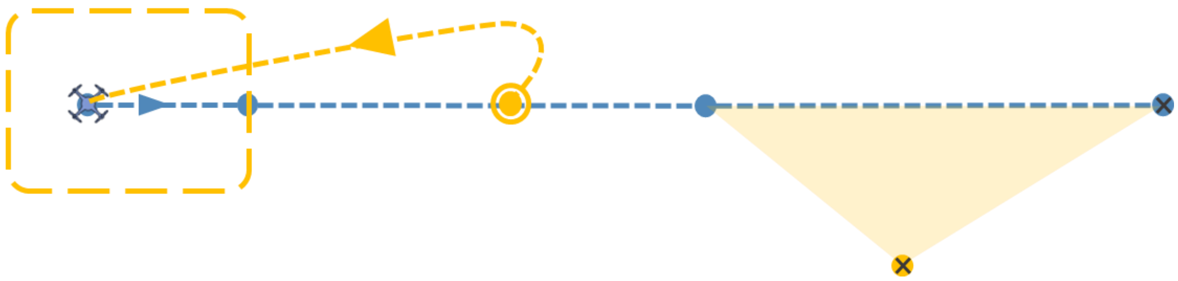


Figure 25: Visualization of different contingency strategies applicable in the same mission

For every type of contingency event, two scenarios have been simulated addressing a different impact on the drone traffic. For the first type of contingency event (closure of vertiport), two scenarios have been modelled:

- Contingency Event Scenario 1: Simulation of closure of distribution centres for 30 minutes. Only affecting package delivery operations.
- Contingency Event Scenario 2: Simulation of closure of nominal vertiport for 1 hour. Affecting all operations.

For the second type of contingency event (degradation of navigation performance), two further scenarios have been modelled:

- Contingency Event Scenario 3: Simulation of GNSS disruption for 1 hour due to satellite misleading information. Affecting all operations.
- Contingency Event Scenario 4: Simulation of GNSS disruption over 12 square kilometres for 1 hour due to unintentional RFI source. Affecting all operations.

To realistically simulate these scenarios, the planned operations outside the contingency event have been also modified. The following two tables summarize the actions carried out for the four scenarios:

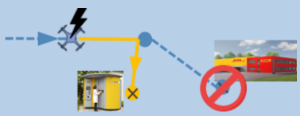
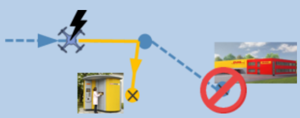
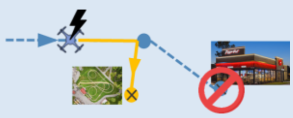
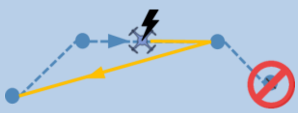
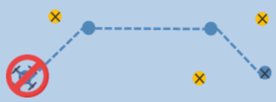
Scenario 1	**Case: drone airborne at time of contingency event**	**Case: drone not airborne at event time but to operate in future time**
Package Delivery	Activate contingency strategy: divert to package centre 	Delay operation 
Food Delivery	*Not affected by contingency event*	*Not affected by contingency event*
Traffic Surveillance	*Not affected by contingency event*	*Not affected by contingency event*
Infrastructure Inspection	*Not affected by contingency event*	*Not affected by contingency event*

Table 37: Case description in Contingency Scenario 1

Scenario 2	**Case: drone airborne at time of contingency event**	**Case: drone not airborne at event time but to operate in future time**
Package Delivery	Activate contingency strategy: divert to package centre 	Delay operation 
Food Delivery	Activate contingency strategy: divert to park 	Cancel operation 
Traffic Surveillance	Activate contingency strategy: return to base 	Cancel operation 

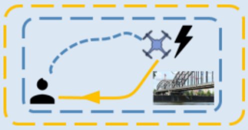
Scenario 2	Case: drone airborne at time of contingency event	Case: drone not airborne at event time but to operate in future time
Infrastructure Inspection	Activate contingency volume and return to base 	Delay operation 

Table 38: Case description in Contingency Scenario 2

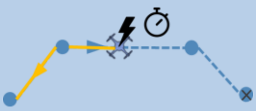
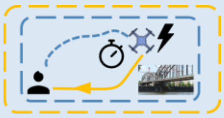
Scenario 3 and 4	Case: drone airborne at time of contingency event	Case: drone not airborne at event time but to operate in future time
Package Delivery	Activate contingency strategy: climb and wait approach, then apply procedure per phase 	Delay operation 
Food Delivery	Activate contingency strategy: climb and wait approach, then apply procedure per phase 	Cancel operation 
Traffic Surveillance	Activate contingency strategy: climb and wait approach, then return to home 	Cancel operation 
Infrastructure Inspection	Climb and wait approach and revert to manual control 	Cancel operation 

Table 39: Case description in Contingency Scenario 3 and 4

From this modelling, the progression of traffic demand is changed with respect to the traffic load without the simulation of contingency event. The figure below depicts these scenarios. Here it can be clearly seen how several operations are delayed (especially in Contingency Scenarios 2, 3 and 4), which results in a higher demand after the contingency event is solved/mitigated.

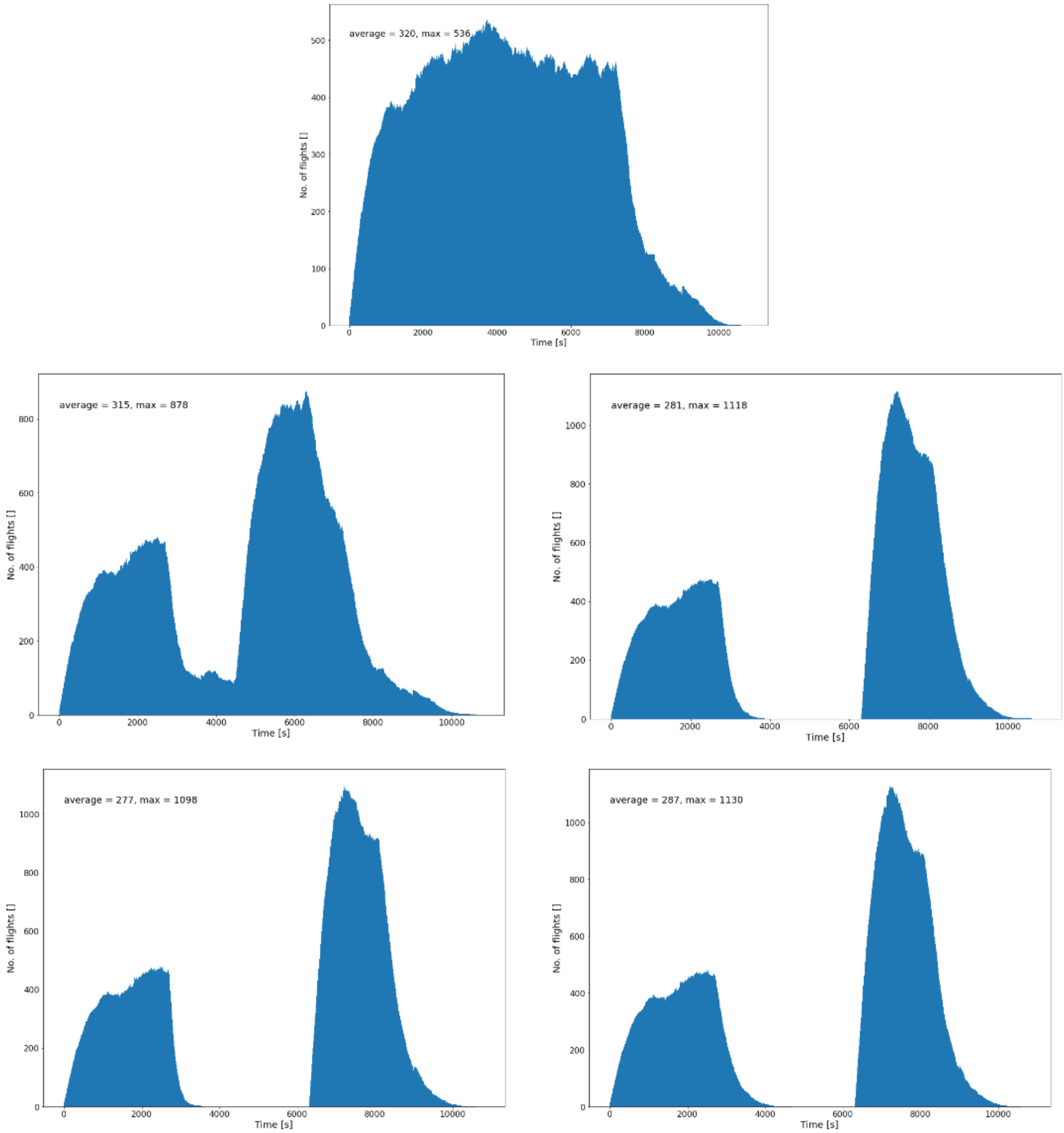


Figure 26: Airborne drones in nominal operations.

The figure shows the Baseline scenario (top) and Contingency Event Scenarios 1 (middle left), 2 (middle right), 3 (bottom left) and 4 (bottom right).

To get a **consolidated picture of the overall Collision Risk and Social Impact hotspots** resulting from the DCM service calculations, the hotspot appearances in the whole urban area have been extracted and are shown in the figure below. It can be noted that in most areas affected by Social Impact hotspots, Collision Risk hotspots also appear. Further, additional cells with Collision Risk hotspots in surrounding areas arise. Overall, it can be stated that **both types of hotspots appear mainly in the urban area of Frankfurt**, whereas over suburban areas only certain areas are affected by hotspots.

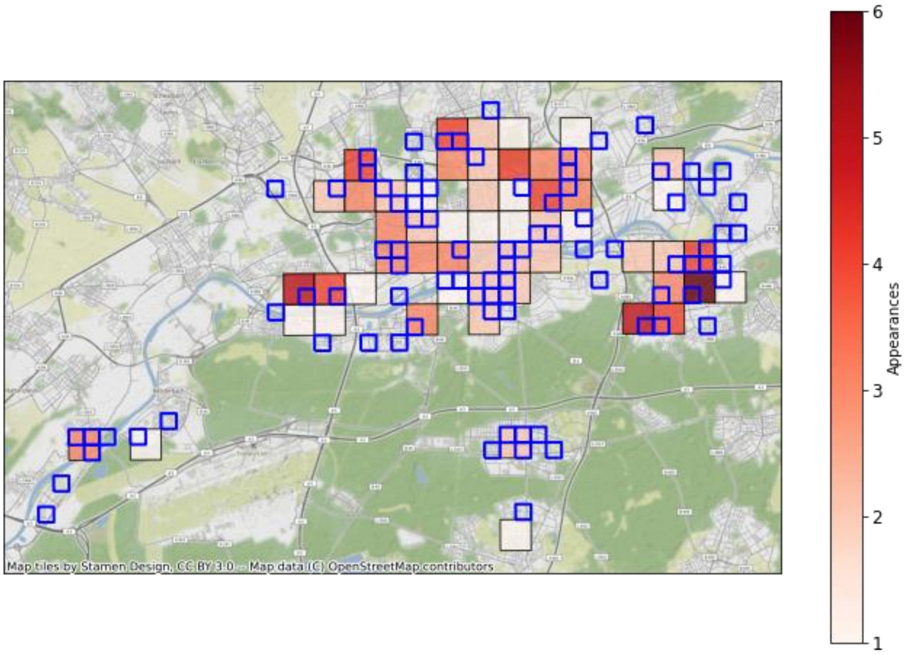


Figure 27: Number of combined hotspots with 10-mn duration in nominal operations (Baseline).

Two main analyses were performed with the four simulated contingency event scenarios:

- Detailed comparison analysis of **Social Impact Hotspots** resulting from **Contingency Scenario 1** against our Baseline Scenario (nominal operations).
- Detailed comparison analysis of **Collision Risk Hotspots** resulting from **Contingency Scenarios 1 to 4** against Baseline Scenario (nominal operations).

For the first analysis, the Social Impact Hotspots (including noise/visual exposure and annoyance values) are examined. The figure below shows the cumulated time of Social Impact hotspot appearances (Noise and Visual) for all contingency scenarios. From this overview it can already be seen that due to contingency events, the already affected hotspots areas (baseline) have in general a **lower sum length**.

However, **new affected hotspot areas** arise. As an example, in Contingency Scenario 1 there is an increase of 8% of cells affected by Social Impact hotspots with respect to the baseline scenario.

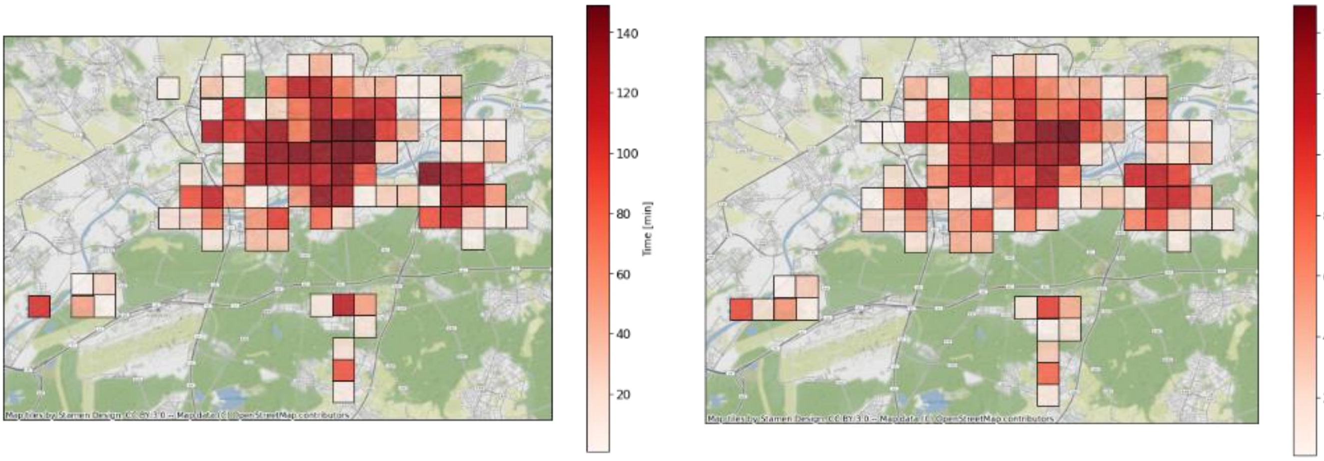


Figure 28: Cumulated time of Social Impact hotspots in nominal operations

The figure above Shows the baseline on the left and contingency event scenario 1 on the right.

Another interesting metric to look at, is the number of hotspot appearances that have a time length over 10 minutes (long exposure). The figure below shows the results of this metric.

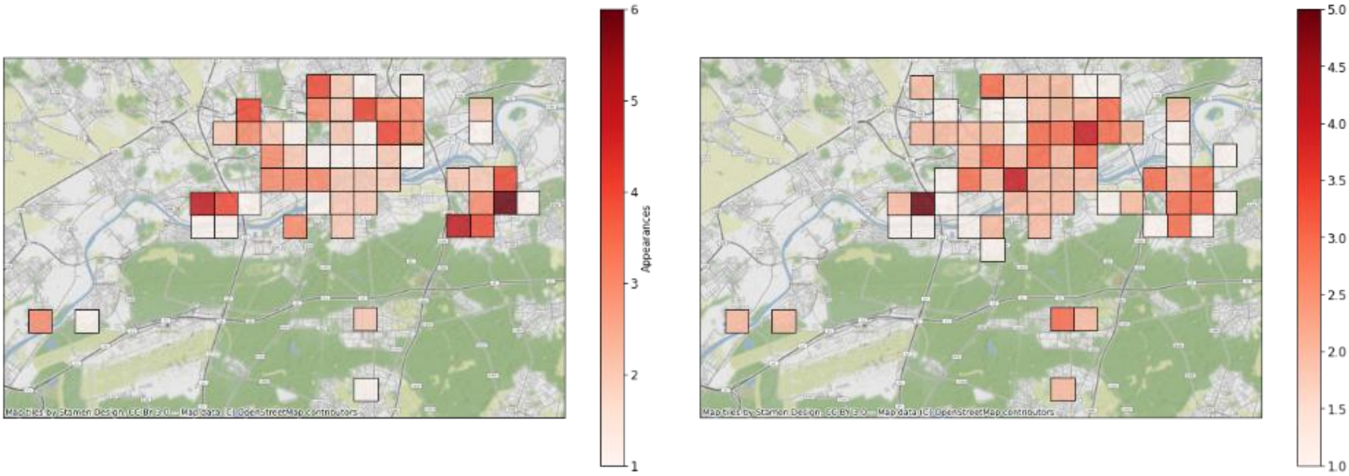


Figure 29: Number of Social Impact hotspots with length over 10 min in nominal operations.

The figure above Shows the baseline on the left and contingency event scenario 1 on the right.

Here, a similar outcome as in the previous analysis can be seen. New hotspots arise in areas that were not affected in the baseline scenario. Besides, the re-distribution of hotspot appearances with a long time is more evident, as the darkest coloured cells shift to different urban areas.

Concerning the second analysis, the re-distribution of Collision Risk Hotspots due to the contingency events is depicted in the figures below and compared against the nominal hotspot view.

For this assessment, we have analysed both **maximum and average collision risk values**.

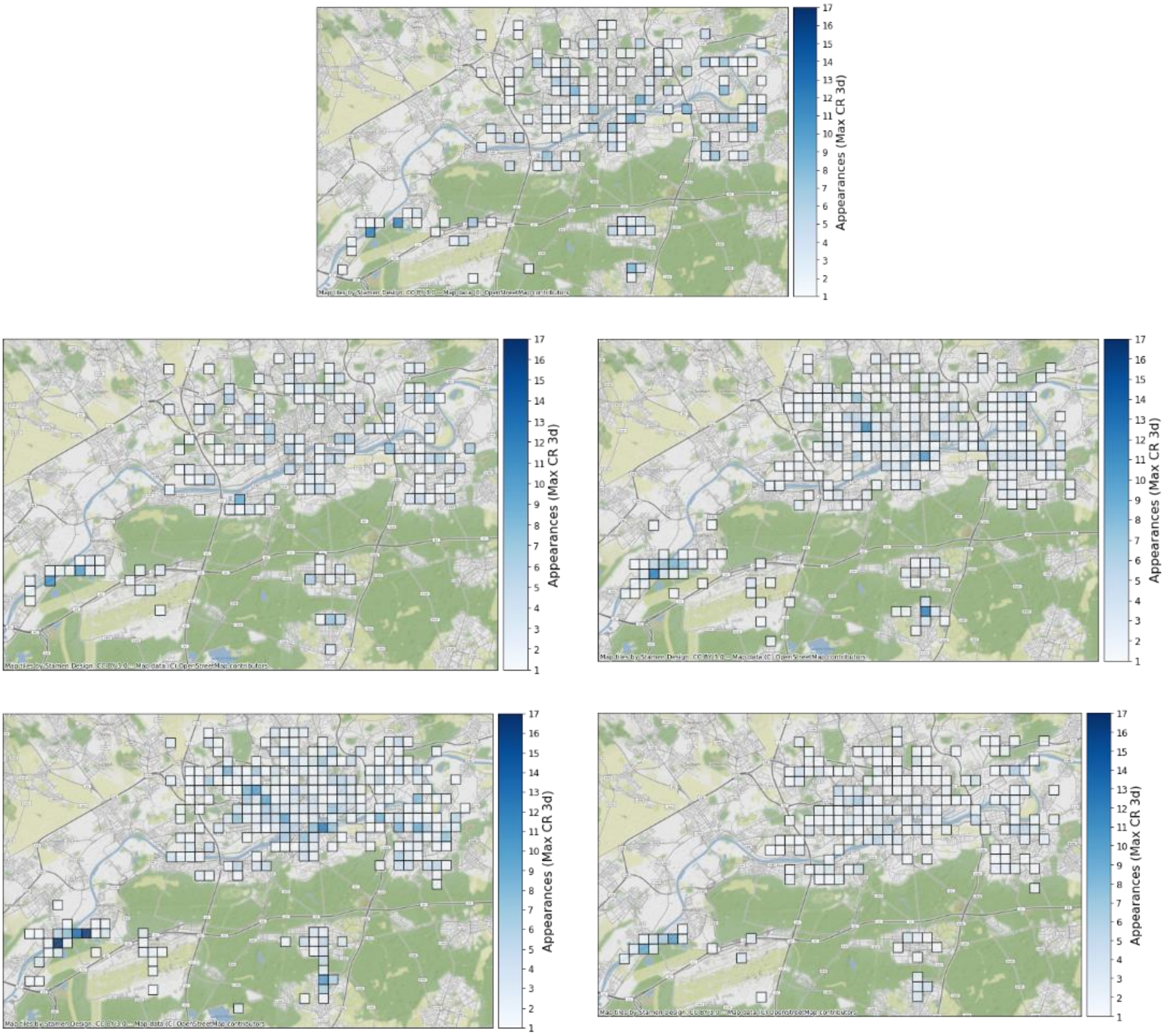


Figure 30: Number of Collision Risk hotspots in nominal operations

Figure 30 Shows the baseline scenario (top) compared to all the Contingency Event Scenarios: 1 (middle left), 2 (middle right), 3 (bottom left) and 4 (bottom right).

From this initial overview, it can be confirmed that in **general the number of appearances increase** in all four contingency event scenarios. The displacement of operations due to the delays originated from the contingency event leads to a higher appearance of hotspot cells. Especially in the Contingency Event Scenarios 2, 3 and 4 there is an evident increased number of appearances.

When looking at the maximum Collision Risk values (maximum instantaneous value) per cells (figure below), we can confirm that a **considerable higher number of cells are affected with critical values**. Within all contingency event scenarios, the maximum instantaneous Collision Risk values increase considerably with respect to the values in the baseline scenario (from 10 to 100 times higher). A summary of the comparison analysis is provided in the table below. We can confirm here that the collision risk values increase in all contingency event scenarios. Particularly, in the Contingency Event Scenario 3 maximum collision probabilities (meaning exact drone operations encounters in time and location) were calculated. This results from the overloaded TOLA capacity after the operations are programmed to start with their mission after the simulated large-scale delay.

Metric	Baseline	Contingency Event Scenario 1	Contingency Event Scenario 2	Contingency Event Scenario 3	Contingency Event Scenario 4
Average Collision Risk (maximum value in the 3h simulation time)	4,98E-07	1,26E-06	0.0005	0.0011	0.0015
Number of cells with Collision Risk hotspots	156	151	263	277	186
Total number of Collision Risk hotspots	412	383	536	746	331
Maximum Collision Risk (maximum instantaneous value)	0.0032	0.0260	0.1379	*Max collision probability*	0.0324
Time with highest number of drone operations involved in Collision Risk hotspots (involved drone operations)	17:05:00 (8)	17:19:00 (17)	17:48:00 (43)	17:49:00 (26)	17:54:00 (17)

Table 40: Comparison of the results from the Collision Risk model

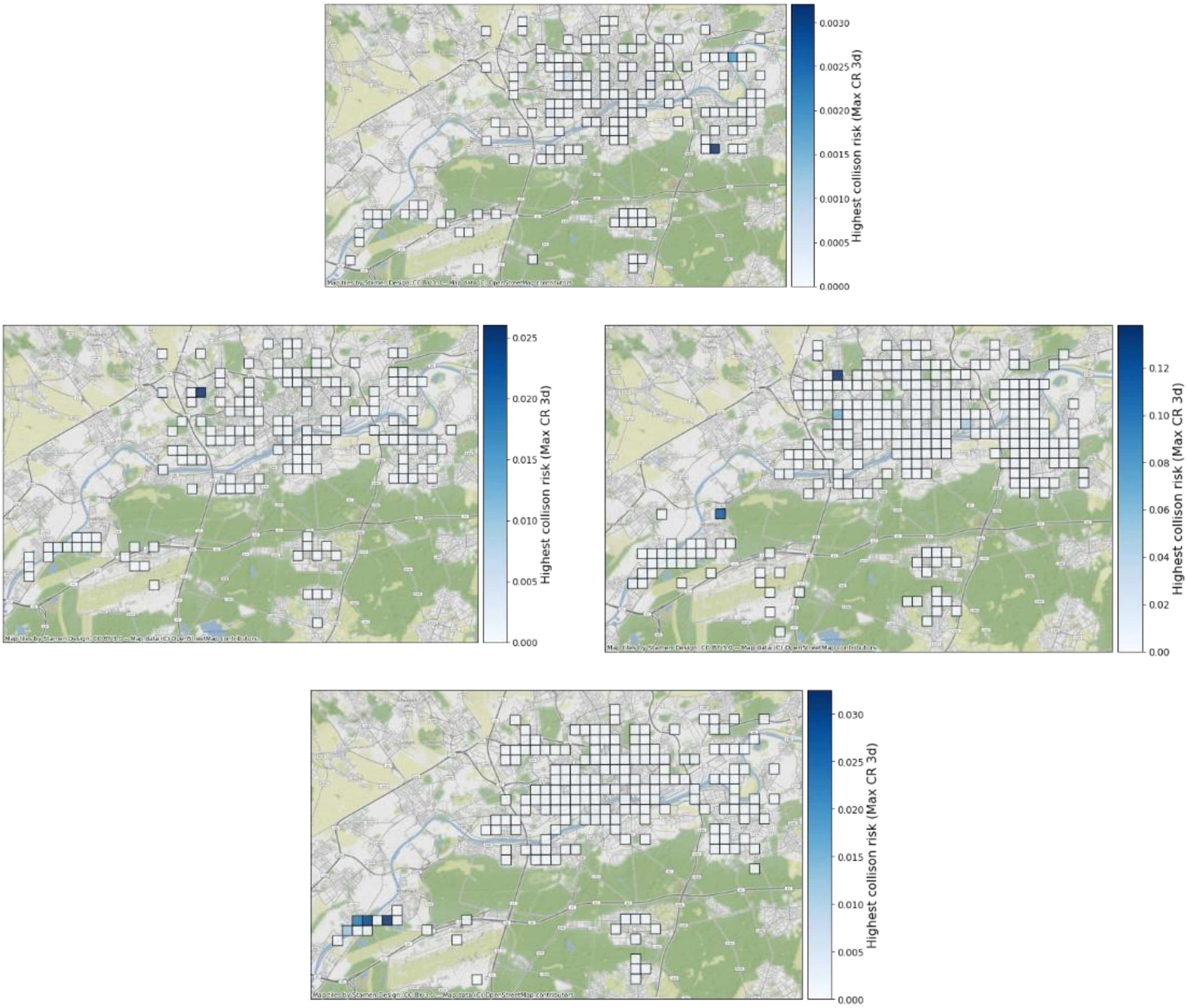


Figure 31: Maximum instantaneous Collision Risk values in nominal operations.

Figure 31 shows the Baseline, (top) and various Contingency Event Scenarios: 1 (middle left), 2 (middle right) and 4 (bottom).

In the assessment of the impact of the modelled contingency event scenarios, we can derive the initial conclusion that all modelled scenarios have an overall impact of the hotspot generation, and **Contingency Scenario 3 and 4 have the largest impact**.

Contingency Scenario 3 is the simulation of nominal vertiport closure for 1 hour and Contingency Scenario 4 is the simulation of GNSS disruption (for example due to satellite misleading information) for 1 hour.

B.2.2 Impact of operational uncertainty

In the scope of this experiment, the operational uncertainty expressed in the DOP as time uncertainty has been examined. From the available DCB models, only the Collision Risk Model is able to process this information and is able to calculate hotspots based on a defined uncertainty expressed with a temporal component. Within the consortium it was agreed that it is reasonable to simulate an **operational uncertainty of 5 minutes**, as it is a conceivable time that can occur in all considered mission types. Therefore, this value was included in all drone operation plans from the take-off time, and carried through the complete flight time. This type of simulation which would represent the simulation of a worst-case scenario examination. To evaluate the impact of this uncertainty level, the maximum collision risk values and appearances are shown in the figure below.

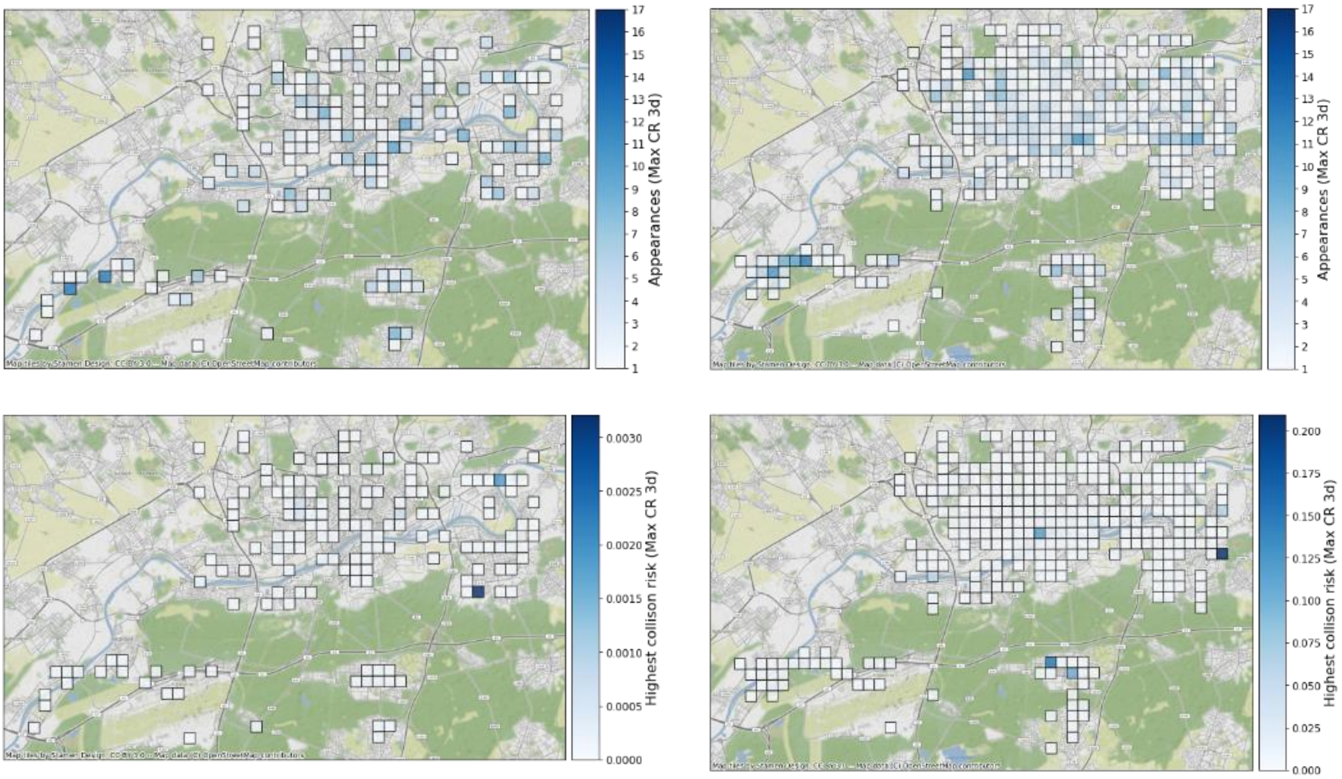


Figure 32: Collision Risk Hotspots in nominal operations

The figure shows the Baseline, (upper left) and Operational Uncertainty Scenario (upper right). In the lower row, the highest value per cell of maximum instantaneous Collision Risk Hotspots in nominal operations (Baseline, bottom left) and Operational Uncertainty Scenario (bottom right) is also shown.

Looking at the overall comparison of Collision Risk hotspot results, it is evident that the lack of information in the temporal feature of the flight trajectory leads to the estimation of a higher number of Collision Risk values per cell (hotspot view in the bottom part right), as well as a generally increased Collision Risk hotspot appearances in the considered area. Particularly, new affected areas with Collision Risk values arise in the Frankfurt downtown, as well as in the upper region of the airport.

A summary of the comparison analysis is provided in the table below.

Metric	Baseline	Operational Uncertainty Scenario 1
Average Collision Risk (maximum value in the 3h simulation time)	4,98E-07	2,59E-06
Number of cells with Collision Risk hotspots	156	300
Total number of Collision Risk hotspots	412	714
Maximum Collision Risk (maximum instantaneous value)	0.0032	0.0209
Time with highest number of drone operations involved in Collision Risk hotspots (involved drone operations)	17:05:00 (8)	16:16:00 (16)

Table 41: Summary of comparison analysis using the results from the Collision Risk model

B.2.3 Wind Impact

Wind impact on drone classes

The objective of this experiment is to investigate up to what point **high turbulences / high winds affect low weight drones**, in order to identify the areas to be avoided by this type of drones. Therefore, several detailed micro weather reports for two areas of interest have been created in the experimental domain. One is located in Frankfurt Downtown and features high buildings up to several 100 meters. The second one is south of Frankfurt in the sub urban & industrial area of Neu-Isenburg (N-I). Here we found the typical layout of 2-3 story high residential areas and 5 – 6 story high industrial buildings. The local wind fields have been calculated in 4 different scenarios that cover mesoscale weather conditions that 1st are likely to appear and 2nd expected to have an impact on typical drone types.

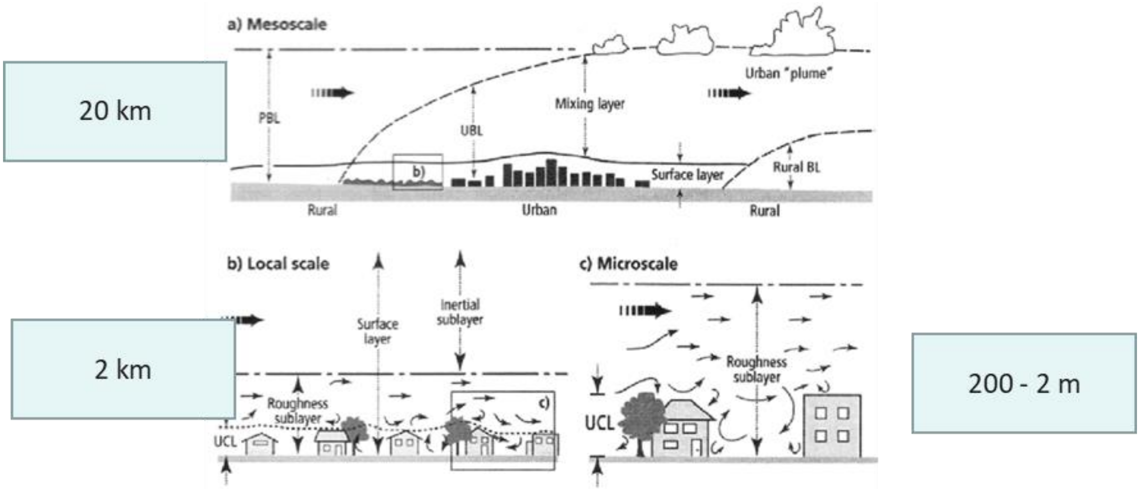


Figure 33 Example for typical relation between meso and micro scale weather

So, for N-I we calculated a CFD simulation with the RANS method in an area as large as 2x3.8 km. The external conditions where either 5 or 10 m/s wind speed and a main wind direction of west or south wind. Our data foundation was 3D models coming from the Open Street Map repository. Based on this we were able to transform them into STL data, CAD data and finally a high resolution % watertight surface model that could be transferred into a volume mesh. This final mesh has had over 180 Mio. Cells with element in between 0.3 and 25 meters and 9 different prism layers. A calculation of the RANS model was only feasible at the Lichtenberg II Supercluster at the partner university TU Darmstadt. Though supported by 480 cores, computation for a single scenario took several days of computing.

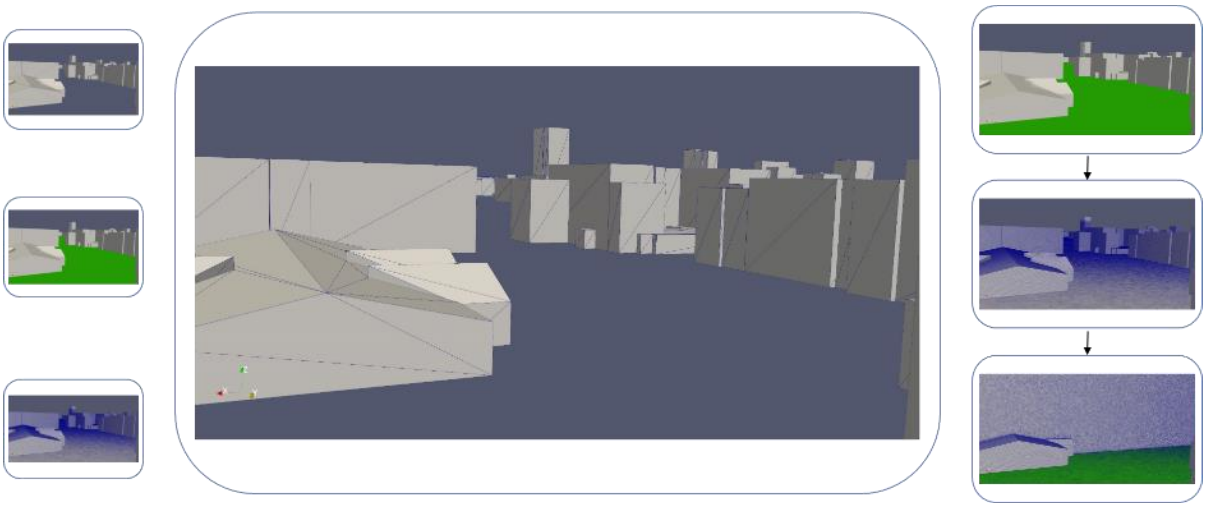


Figure 34 Different intermediate steps of the weather data

Since the data output still renders 50 million data points of wind information, the final resolution was transformed to a 10x10x10 meter grid by averaging a distinct percentile of the largest wind vectors in a cell. This symbolizes a risk based but also computing efficient approach. For planning through a certain cell, the lowest wind vector possible is not relevant, but for the highest. A mean of a certain percentile eases the influence of potential outliers.

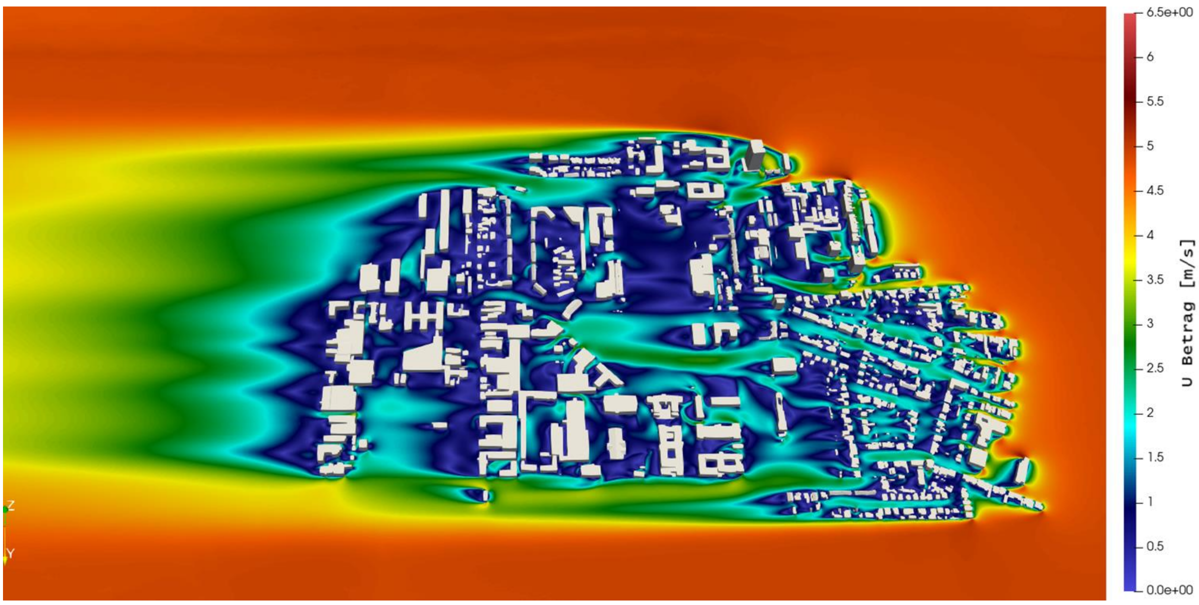


Figure 35 Representation of the full data set for east wind (5 m/s) at 3 m height

For the experimental area in Frankfurt, the simulation system PALM has been utilized. The obvious differences in the canopy layer result in diverse wind fields. Compared to the N-I site, the Frankfurt wind fields are accelerating slower with rising altitude, which can be linked to a generally higher roughness of the model surface. It leads to a more turbulent, less laminar flow. This reduces wind speed but at the same time increases turbulence occurrence.

Figure 36 Comparison of Urban Layouts in FFM (left) and N-I (right)

Furthermore, we identified that the highest buildings in Frankfurt are generating larger areas of high wind speeds zones in low altitude, which are strongly dendept on the main wind direction.

In regard to the overall objective of the research in DACUS, in this section we will discuss the actual influence of the different scenarios chosen from the manifold calculations. In regard to actually seeing an influence on the different DCB and traffic-related key, it is necessary to determine which weather scenario impacts what type of traffic in which extent. It is not leading to any insight if there is a lack of understanding of the effect of the winds on the traffic mix and operation types.

Analyses of the impact on different drone classes

For the purpose of understanding the different impacts the gridded weather data has been translated into a 15-layer risk map (up to 150 meters). Therefore, performance data has been utilized, which has already been used in the modelling phase in the beginning of the DACUS project. According to the traffic mix in Experiment 2, the focus was on multicopters, fixed wing drones and more robust drones such as larger hybrids (see table). Unfortunately, OEM did not provide sufficient information on turbulence sensitivity. Though our models were able to provide turbulence scenarios, we decided to skip this objective, since would not have been able to make a reasonable decision about the impact.

drone Class	Use case	Weight	Wind speed restriction value
Robust Copter	Package Delivery	15kg	15m/s
Multicopter	Food Delivery	13kg	10m/s
Fixed Wing	Surveillance	4kg	12m/s

Table 42: Wind speed restrictions per drone type

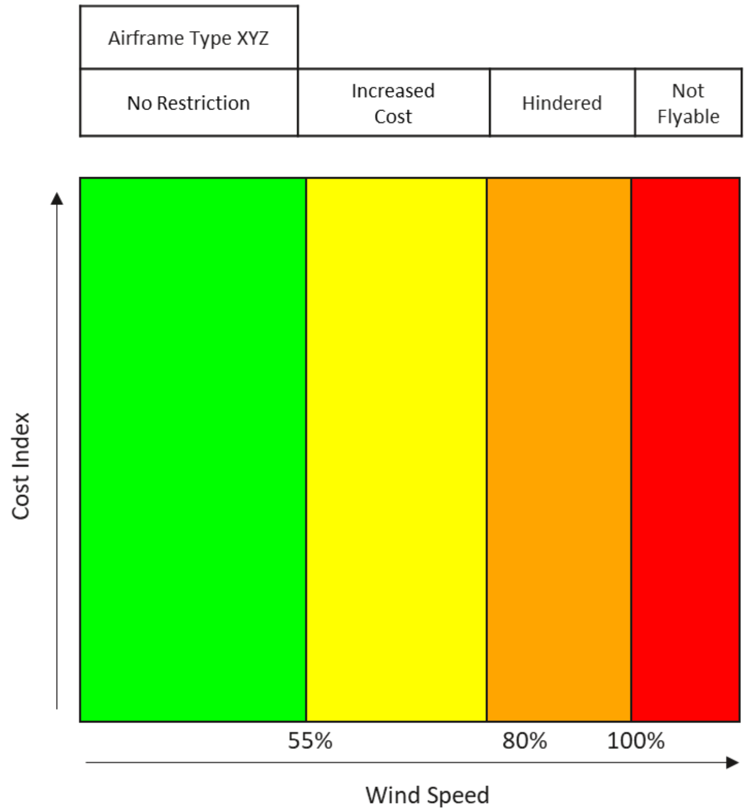


Figure 37 Segmentation of wind speed restrictions of different UAV

The segmentation into a cost index enables the usage in the flight planning system that creates the trajectories for the hotspot identification process. In the next picture there is an example for the different risk zones, which depict the effects of high building wind shadow, turbulences on the front surfaces and high wind speeds in the wind directed streets due to the Venturi effect.

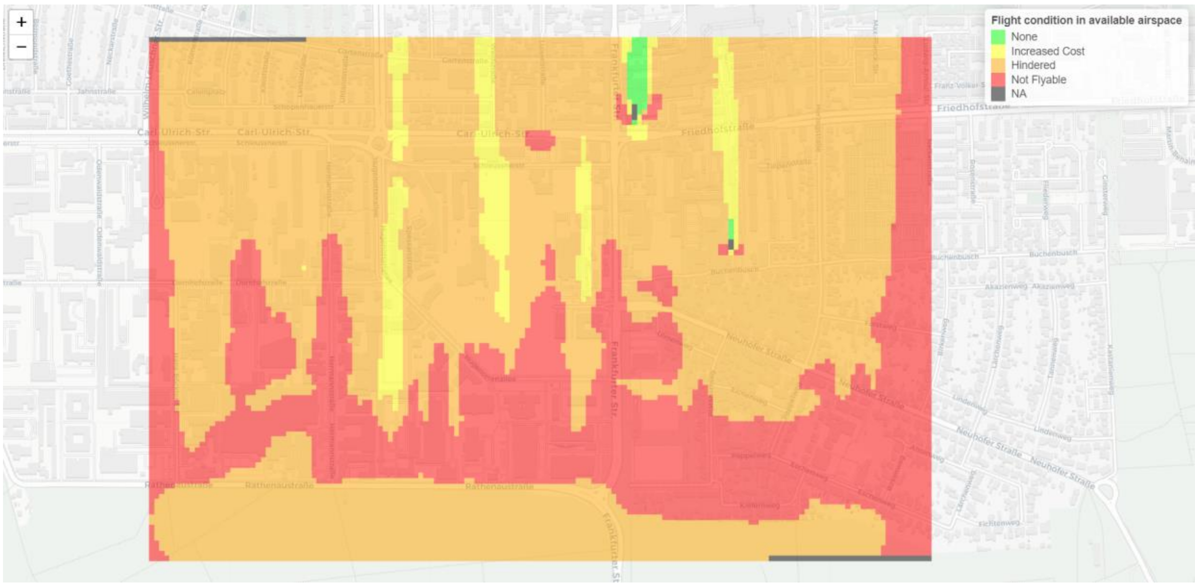


Figure 38 Example of risk map output with Southwind (10 m/s) for multicopter in 30 m layer

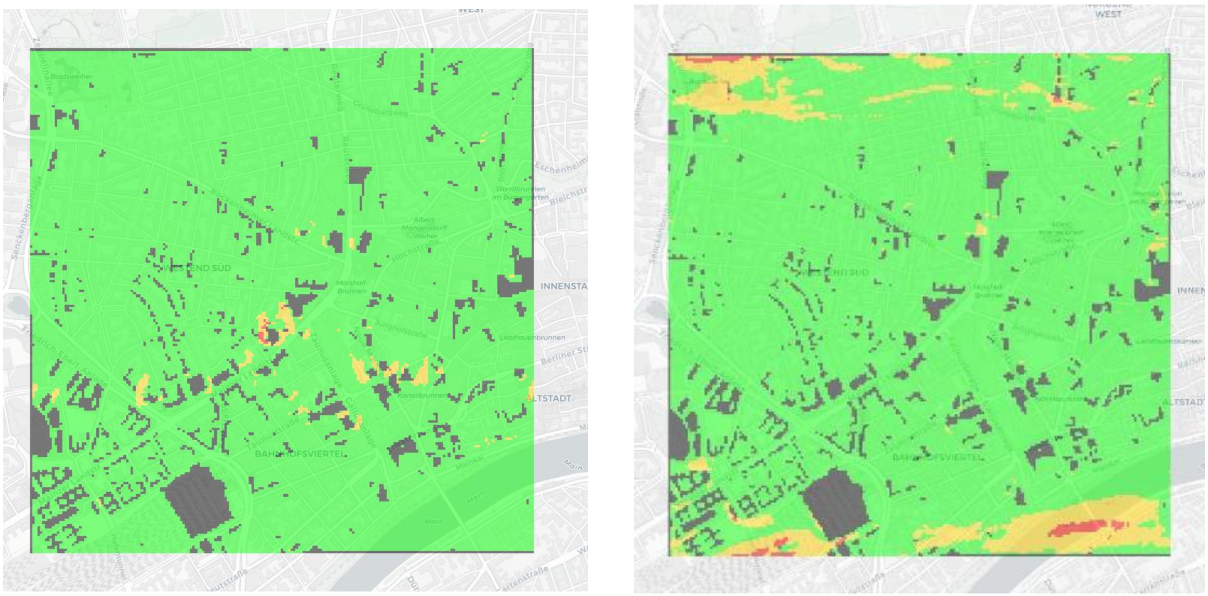


Figure 39 Comparison of FFM Downtown 10 m/s South and West (right)

As represented in the following graphs, the impact on drones varies heavily based on the class and the observed wind scenarios. Only the most sensitive airframe used in the simulation, the multicopter would be slightly affected by the medium wind condition of 5 m/s. Fixed wing and robust drones don't show any relevant effect at all. At the 10 m/s scenario on the contrary, all three types show a certain impact. Especially the multi copter and fixed wing drones will struggle to operate in the upper air space layer above 50 m (multicopter) and 100 m (fixed wing). Robust drones will still be able to operate, but at higher cost due to wind speeds and non-direct routings. Also, to be find here the same methodology applied to the FFM scenarios. As expected, the lower wind speeds result in less impact on the availability if airspace volume.

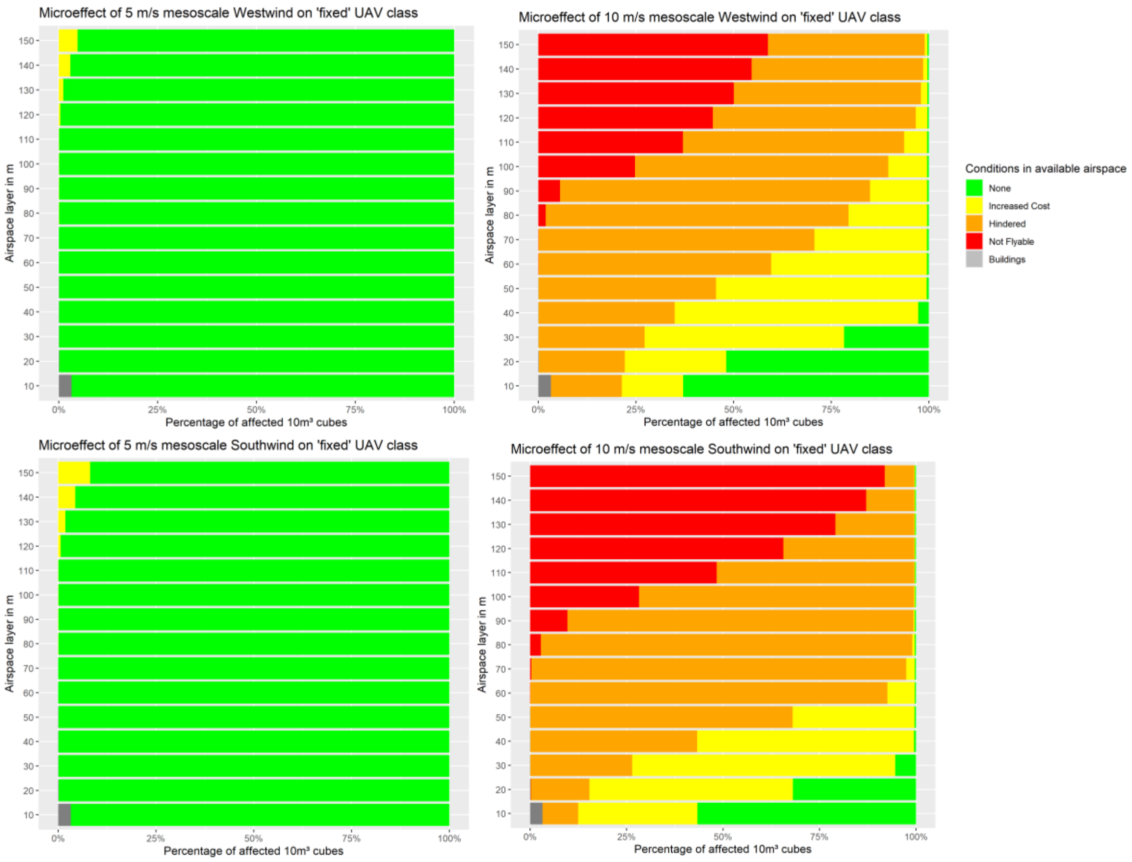


Figure 40 Airspace layer availability for "Fixed" UAV Class in N-I based on Wx scenarios

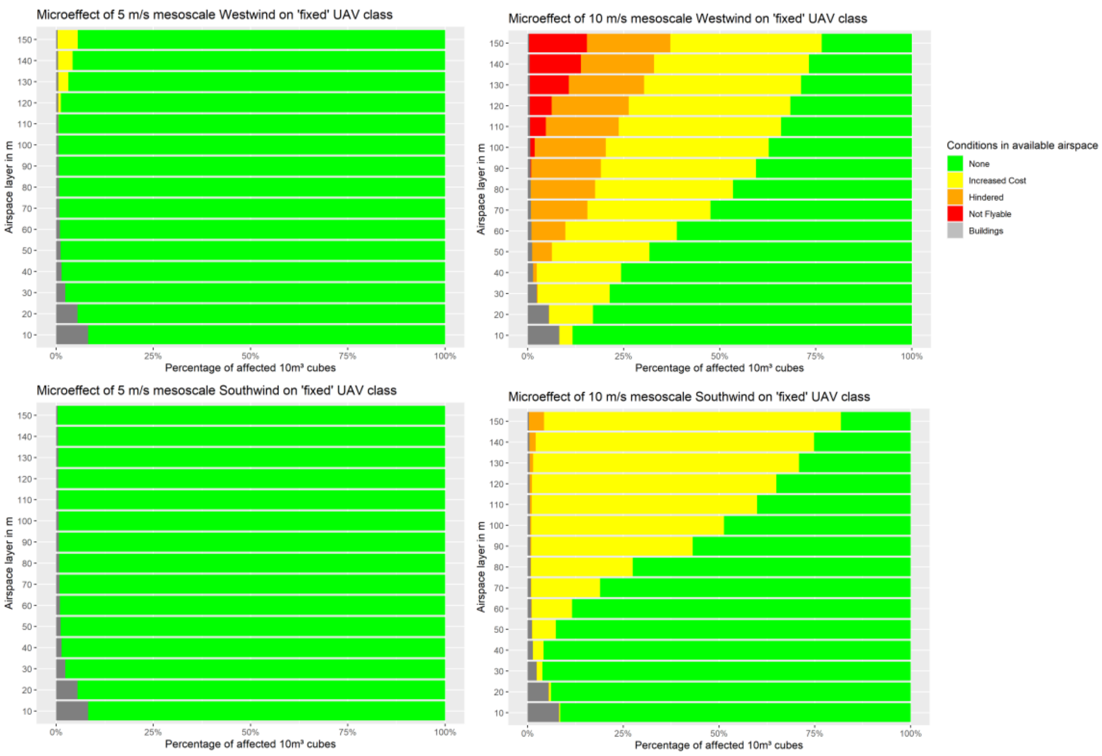


Figure 41 Airspace layer availability for "Fixed" UAV Class in FFM based on Wx scenarios

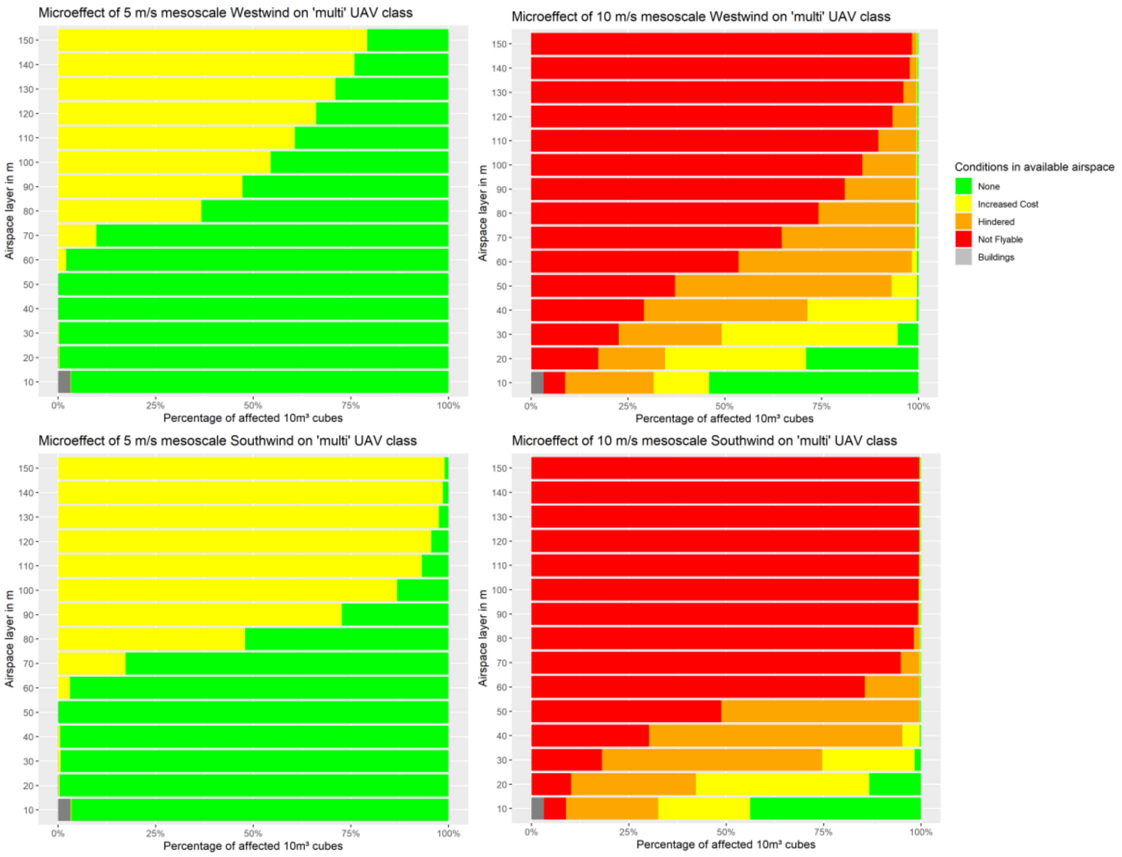


Figure 42 Airspace layer availability for “multi” UAV Class in N-I based on Wx scenarios

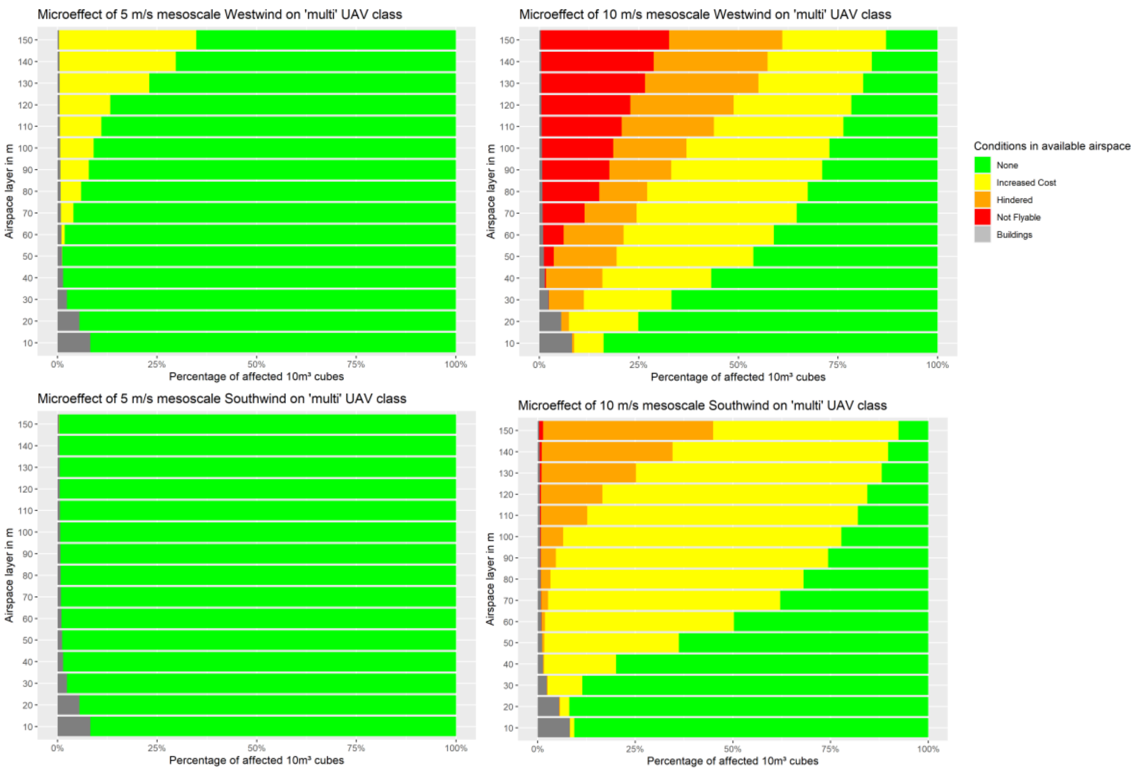


Figure 43 Airspace layer availability for “Multi” UAV Class in FFM based on Wx scenarios

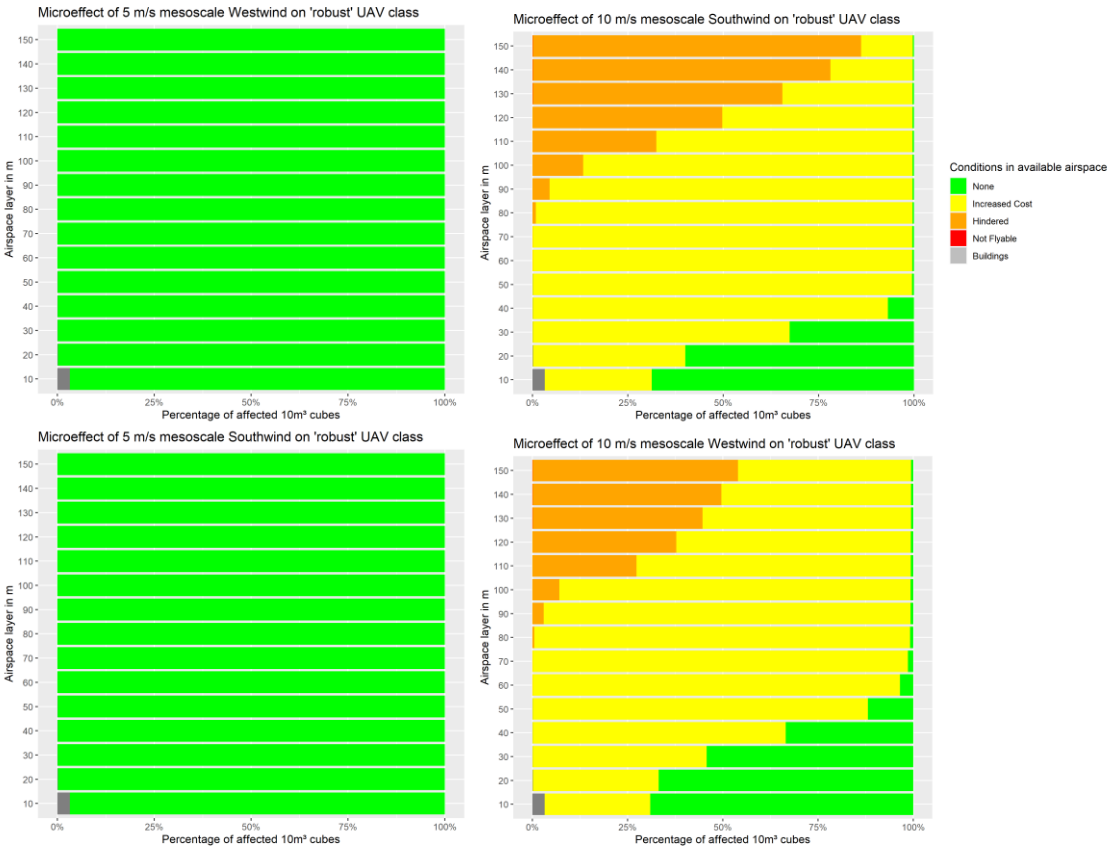


Figure 44 Airspace layer availability for “Robust” UAV Class in N-I based on Wx scenarios

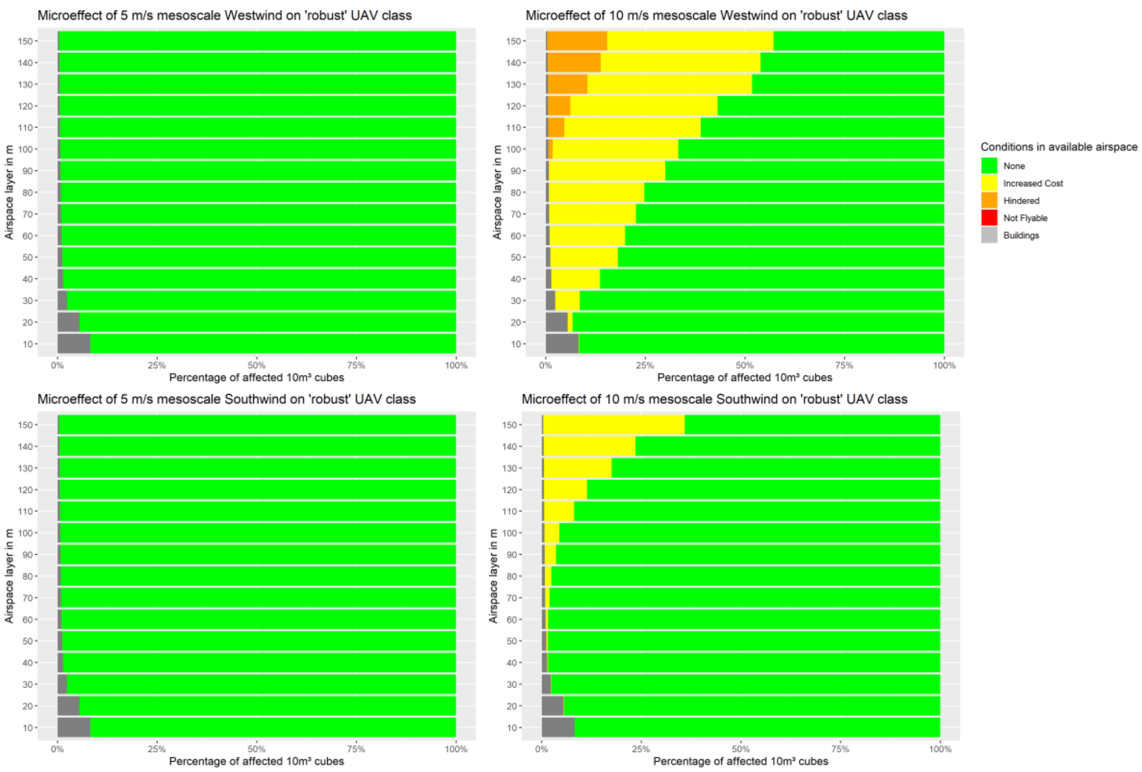


Figure 45 Airspace layer availability for “Robust” UAV Class in FFM based on Wx scenarios

Impact of adapted trajectories based on wind impact on drone classes

The previous assessment demonstrated the relevance in considering the wind impact on different drone classes and mission types (in our experiment single drone classes were assigned to specific mission types). When taking this impact on board into the drone operator flight planning process, it is feasible for the **Trajectory Planner prototype to adapt the trajectories based on the wind impact**, and therefore minimize the potential risk when operating drones near or above their wind limitation.

To this end, the cost index segmentation as shown in Figure 37 was implemented in the trajectory modelling capability, and the nominal trajectories were re-modelled following the defined criteria. It was expected that the re-distribution of the simulated traffic would generally avoid the hindered wind impacted areas and shift towards the "green" areas with low or none cost indexes.

In fact, this is the case and we could extract also a new hotspot view. To simplify the hotspot view, we show in the following figure the combined hotspot results for the urban & industrial area of Neu-Isenburg, where the wind model from the CFD simulation was used.

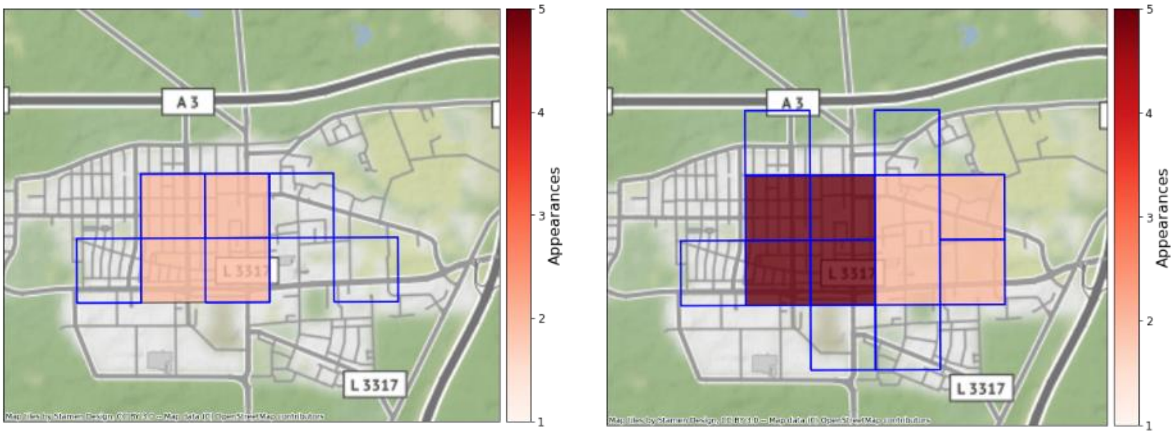


Figure 46: Combined Social Impact and Collision Risk Hotspots in nominal operations.

The figure above shows the Baseline, (left) and Scenario with Adapted Trajectories based on Weather Impact (right).

Due to the reduced number of affected areas from the combined hotspots, it is clear to see that the re-distributed traffic generates one more Social Impact hotpot appearance. **More evident is the newly cell areas that are affected with Collision Risk hotspots**. We believe that this is a significant outcome that should be further addressed as part of the DCB processes. A summary of the comparison analysis is provided in the table below.

Metric	Baseline	Weather Scenario
Average Collision Risk (maximum value in the 3h simulation time)	4,98E-07	0.00011
Number of cells with Collision Risk hotspots	156	307

Metric	Baseline	Weather Scenario
Total number of Collision Risk hotspots	412	742
Maximum Collision Risk (maximum instantaneous value)	0.0032	0.2236
Time with highest number of drone operations involved in Collision Risk hotspots (involved drone operations)	17:05:00 (8)	16:08:00 (16)

Table 43: Summary of comparison analysis using the results from the Collision Risk model

Weather impact on DCB in high drone densities

Contingency Sites Analysis

To assess the impact of wind conditions on contingency sites in urban environments, the available weather model inside the city of Frankfurt has been applied. In this area, the contingency sites used for the Contingency Event Scenarios in previous sections have been examined. In general, the contingency sites are classified in two types, namely package stations from the post office that could act as emergency landing areas; and open green areas acting as emergency landing areas for food delivery operations. The figure below shows the location of these sites and coverage area of the applied weather model.

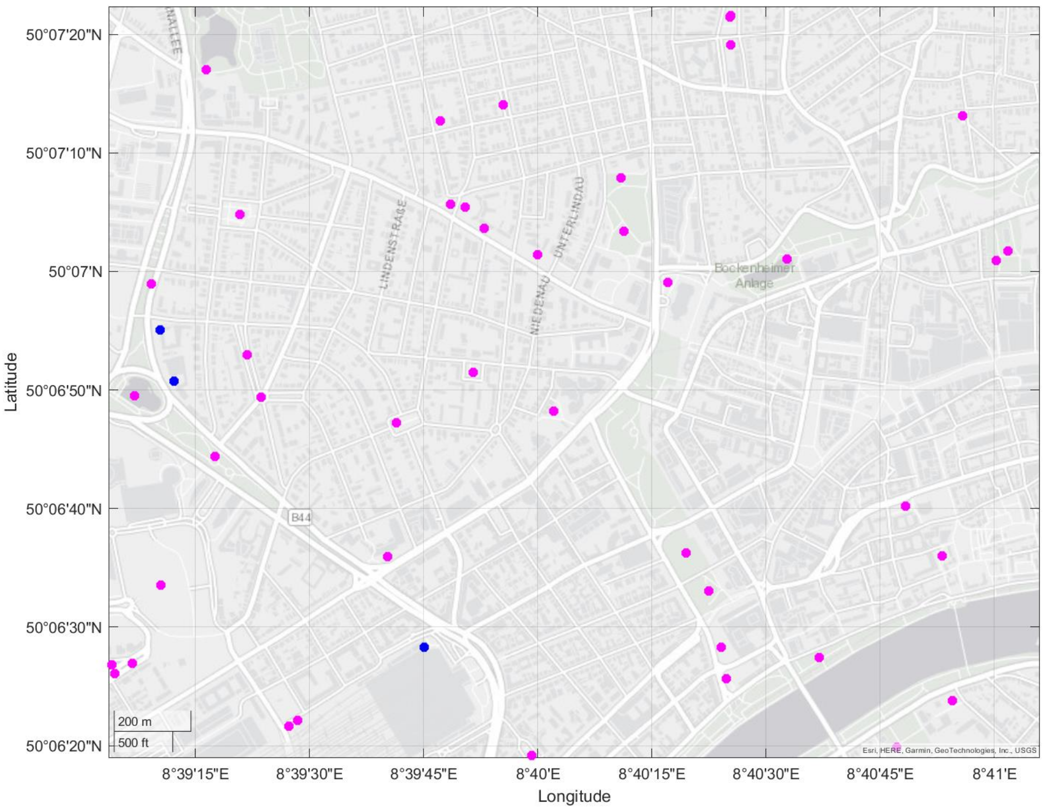


Figure 47: Weather model area and contingency sites

The weather model provides wind speed values in 10m layers. Similarly to the simulated delivery operations in the previous assessments, a low-level altitude (below 50m) of the operations is assumed. Using the cost index as presented in Figure 37Figure 37 Segmentation of wind speed restrictions of different UAV

, the vertical profile of multi-copter operations is analysed. It was shown in previous assessments that this vehicle type is the most sensitive to adverse weather conditions and it is also expected to be used in future delivery operations. The figure below depicts a situation where the risk level originated from windy conditions increases with the altitude level

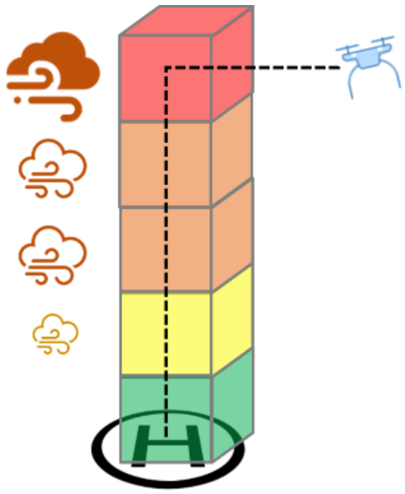


Figure 48: Vertical risk profile originated from adverse weather conditions over contingency sites

The following diagrams summarize the results from the assessment of the vertical risk profile originated from windy conditions over contingency sites. Two different types of weather models were applied: initial 10m/s wind speed from south side and from west side. The figure below the results for the contingency sites of package delivery operations.

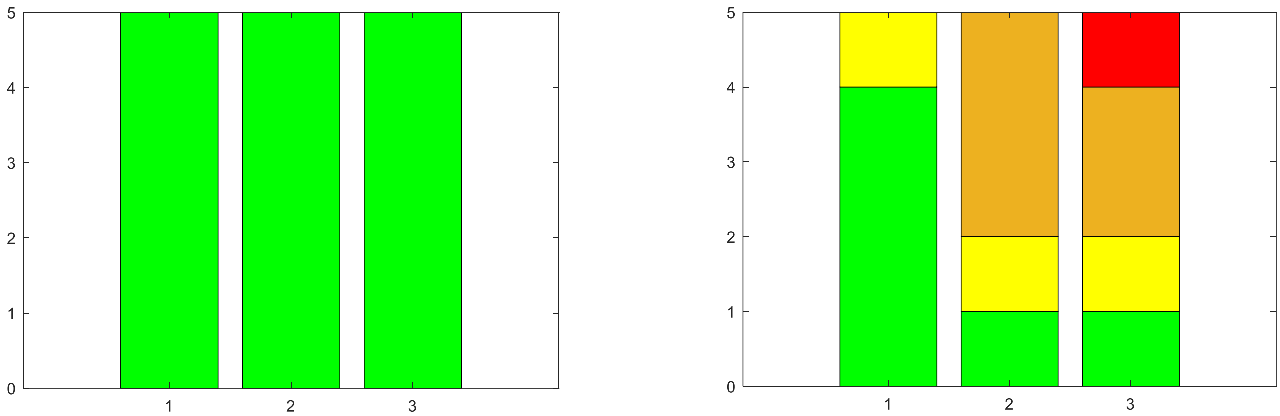
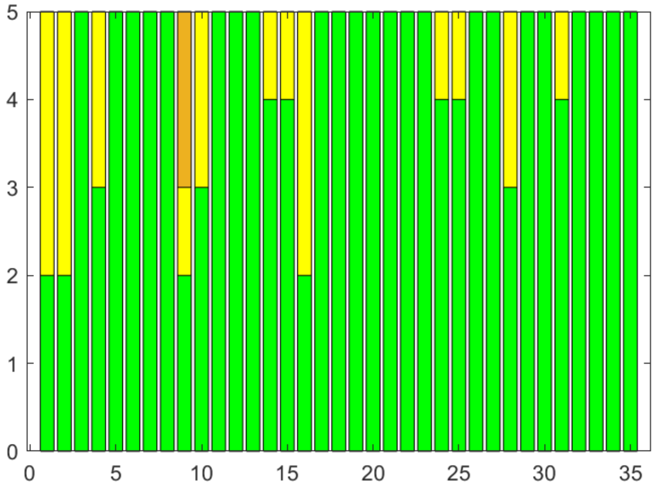


Figure 49: Risk profiles from windy conditions in contingency sites for package delivery ops.

The above figure shows the Initial conditions from south side (left) and from west side (right). Results show a relevant difference in the risk profiles depending on the initial conditions in the wind field simulation. In the wind field simulation with wind flow from south, there is no risk for multi-copter operations descending over the contingency sites. However, with a simulated wind flow from west there is a risk level in all sites, and even high-risk level over contingency site 3.

In the same manner, the contingency sites for food delivery operations have been assessed and are presented in the next diagrams.



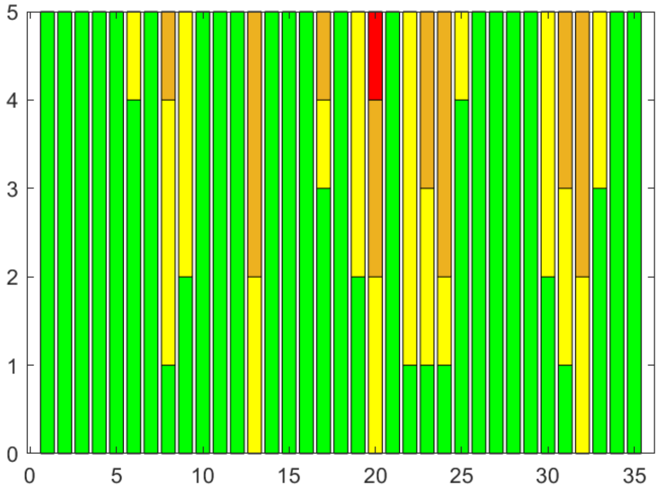


Figure 50: Risk profiles originated from windy conditions in contingency sites for food delivery ops.

The diagrams of the risk profiles (initial conditions from the south side on the left and from west side on the right) show a similar outcome as in the first assessment: **the risk levels with wind flows from west are generally higher as with wind flows from south**. The complete assessment of risk level is given the next table.

	Wind field simulation with south-wind main flow	Wind field simulation with west-wind main flow
Percentage of contingency sites with a very low / no risk levels	68%	53%
Percentage of contingency sites with increased risk levels	32%	47%
Percentage of contingency sites with hindered risk levels	3%	26%
Percentage of contingency sites with high risk levels (not admissible for vehicle type)	0%	5%

Table 44: Summary of analysis of contingency sites affected by wind conditions

Delay in the Trajectories originated from Adverse Weather Conditions

The applied cost index based on adverse weather conditions (Figure 37) has been used to adapt the baseline trajectories, with the goal to decrease the risk levels. Comparing the adapted trajectories with baseline trajectories, it is possible to analyse the effects of the changes in the trajectory modelling in terms of time delay and extra distance covered. This type of assessment is useful for extracting the additional time and distance covered of adapted trajectories, which imply drone operations that are using longer time the airspace.

193 flights changed (156 package, 37 food)	Max	Average	Average change compared to baseline
Time delay [sec]	474	99	18%
Extra way [m]	1588	182	6%

Table 45: Time delay and extra way covered from adapted trajectories

Vertiport capacity Simulations

As the more delicate operation of a drone under non-nominal weather conditions is moving close to buildings and objects, it is expected that take-off and landing operations will be especially sensible to weather. This would mean that the capacity of vertiports is a potential limiting factor for the high number of concurrent drone operations under non-nominal weather.

For this reason, it is expected that the effect on high winds and turbulence is especially impactful in vertiports. An independent simulator within experiment 2 was developed to study this impact.

Over the base of this specific piece of software, to study the effect of weather on vertiports capacity, a set of simulations was realized reusing the scenarios and drone models of experiment 2. This sub scenario is set around an isolated vertiport in central Frankfurt.

In the ATM world, each runway of an airport can be open for either take-offs, landings, both, inactive or closed. The weather will affect in two ways:

- At a basic level, if the weather is considered too dangerous to operate some or all the runways, these would be closed for the time that the conditions last, since the weather prediction allows to know with a high degree of certainty that this will happen.
- When the weather conditions are within range of allowing operation in the airport, it will still have a high impact on the configuration of the airport being actually the most important factor on determining which runways are used for arrivals and departures at any given time. It can also impact the SID & STAR procedures assigned to every movement in the airport.

For the simulator of weather effect on vertiports in cities the intention is to also capture effects beyond the open/close due to weather being above a certain threshold. But, as opposed to traditional aviation most drone platforms are multi-copters that can hover the configuration of the pads a definition of SID and STAR procedures did not feel like a good match to the problem. In order to have flexibility enough to capture the effect on the capacity of the vertiport we designed the simulator to be able to process drone flights going in and out of a specific vertiport and build a probabilistic model that captures how the time to perform the landing/take-off would depend on the weather conditions, and therefore affect the capacity of the vertiport.

As an added benefit, we think that a model as the one presented here shows that benefits of having a dynamic slot size for vertiport movements, as that would be a natural adaptation to the elongated average movement time that the take-offs and landings can suffer due to weather. This would minimize the need to tactically delay other drone operations and avoid many cascade effects at the high utilization times.

Simulator for vertiport capacity

The simulator is focused on single vertiports simulations, composed by a number of pads, which are loaded with many scheduled movements for a single day of operations. The drones are injected in the pads for departure movements and in the perimeter of a 4 square kilometre area around the vertiport location for the arriving ones. The next sections describe the simulator in further detail.

The simulator is module based and developed in C++. It is capable of fast time simulations. It has been developed with the idea to be further extended and used in future research project and we expect it to be the first step towards a High Fidelity Urban Vertiport simulator.

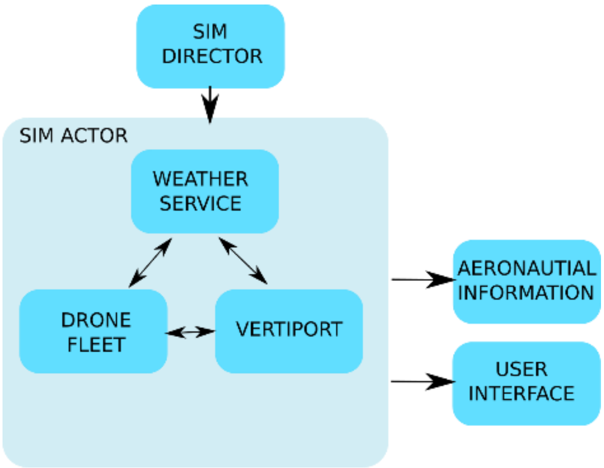


Figure 51: Modular structure of Vertiport Simulator

The simulator is composed of six modules:

1. Weather service Module:

   It is an encapsulation of the Micro-scale weather service that has been developed for the DACUS project. It used the PALM model developed as an open-source tool and led by the Hannover University.

   The data served during the simulation is precomputed due to the long time it takes to compute it.

   This model produces the weather data from a set of configuration inputs, most importantly in our case, the boundary conditions and the city geometry.

   The boundary conditions used are the same ones used in the broader experiment 2, winds on 5 and 10 meters per second from the west and the south, that is the same four scenarios. In a real deployment of the weather service this would be the actual meso-scale weather prediction at the time.

   The city geometry is generated by a tool developed during the DACUS project that allow us to fuse the general geometry coming from the Open Street Map data, with the orography of the area with buildings that we decide to inject. In the case of the vertiport simulator, the building containing the vertiport is inserted in central Frankfurt. This provides all the required flexibility to modify the geometry of the vertiport as desired while still including the publicly available data about the city.

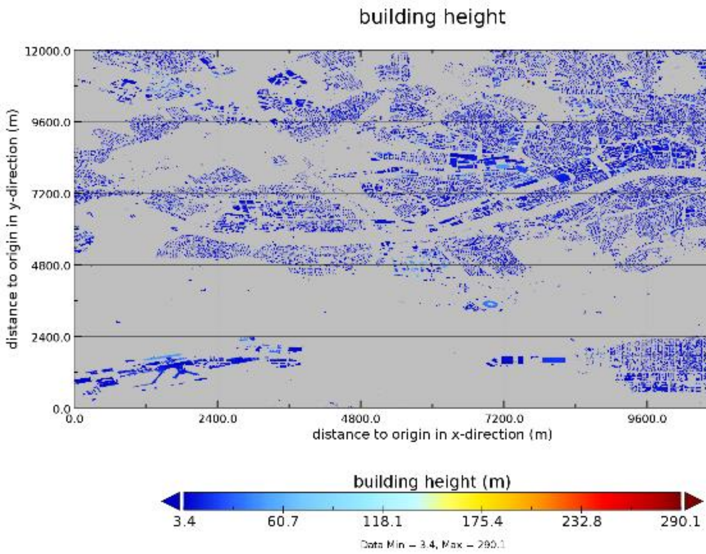


Figure 52: Height Map of Frankfurt Area

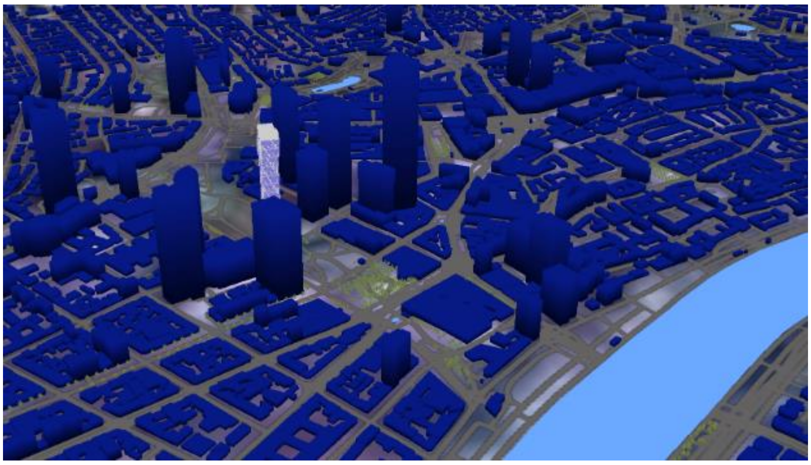


Figure 53: Geometry of central Frankfurt with vertiports building inserted

The data generated by the PALM software in postprocessed and adapted to be used by the other simulation modules.

The variables computed by the model include temperature, wind speed (three components) and turbulence index. For the DACUS project, due to the limited availability of performance data of the drone models used, wind speed has been the main variable used to determinate the effect of weather.

The PALM simulator is able to be configured to run nested simulations. This experiment exploits this characteristic by computing a lower definition weather data (4 meters grid for and area of 4 square kilometres around the vertiport and a high-resolution cube of 1-meter resolution in a configurable sized cube around the vertiport (128 meter of size in our simulations for this scenario).

 Co-funded by the European Union

Both the detail of the input geometry and the output's resolution of the weather data matches the resolution of these grids.

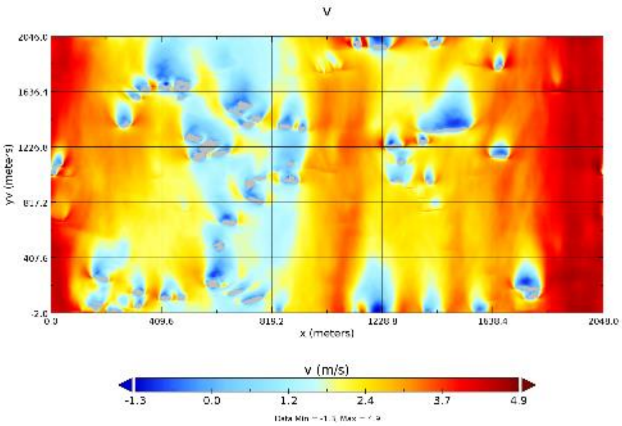


Figure 54: Example of wind speed data representation

2. Vertiport Module

The Vertiports Module allows for the simulation of a single vertiport composed by any given number of pads. While the simulator allows for the insertion of more than one vertiport, only simulations with one at a time had been performed as the interactions between them has not yet been modelled.

The vertiports characteristics are defined by a JSON configuration file. This file dictates all geometry details such as the building location, pads distribution and 3d model file plus all functioning parameters, as the configuration schedule for each pad. It can also include other characteristics such as the types of drones that can land in every pad and the vertical clearance that the drones need to cover to take-off or land from each pad.

For simplification, all landing and take-off procedures consist simply in a vertical segment of a configurable length (by default it is set to 25 meters for all drone categories) from the centre of each pad plus another horizontal one covering the last/first 50 meters from the point right above the pad and following the direction the flight's plan mandates.

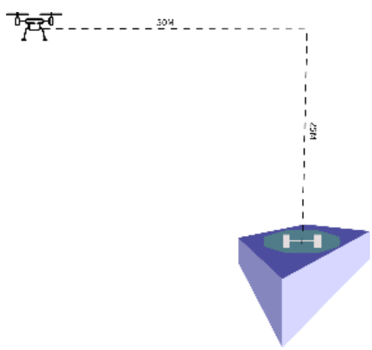


Figure 55: Land & Take-Off procedure

Previous to the start of the simulations all participating drones request and slot from the vertiport, either to land or take off. For the sake of flexibility, the slots petitions can request a specific desired start time, a maximum start time, and a desired duration. The Vertiport module has the capability response to these petitions, respecting the users request and properly populating the movements plan according to the schedule dictated in the configuration file for each pad.

The vertiport also have the capability to delay preassigned slots. drones can also communicate to the vertiport cancelations at any time prior to start the actual movement during the simulations.

Each pad can also have a different threshold for wind speed and turbulence index that would trigger it closure, thus reducing the capacity of the vertiport, potentially zero if this is the case for all pads.


```json
{
    "vertiport": {
        "name": "Central Frankfurt 1",
        "lat" : 50.104734,
        "lon" : 8.652946,
        "alt" : 155,
        "type" : "std",
        "pads": [
        {"id": "1", "diff_x": 5, "diff_y": 5, "diff_z": 0, "bearing": 0, "category": "0", "charging_cat": "none", "vertexes": [
                {"diff_x": 1, "diff_y": 1},
                {"diff_x": 1, "diff_y": -1},
                {"diff_x": -1, "diff_y": -1},
                {"diff_x": -1, "diff_y": 1}],
                "configuration_schedule": [{"start": "20220420T000000", "end": "20220420T053000", "usage": "INACTIVE"},{"start": "20220420T053000", "end": "20220420T240000", "usage": "DEPARTURE_ARRIVAL"}]},
        {"id": "2", "diff_x": 5, "diff_y": -5, "diff_z": 0, "bearing": 0, "category": "0", "charging_cat": "none", "vertexes": [
                {"diff_x": 1, "diff_y": 1},
                {"diff_x": 1, "diff_y": -1},
                {"diff_x": -1, "diff_y": -1},
                {"diff_x": -1, "diff_y": 1}],
                "configuration_schedule": [{"start": "20220420T000000", "end": "20220420T053000", "usage": "INACTIVE"},{"start": "20220420T053000", "end": "20220420T240000", "usage": "DEPARTURE_ARRIVAL"}]},
        {"id": "3", "diff_x": -5, "diff_y": -5, "diff_z": 0, "bearing": 0, "category": "0", "charging_cat": "none", "vertexes": [
                {"diff_x": 1, "diff_y": 1},
                {"diff_x": 1, "diff_y": -1},
                {"diff_x": -1, "diff_y": -1},
                {"diff_x": -1, "diff_y": 1}],
                "configuration_schedule": [{"start": "20220420T000000", "end": "20220420T053000", "usage": "INACTIVE"},{"start": "20220420T053000", "end": "20220420T240000", "usage": "DEPARTURE_ARRIVAL"}]}
        ],
        "gui" : {
            "model_file" : "bld_frtv1.ive",
            "scale"      : "1"
            "show_pads" : "true"
        },
        "simulation" : {
            "start_time" : "20220420T000000",
            "speed_multiplier" : 1.0
        }
    }
}
```


Figure 56: Vertiport module configuration file

When the simulation advances the vertiport grant drones the right to start their operations following the stablished queue during the schedule population.

3. drone Fleet Module

This module controls the behaviour of all drones. It reads from a JSON configuration file the movements to simulate, which will always start with a departure from the vertiport and go to a point in the perimeter of the simulation or, if it is a landing movement, start in the perimeter and end at one of the pads of the vertiport.

For each movement the pertinent petition of slot will be performed to the vertiport module and the starting time of the movement will be set accordingly to the given slot.

During the simulation it contains to lists of drone movements, the scheduled ones and the running ones. The scheduled ones are the planned movements, that already have slots assigned at the vertiport but whose initiation time has not been reached by the simulation clock. The running ones are the drone movements that are currently in the simulated air and are either going to the vertiport or coming from it.

In every time step of the simulation the running movements advance according to their flight plans and any scheduled flight whose starting time stamp is met is moved into the active drone movements queue.

There is a third list of drone movements for finished ones. All drone eventually ends in this list, either by finishing their planned flight or by being cancelled.

Due to time constraints, interactions between drones are not considered.

This simplification entails that, while all traffic is considered when allocating the slots in the vertiport, once each drone movement has been assigned one and conformed a trajectory according to it, no further interactions with other aircrafts are considered.

This means that the propagation of delays due to capacity reduction in vertiports caused by weather is not considered. Much of the infrastructure of the simulator is designed to capture this behaviour and we plan to enable this functionality in future works.

4. Sim Director Module

   This module controls the flow of the simulation and pass of time in the rest of the modules that are considered simulation actors, that is, that are stateful and interact with other modules. It only supports fixed size simulation time steps in the simulation clock.

   It starts, configures, and stops the rest of modules and send the time-step events to them. It also has the ability to detect overflow events, that is when the simulator is mandated to run at a higher speed than it actually can. If this happens, it hints that the hardware is not able to meet the computational requirements of the simulation and the mandated speed. the simulation needs to be started with slower simulation step.

   At the end of the simulation, that is when there is no more drone neither in the scheduled nor running list, it collects data from the vertiport module and the finished list from the drone flee module to measure the average delay in the operations and the effective deviation on the duration of the movements.

   Running the same scenario with different weather data allows to measure the effect this has over the capacity of the vertiport for every weather condition tested.

5. Aero Info Module

   This is a stateless module that allow other ones to find each other and also consult static aeronautical data used for convenience, as for example translate named waypoints into coordinates.

Simulation Flow

Here is a simple description of the different steps for the simulations:

- Preparation:

  The user interface module is initiated with the desired location and size for the simulation.
  The publicly available data in the Open Street map repositories is accessed to recreate the geometry of the scenario. Orography data can also be used automatically instead of a flat earth model. Water masses and vegetation data is also included (but not used at this time to reduce computation time). Then, extra geometry is injected following the requirements of the configuration files. In this simulation the vertiport module registers it corresponding building if desired.

The resulting combined geometry is sampled to produce the input files required by the PALM models to simulate the weather in the desired volume.

The boundary weather conditions for this volume are the other required input by the PALM model. In real use this would be generated from the weather prediction of a meso-scale models that covers this region (REF) but in the DACUS project, an in particular in the experiment two, we are using fixed profiles of wind for this as explained before.

With all this data the PALM weather model is run and the detailed weather data prepared for publication by the weather module.

- Initialization:

  The Sim director module is passed a configuration file that references all configurations files for each of the modules: The weather module is passed the storage location for the precomputed weather data as generated by the PALM model during preparation.

  The Vertiport module loads a configuration file this includes the usage schedule for each pad and prepares the slots for allocation. Then the drone fleet module traverses the list of scheduled drone movements, requesting slots to the vertiport for each of them reading from the file the desired start time, maximum start time, and desired duration and building a straight flight plan in (for arrivals) or out (for departures) from the pad assigned by the vertiport module forming a straight line from the previous/next waypoint in the desired flight plan. For simplification, only two points exist in every flight plan and this results into trajectories that have two flight segments, including the purely vertical that lands/takes-off from the pad.

  After the initialization the drone fleet module has the list of scheduled movements ready, with every element having full data about the performance of the drone (provided in another JSON file per drone model) and a planned trajectory, including speeds and time stamps.
  The Vertiport module has also the full list of expected movements. While it is capable of accepting cancelations, request for slots during the simulation loop & propagation of delays, this part has not been enabled due to time constrains, so each movement behaves independently from the rest and only direct weather effects are measured during the simulation loop.

- Simulation Loop:

  Once the initialization is finished the director module sets the clock to the initial time described in the main configuration file and start broadcasting time events of a fixed time step, that is also a parameter, in this case set to one second
  All connected modules receive this event and process its internal data according to the new time stamp. Once a module is done processing it sends a message to the director module indicating it has finished processing the time step. When the director receives this message from all simulation actors the next simulation step event it broadcasted.
  If at any point a module receives another simulation step event before ending processing the one before, a simulation overrun error is raised and the simulation is aborted.

In these set of simulations, the relevant events to measure the weather effect of the time taken to either take off or land are the one that take the active drones in the drone fleet module for every time step during the traversal of the inverted “L” shaped manoeuvre detailed in figure 18.

For each of this step the drone position is used to sample the weather model data, collecting wind speed and turbulence index, though only wind speed is used at the moment, for that particular position (the closest value in the grid provided by the weather module is used). Then a function called *droneManouvre* is invoked with the wind speed and turbulence values as its parameters.

drone Manoeuvre Function

This is a simple state full function that models how the controller of the drone tries to advance in its path while dealing with the external wind making a compromise between speed and capacity to compensate external forces. This process is modelled with a set of stochastic models that depend on the drone performance model.

It is designed for rotatory wind vehicles and based on two assumptions: first that the same actuators that are used for stabilization and movement control are the same. This is true for most multi-copters and regular helicopters. And second that the higher the speed that the drone is flying at, the less dynamic range the actuators have to compensate for external perturbations.

To capture the mentioned behaviour a state machine is implemented inside the function, in which the drone controller starts in a nominal state, in which the drone will advance at the standard horizontal & vertical speeds during the manoeuvre and a series of safety states in which the speeds of progression are lower but it is more resilient to higher wind speeds. The drone models used for this experiment use 2 safety states. Each of these states has a maximum external wind parameter (used to normalize the wind speed value) and a function defined by 10 parameters that dictate what chances the controller have to respond to each value of the external wind in terms of its normalized value. It is referred in the simulator as the risk function of the state. The performance model file for each drone type contains the parameters that define it for every state.

An example of this set of functions for a drone model in shown in the next figure. In this example, for the nominal function, it can be seen that the risk of changing state (and thus getting closer to cancellation) is close to cero and then it starts to grow exponentially as the wind gets closer to 1 (max wind value), where the aircraft will trigger safety in once every 20 seconds making very hard to perform the manoeuvre as one would expect.

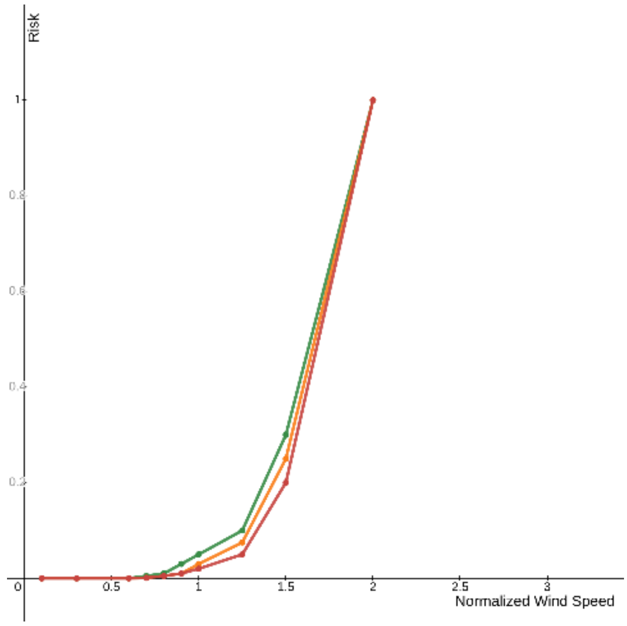


Figure 57: Risk functions for safety (green), safety-1 (yellow), safety-2 (red) states - package delivery drone (experiment 2)

When in one simulation step this function is called:

a. The external wind speed is divided by the maximum wind speed parameter of the present state.
b. The resulting value is used as input in the function (defined used the present state parameters). The output is a value between 0 and 1 that indicate the probability of triggering a safer controller.
c. A uniform random variable between 0 and 1 is sampled.
d. In the value is lower that the threshold found in b, the machine transitions to a safer state. In is it already in the safest state (slowest & more resilient) the flight is cancelled. In order to model the capability to recover the nominal behaviour after a sporadic transition to safety-1, the drone is allowed to transition back from safety-1 to nominal after 10 seconds if no further triggers have been reached.
e. Each state as a fix advancing length per unit of time that is multiplied by the time step to evaluate how much the drone has advanced in the advance of the manoeuvre. This amount is added to the drones last position before the next time step.

After the required number of steps, one of two outcomes are possible, either the drone finishes it manoeuvre or the movement is cancelled. When any of this this happen the final state of the drone and the total time employed are logged.

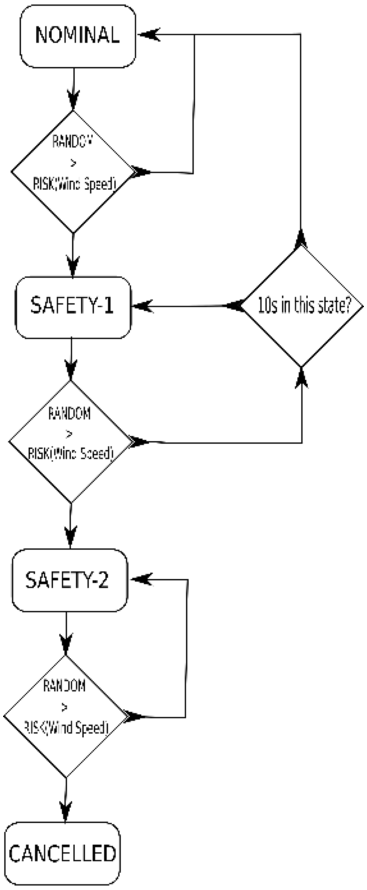


Figure 58: Flow diagram of internal state of the droneManouvre function

This output is processed to generate the statistics of the average duration of the movements of the simulated vertiport. This data could be used to plan the duration of the slots given a weather prediction. The number of cancelled flights resulting from the simulation can also be used to decide if the full the closure if a particular pad (or full vertiport if it happen in all pads) is advisable as a high number of cancellations indicate, not only that capacity would be greatly reduced but also that the risk of losing platforms due to weather is high under the simulated conditions.

Of course, as each drone model as a different performance model so the average time to perform the landings and take-offs can greatly change. This means that for some conditions it might be advisable to only allow operation of some types of airframes in some pads.

In any case it is clear that this kind of simulations would be an essential tool in order to plan the capacity, and design the configuration schedule to maximise it, of an urban vertiports, especially in the case of light drones.

Results

There are three drone types defined in scenario two: a multi-copter for package delivery, a smaller one for food delivery, and a fixed wing for surveillance missions.

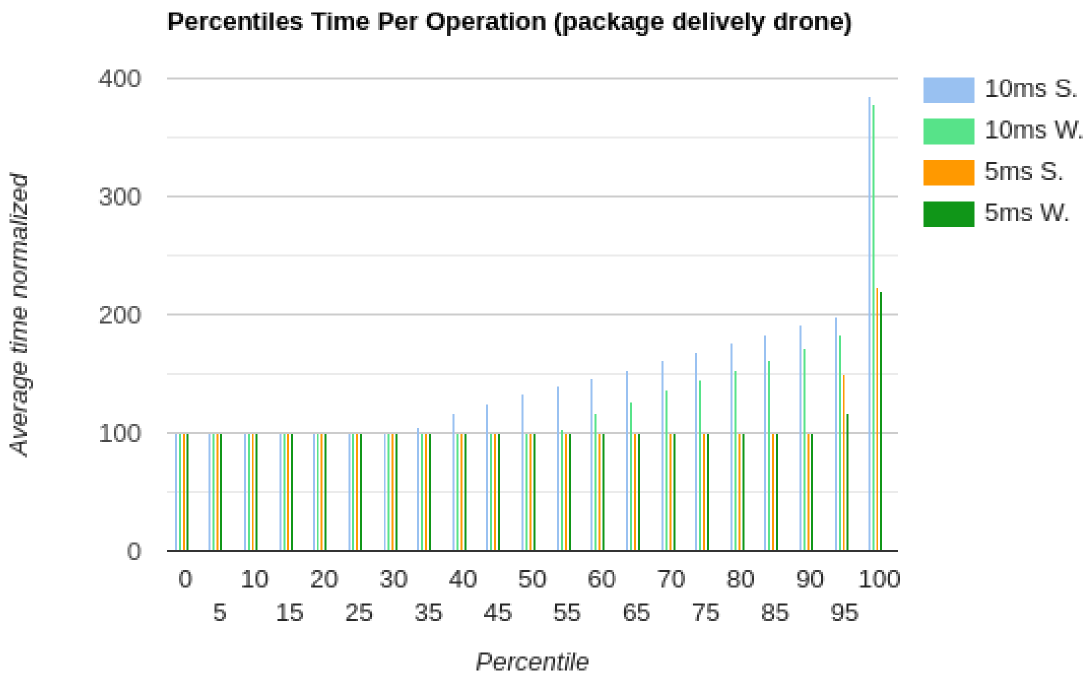
As the assumptions of this simulator only apply to rotary wing drones, a detailed performance model was created for each of the existing two of this kind. Wind associated risk functions were defined as described in the drone Manoeuvre Function section, with all parameters for the curve's definition (as shown in figure 20) described in a JSON file for each of the drones.

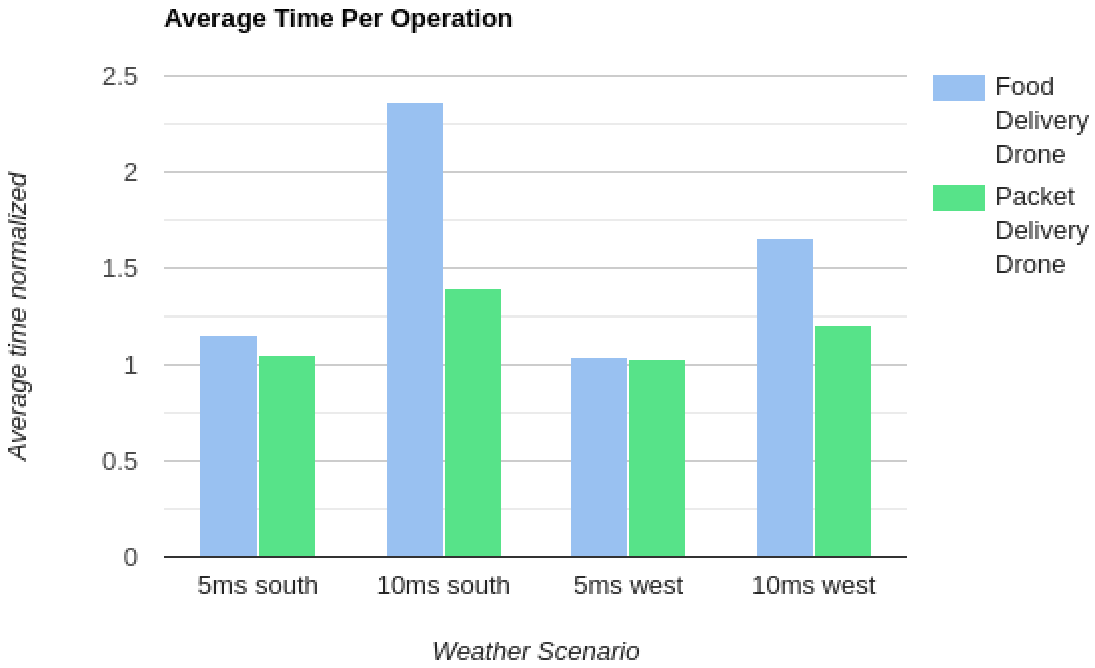
The location selected for the vertiport was selected in central Frankfurt, surrounded by many high buildings. The specific location is: *Latitude 50.1111901 Longitude 8.652946 Height: 90 m*. A building was injected into that location as shown in figure 16.

For each of the two drones modelled all four weather scenarios where tested.

For each scenario a total of 3600 movements approaching the pads and leaving the pads where simulated. These are evenly distributed with origins/destinations in all directions from the centre of the vertiport (100 for every 10-degree range).

For each of the weather scenarios the average normalized time taken by the any vertiport movement was measured:





It can be seen that the vertiport looks to behave better when the dominant wind is coming from the west. This indicated that the surrounding buildings partially shield this location from winds coming from this direction.

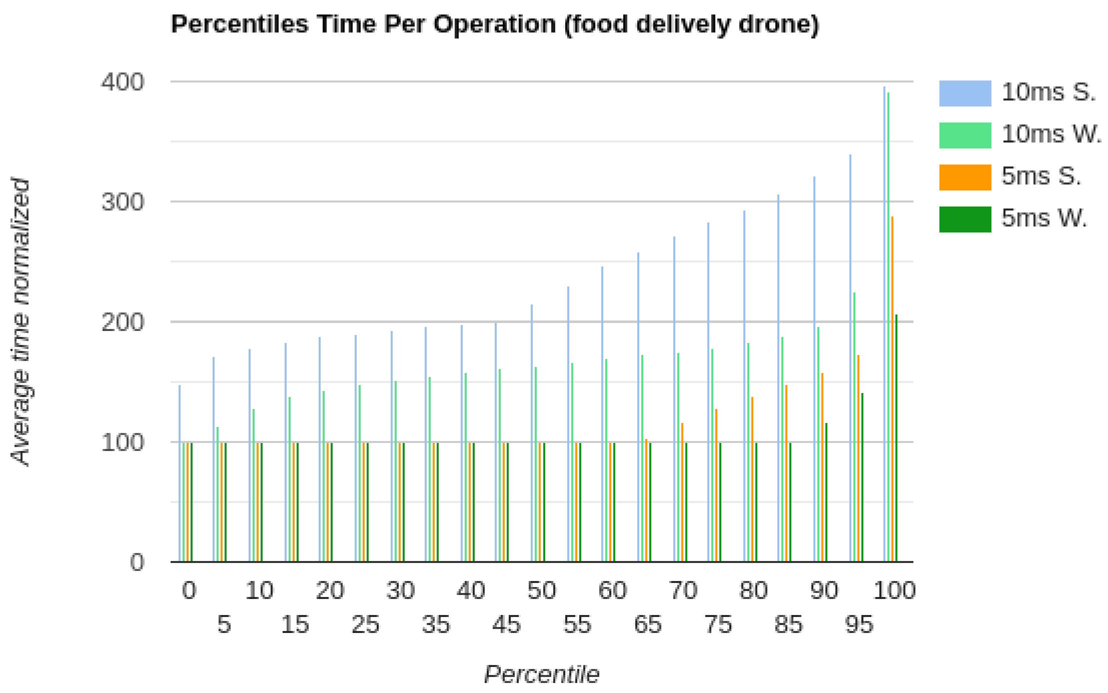
For the scenario of 5 m/s winds from the west the averages are only around 2% and 4% deviated from the ideal duration for package and food delivery drones respectively. There were also no cancellations for neither the heavier ones nor the lighter type (food delivery).

For the scenario of 5m/s winds from south, the heavier model is still affected very little but the average time for the lighter one is 16% higher. There were also no cancellations for the heavier ones and 0.03% for the lighter type.

Switching to the 10m/s scenarios the effects are more dramatic as to be expected. For the west scenario the heavy platforms take an average of 23% more time per movements while suffering 2 cancellations out of 3600 movements. And the food delivery drones take an average of 65.5% more time suffering close to 0.7% cancellations.

The last scenario (south 10m/s wind) shows the most extreme situation: Heavy drones take an average of 40% more time per movements suffering 0.23% cancellations and the light ones deviate 136.8% from the average operation time, more than doubling the total time required per movement, and suffer 515 cancellations out of 3600 movements, indicating a high change of losing platforms of this type under these conditions.

To see in more detail the effect of weather in the time taken for the operations the percentiles for all scenarios are shown below:



It can be seen that even in the best weather simulated (5ms W.) the slowest movement (100th percentile) is double the nominal one even for the heavier drone. This is to be expected as out of thousands of operations having one sensibly delayed seems reasonable. It is easy to see that these are outliers as the 95th percentile has already a deviation of only 17% and the 90th is at less than 1%.

In other, more severe scenarios such as 10 m/s South, for both platforms the average time increases. In particular, the food delivery platform 40th percentile is already at double the nominal duration and more than 10% of the operations took more than triple. While these details are not very relevant for this case, as the high number of expected cancellations already recommend not flying this type of drones in this weather scenario, for the bigger platforms it is.

For the package delivery drones less than 5% of the flights take more than double the expected time, and with the average indicating only a deviation of 40%, making slots around 50%-60% longer should avoid congestion. Of course, the simulation including the interactions between drones should be performed in a real scenario to account in detail for the queueing effect.

As it can be seen the average time and the distributions can change in a meaningful way due to weather conditions and, while the models used for these experiments require validation and refinement once better performance models are provided by drone manufactures, providing details similar to those offered by the BADA models for the traditional airliners, we think that taken into account the weather effect on vertiport capacity would be key in any U-space deployment that intends to scale well with high demand scenarios.

Appendix C Experiment #3 Detailed Report

C.1 Summary of experiment and objectives

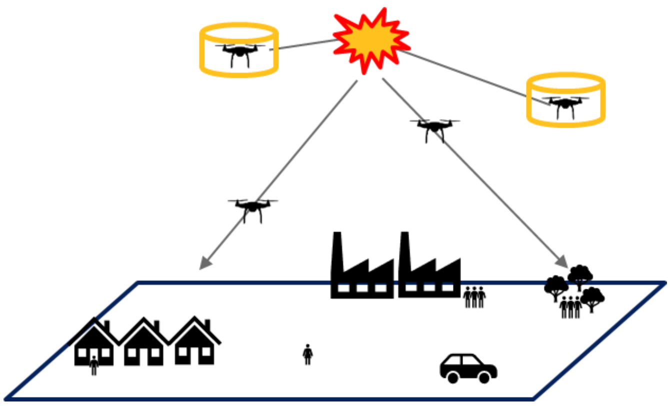
This experiment applies the Collision Risk Model developed in WP3 (see D3.2) to different scenarios in the Strategic Phase to test the effect of considering different CNS performances and defining different airspace structures on the maximum acceptable capacity in a certain scenario.

UAS operations imply risk both in the air and on the ground. It is essential to keep the level of risk below a given value to ensure operations are carries out safely. In this approach, it is taken as a reference the target level of safety (TLS) proposed in the SORA methodology, with the established value being 1E-6 fatalities on the ground per flight hour. It should be noted however, that given on-going research regarding the TLS threshold that this value may be subject to change in the future, as apparently the SORA's TLS value could be an unsuitable value. For example, other research projects that were carried out in parallel with DACUS such as BUBBLES [15] are considering more stringent values than the level proposed in SORA. Thus, DACUS work does not aim to propose a more suitable value, but design the models to fit different recommended TLS values.

Below it is presented the formula followed to obtain the number of fatalities to third parties on the ground.

Probability of fatal injuries to third parties on the ground = (Collision risk + Failure risk) × The probability of a damage on a person × The probability of the injury evolving into a fatality

As it can be seen in the formula, the fatal injuries on the ground will depend on three main factors: collision + failure risk, probability of damage on a person and probability of the injury evolving into a fatality. The first term depends on several factors: characteristics of the airspace, number and performance of the aircraft, structuration of the airspace, etc. The second one depends on the density of population on the ground (level of occupation will determine the probability of falling over an "occupied" zone) and on the sheltering factor, that measures the protection that trees, buildings, cars, etc., offer to people. Lastly, the probability that an injury involve into a fatality depends on the characteristics of the drone and the energy of impact.



Testing different CNS performance is essential to set the maximum capacity or minimum separation between aircraft because, depending on how good CNS performance systems are, the greater the capacity of the airspace will be for a given TLS (1E-6 fatalities/flight hour, as per SORA methodology. On the other hand, defining different airspace structures and the risk associated to them will be useful to find the structure which allows the greatest capacity while maintaining an acceptable level of safety.

Main objectives of this experiment are:

- To study the improvement of flying with a U-Space system.
- To study the impact of the CNS system´s performance into the collision risk.
- To estimate the maximum capacity of an airspace without any strategical mitigation based on collision risk and the overflown area.
- To study the impact on collision risk of introducing separation between aircrafts.
- To study the impact on collision risk of introducing airspace structures so the direction of flight is restrained.

C.2 Development of the experiment

The procedure followed throughout the development of this experiment is as follows: First, a free-flight scenario is tested, and the impact of the CNS systems performance and the improvement introduced by U-Space is analysed. With the results regarding collision risk and the average fatality derived from a collision, the maximum capacity was obtained for different cities. Then, some strategic mitigations such as separations and airspace structures has been tested to study the decrease in collision risk.

The following simulations were developed:

- Reference scenario: GPS L1 Rx, no integrity errors, 1 second communications update rate, 100% probability of detection and free-flight.
- CNS Scenarios:
    - NAV Improved receiver (1): GPS+Galileo+SBAS Rx.
    - NAV Integrity: Integrity risk (large error for 0.1% of the drones).
    - COM: Update rate 3s & 5s.
    - SUR: Probability of detection 95% & 90%.
- Airspace Structures Scenarios:
    - Layers.
    - Sectors.

Each of them is run several times, increasing progressively the number of drones, i.e. the capacity, till the risk equals the TLS (1E-6 fat/f.h.).

A series of simulations have been carried out considering different setups in terms of CNS performances (navigation accuracy and communications update rate), conflict margin and number of aircraft. Each of these factors have an impact on the risk of collision, which, depending on the area overflown, will determine the fatality risk, as well as on the detection rate.

The proposed setups combine assorted factors to analyse the impact of each one of them on the overall fatality risk. The scenarios are:

- **Scenario 1.** Collision risk reduction with U-Space Tactical conflict resolution.
- **Scenario 2.** Impact of Navigation accuracy on the Conflict detection rate and the remaining collision risk.
- **Scenario 3-**Fatality risk and maximum capacity in different overflown cities with and without UTM system.
- **Scenario 4-** Collision risk reduction introducing separation.
- **Scenario 5-**Collision risk reduction introducing airspace structures

All the scenarios have been tested considering only small multirotor UAS of 1,5 m size and speeds up to 25 m/s with the same performance characteristics.

The immediate results after running the simulations are the number of conflicts and collisions occurring in the scenario. A collision is considered when the distance between two aircraft is lower than a given margin of safety. A conflict is declared, for its part, when the distance between two aircraft is lower than a given margin of conflict. Before presenting the scenarios and results, some essential concepts must be introduced:

- **Potential collisions**: They are those which would occur if there were no tracking and monitoring service in place, just generating random positions and speeds and checking what trajectories converge. That is, all the convergent trajectories whose minimum distance is lower than safety margin.
- **Detected collisions**: Collisions that are also detected as conflicts.
- **Avoidable collisions**: They are those collisions that can be avoided, i.e. when the time until the collision is long enough to detect and avoid it.
- **Non-avoidable collisions**: They are those collisions that can't be avoided, i.e. when the time until the collision is not long enough to detect and avoid it.
- **Non-detected collisions**: Collisions that are not detected as conflicts due to the error in position and headings.
- **False alerts**: Conflicts that do not lead to a collision.

For more details regarding the experiment, DACUS deliverable D 3.2 could be reviewed.

To test the assorted objectives, a series of independent variables and concepts are introduced in order to set up the scenarios. The definition, values and ranges considered in these variables are presented below:

1. **Deconfliction service**: The effect of deploying a U-space Tactical Conflict Resolution Service is tested considering two possible situations. The first situation is one in which no U-space deconfliction is provided (reference scenario). In the scenario this means that all potential

collisions will occur since there is no U-space service in place to detect and prevent them; it is assumed that drones are not equipped with any kind of collision avoidance system. In the second scenario, a U-space Tactical Conflict Resolution Service is considered, which would detect pairs of drones in risk of collision once they converge closer than a predefined conflict margin.

2. **CNS performances**: The next independent variables concern CNS performance. In particular, two fundamental aspects for detecting potential collisions are considered. The first is the accuracy of the navigation system, which considers a position error following a normal distribution. The second is the update rate, i.e. how often the position of the UAV is reported.

Navigation accuracy	**Description**
GPS L1	Deviations: $\sigma_x, \sigma_y = 1.633\text{m}, \sigma_z = 2.55\text{m}$
GPS+SBAS	Deviations: $\sigma_x, \sigma_y = 1.02\text{m}, \sigma_z = 1.1\text{m}$
Communications update rate	**Description**
1 s	High, one update every second
3 s	Medium, one update every 3 seconds
5 s	Low, one update every 5 seconds

Table 46. Overview of CNS performance-related variables: Navigation accuracy and update rates.

3. **Conflict margin**: For the experiments, three different conflict margins are considered to evaluate the impact on detected collisions.

Conflict margin	**Description**
3 m	Conflict is declared when the distance between two UAVs is less or equal to 3 m
5 m	Conflict is declared when the distance between two UAVs is less or equal to 5 m
10 m	Conflict is declared when the distance between two UAVs is less or equal to 10 m

Table 47. Overview of the three different conflict margins tested in the experiments

4. **Overflown area**: Regarding overflown areas, cities with different population density and sheltering factor are considered to evaluate the fatality risk of overflying them in several situations with different collision risks. Sheltering factor is a measure of how protected people are from the impact of a drone by buildings, trees, cars, etc.

Environment	Population Density (inh/km2)	Sheltering factor
Toulouse Outskirts - Industrial	5500	Very High
Toulouse City Centre	5500	High
Madrid City Centre	4000	High
Toulouse Outskirts - Residential	2200	High
Toledo City Centre	900	High
Toledo Outskirts	350	Low
Toledo Rural	60	Very Low

Table 48. Cities with population density and sheltering factor

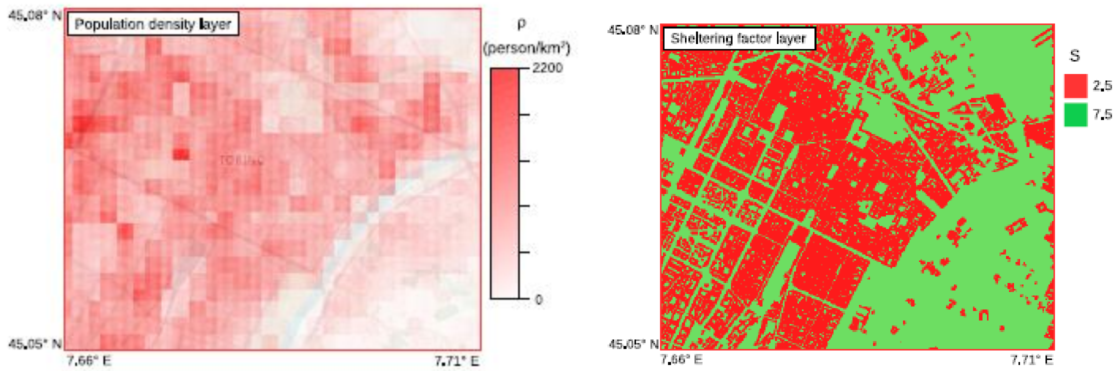
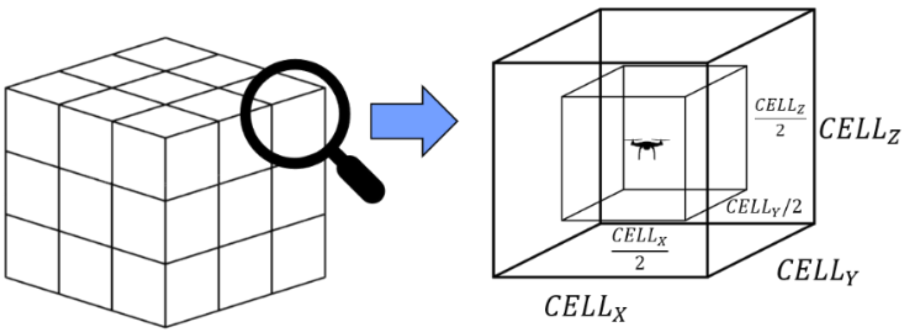
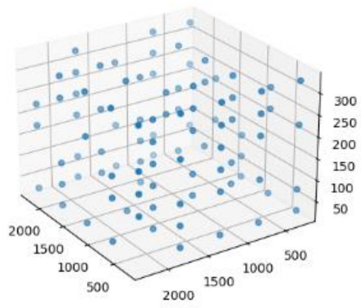


Table 49. Population density map and sheltering factor map

5. **Separation:** It is expected that separation has a beneficial impact in the level of risk since it can reduce the number of unavoidable collisions. For that, the control volume is divided in cells and each UAS is located in one of them at the beginning of the simulations.





6. **Airspace structures:** The goal of introducing airspace structures is being able to accommodate different demands while maintaining a certain level of safety. In DACUS project, several airspace structures have been proposed such as layers, sectors or tubes.

    a. **Layers:** In each of the layers, the direction of flight is restricted

    b. **Buffer:** Vertical separation between layers

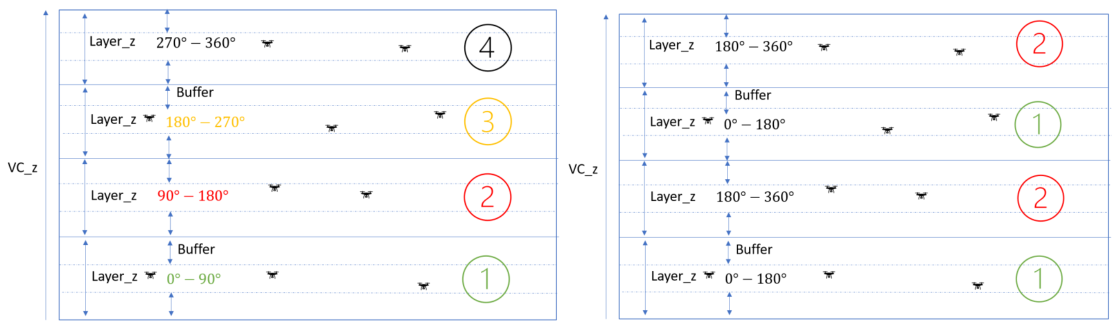


Figure 59. Organization per layers in EXE3

Layers characteristics	
Layer thickness	5 m
	10 m
	25 m
	50 m
Buffer	1 m
	2 m
	3 m

Layers characteristics	
	4 m
	5 m

C.3 Scenarios and results

Since there are several aspects to be tested in this experiment, different scenarios setups must be considered, so the influence of each factor could be analysed independently. By combining the concepts presented before, collision and fatality risk could be estimated in different situations.

C.3.1 Scenario 1.- Collision Risk reduction with U-space Tactical Conflict Resolution service

This scenario compares the total collision risk with and without U-space services. For that, and considering the effect of the update rate, the collision risk in both cases is analysed. Update rate will have an impact on the number of collisions that can be avoided. Note that, for an airspace without U-space services, all the potential collisions are assumed to occur, so the update rate has no effect. However, flying in U-space environment, it will have an impact. In this scenario, it is assumed that all avoidable collisions are detected by the system.

Scenario 1 setup	
Number of aircraft	20 aircraft/km^2
U-space deconfliction	YES/NO
CNS: Update rate	1 s/3 s/5 s
CNS: position accuracy	GPS+SBAS

Table 50. Scenario 1 setup in EXE3

As expected, results for scenario 1 show a much lower collision risk for an environment with U-space deconfliction in place than without in all cases, by a factor of ten (Table 51);the collision risk is constant without U-space system (no effect of the update rate, beyond slight variations which would disappear with a larger number of simulations), but it increases with the update rate when there is U-space in place (as expected).Out of the scenarios which provide deconfliction, as expected, the ones with the highest update rate provide for the lowest collision risk overall.

Update Rate	**Without U-space system (Potential collisions)**	**With U-space (Non-avoidable collisions)**
1 s	3.41E-02	2.86E-03
3 s	3.44E-02	4.68E-03
5 s	3.40E-02	7.60E-03

Table 51. Collision risk (Collisions/Flight Hour) results for 20 UAVs/km2 and GPS+ SBAS scenario.

C.3.2 Scenario 2.- Impact of Navigation accuracy on the Conflict detection rate and the remaining collision risk.

After having established that providing U-space deconfliction with an update rate of one per second yields the lowest overall collision risk, the impact of navigation accuracy on the ability to detect conflicts was tested. This is due to the fact that the position reported by the drone will differ from the real position depending on this accuracy (navigation system error), so part of the avoidable collisions will not be prevented if the U-space service is not able to detect them; the remaining collision risk will be calculated from the sum of the unavoidable collisions and the non-detected avoidable collisions. This means that the navigation accuracy has no effect in the number of potential collisions, but it determines the ability to detect avoidable collisions. Moreover, different conflict margins are also introduced into the assessment.

Scenario 2 setup	
Number of aircraft	20 aircraft/km^2
U-space deconfliction	YES
CNS: Update rate	1 s
CNS: position accuracy	GPS L1/ GPS+SBAS
Conflict margin	3 m/ 5 m/ 10 m

Table 52. Scenario 2 setup

Results show a clear reduction of collision risk for SBAS augmented GPS at lower conflict margins (see Table 53). The lowest overall collision risk was found to be situated between the 5 and 10-meter conflict margin for the GPS+SBAS case. As the margin of conflict increases, the improvement introduced by SBAS is attenuated since most of the conflicts are detected even with the highest error (GPS L1). In the case of the conflict margin, for GPS L1, the greater the conflict margin, the lower the collision risk (more potential collisions detected). With GPS+SBAS, the effect is similar, but a 5m conflict margin is enough to detect most of the potential collisions, so there are no additional gains increasing the margin to 10 m (results for 5 m and 10 m are equivalent).

Conflict margin	**GPS L1**	**GPS+SBAS**
3 m	2.33E-02	1.21E-02
5 m	1.32E-02	3.78E-03
10 m	3.93E-03	3.83E-03

Table 53. Collision risk (Collisions/Flight Hour) results for 20 UAVs/km2 and 1s update rate

Conflict margin	GPS L1	GPS+SBAS
3 m	63%	24%
5 m	26%	2%
10 m	2%	1%

Table 54. Percentage of undetected collisions for 20 UAVs/km2 and 1s update rate

Table 53 and Table 48 show that, as the margin of conflict defined increases, the percentage of undetected collisions drastically decreases. However, as the margin of conflict increases, the number of false conflicts per flight hour also raises exponentially (see Table 55). Therefore, it is necessary to find a trade-off between ability to detect conflicts and efficiency. Based on the results obtained, this could be GPS + SBAS with a margin of conflict of 5m, whereas in cases of drones equipped only with GPS L1, a conflict margin of 10 m would be required, causing therefore many more false conflicts.

Conflict margin	GPS L1	GPS+SBAS
3 m	0.122985401	0.107963504
5 m	0.353832117	0.336255474
10 m	1.46589781	1.46749635

Table 55. False conflicts per flight hour

C.3.3 Scenario 3-Fatality risk and maximum capacity in different overflown cities with and without UTM system.

Scenario 3 setup	
Number of aircraft	20 aircraft/km^2
U-space deconfliction	YES
CNS: Update rate	1 s
CNS: position accuracy	GPS L1/ GPS+SBAS
Environment	Toulouse, Madrid, Toledo

Table 56. Scenario 3 setup

The results presented so far do not depend on the population density since they only consider the risk of collision. However, to set the fatality risk, and subsequently the maximum capacity of an airspace, the characteristics of the overflown area must be considered (population density and sheltering factor).

Environment	GPS L1 1s/5m		
	7 UAS/km2	14 UAS/km 2	21 UAS/km2
Toulouse Outskirts - Industrial	9.3E-06	2.3E-05	4.4E-05
Toulouse Centre	1.4E-05	3.4E-05	6.6E-05
Madrid Centre	9.7E-06	2.4E-05	4.7E-05
Toulouse Outskirts - Residential	3.6E-06	9.1E-06	1.7E-05
Toledo Centre	2.1E-06	5.2E-06	9.9E-06
Toledo Outskirts	1.0E-06	2.5E-06	4.8E-06
Toledo Rural	1.7E-07	4.3E-07	8.3E-07

Environment	GPS SBAS 1s/5m		
	7 UAS/km2	14 UAS/km2	21 UAS/km2
Toulouse Outskirts - Industrial	4.1E-06	1.1E-05	1.3E-05
Toulouse Centre	6.1E-06	1.6E-05	1.9E-05
Madrid Centre	4.3E-06	1.1E-05	1.3E-05
Toulouse Outskirts - Residential	1.6E-06	4.2E-06	5.0E-06
Toledo Centre	9.2E-07	2.4E-06	2.8E-06
Toledo Outskirts	4.4E-07	1.2E-06	1.4E-06
Toledo Rural	7.7E-08	2.0E-07	2.4E-07

Environment	GPS L1 1s/10m		
	7 UAS/km2	14 UAS/km2	21 UAS/km2
Toulouse Outskirts - Industrial	4.1E-06	9.8E-06	1.3E-05
Toulouse Centre	6.1E-06	1.5E-05	2.0E-05
Madrid Centre	4.3E-06	1.0E-05	1.4E-05
Toulouse Outskirts - Residential	1.6E-06	3.8E-06	5.3E-06
Toledo Centre	9.2E-07	2.2E-06	3.0E-06
Toledo Outskirts	4.4E-07	1.1E-06	1.4E-06

Toledo Rural	7.7E-08	1.8E-07	2.5E-07

Environment	GPS SBAS 1s/10m		
	7 UAS/km2	14 UAS/km2	21 UAS/km2
Toulouse Outskirts - Industrial	4.0E-06	8.0E-06	1.2E-05
Toulouse Centre	5.9E-06	1.2E-05	1.8E-05
Madrid Centre	4.2E-06	8.4E-06	1.3E-05
Toulouse Outskirts - Residential	1.6E-06	3.1E-06	4.8E-06
Toledo Centre	8.8E-07	1.8E-06	2.7E-06
Toledo Outskirts	4.3E-07	8.6E-07	1.3E-06
Toledo Rural	7.4E-08	1.5E-07	2.3E-07

Table 57. Overview of fatality risk (fatalities/flight hour) results for different environments, UAV densities and position accuracies.

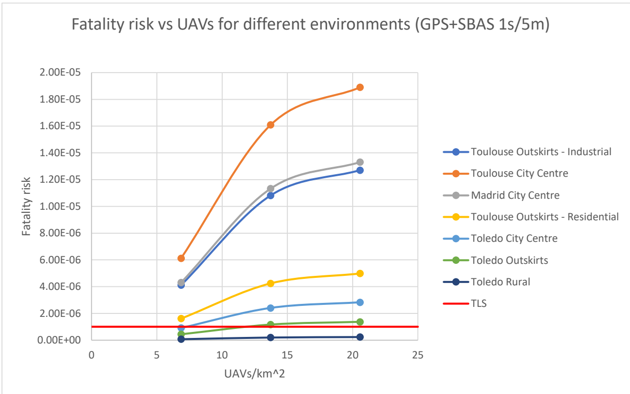


Figure 60. Overview of the fatality risk cause by increasing numbers of UAVs in all environments for the GPS+SBAS 1s/5m scenario.

Moreover, U-space system performance will have an impact on the fatality on the ground and a better performance will allow increasing airspace capacity while maintaining acceptable risk levels. This is shown in Table 57 which presents the fatality risk for the different environments considered, for 5m and 10 m conflict margins and GPS L1 and GPS+SBAS accuracy ranges. The highest performing scenario (GPS+SBAS 1s/5m) is also depicted graphically in Figure 60. Results show that for the methodology applied in this study, the established target level of safety can only be reasonably achieved in low population density environments, lower vehicle densities and high update rates and navigation accuracies.

C.3.4 Scenario 4- Collision risk reduction introducing separation

To evaluate the impact of the initial separation and the time to minimum closing distance on the collision risk, firstly, a fully random scenario is simulated as depicted hereafter in Figure 61 (left). After obtaining the results of the simulations, different initial separations are applied between UAVs to evaluate the impact the initial separation has in the collision risk Figure 61 (right).

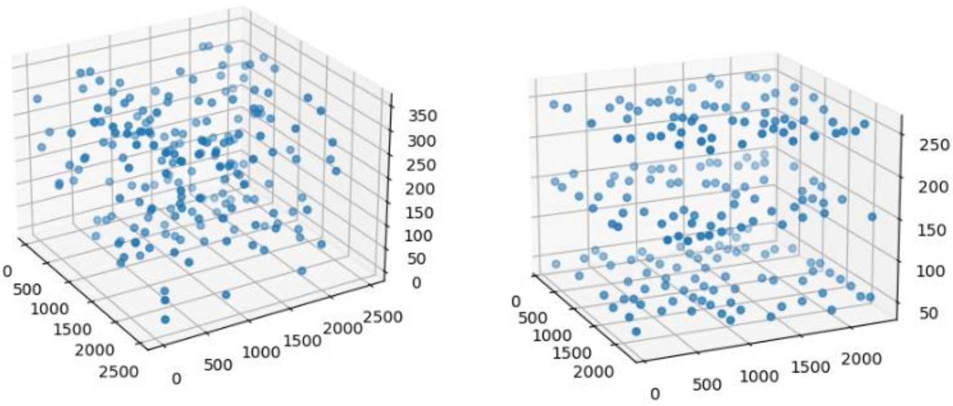


Figure 61. Position of UAVs at t=0 with no separation (left) and with separation (right)

Before continuing with the results and the application of the measurements, some key concepts are introduced:

- **Time to minimum closing time**: It is the time elapsed since the simulation begins until the aircraft are at the point of minimum distance between them. In the

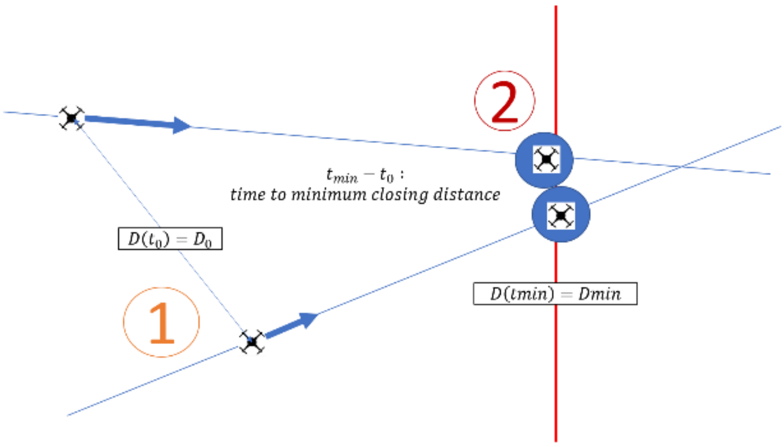


Figure 62. Graphical representation of time to minimum closing point

- **Initial separation:** It is the distance between the UAVs in the beginning of the simulations (t=0).

As part of the process to obtain the required minimum distance, we start simulating a totally random scenario with no separation as depicted in Figure 61 (left), free flight trajectories, within the control volume and number of collisions is obtained. Table 58 presents the inputs considered in these simulations:

	Position (x, y, z)	Speed (v)	Horizontal direction (θ)	Vertical direction (ϕ)	Safety Margin
Without separation	Random	Random up to 25 m/s	Random between 0° and 360°	0°-5°when v<25m/s 5°-90° when v>5m/s	10 m
With separation	Random within cells defined to assure the minimum separation considered				

Table 58: Inputs considered in separation simulations

Next, the results of the simulations are presented for the scenario without separation and with separation. More detailed description of the collision risk model could be found in deliverable D3.2 Capacity Models in support of DCB (Project, 2021).

a) **Without separation**

Once the simulations are run, histograms are generated that allow to know what was the distance at which most of the aircraft which collided were from each other at the beginning of the simulation and how much time (in seconds) it took to get the closest point.

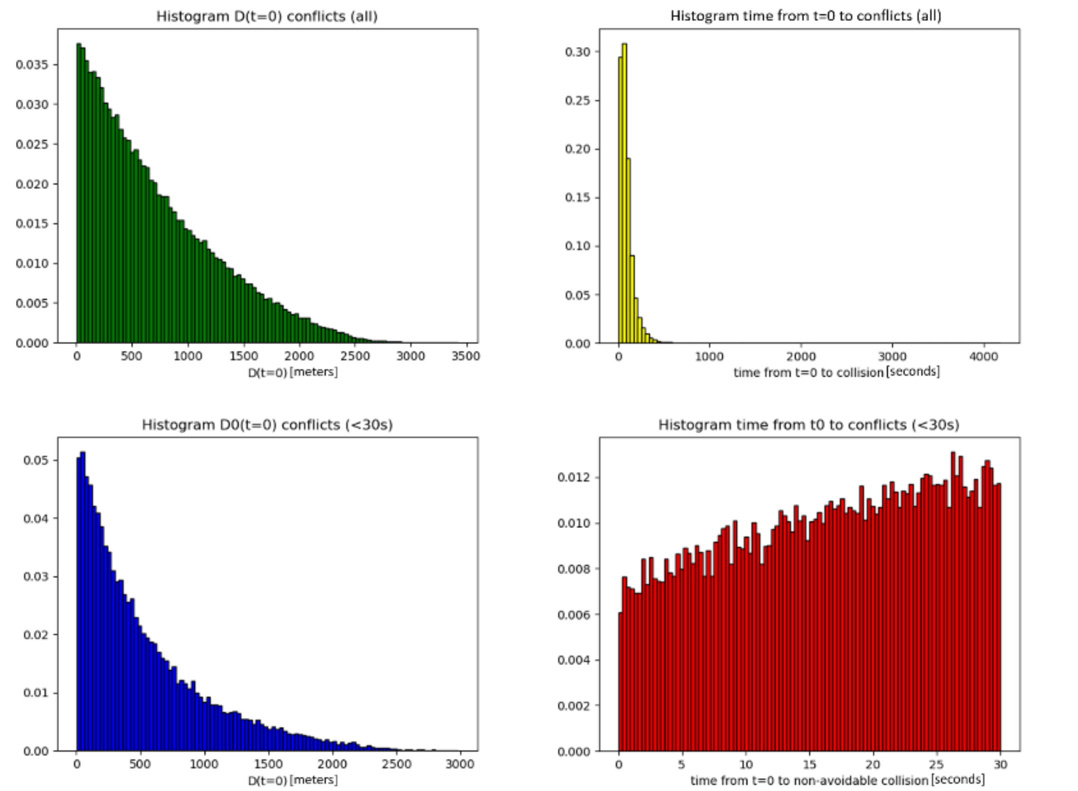


Figure 63. Results without separation

It can be observed that most of the collisions occur in the first seconds of the simulation given that separation is not applied. The objective of setting a minimum separation is to delay them in time so they can be detected and then avoided. In the next section, it is explained the process followed to set the separation and the improvements introduced by it.

b) **With separation**

Hereafter, the process to set the separation is explained and some relevant concepts are introduced. To place the aircraft in the control volume, it is divided in small cells. To set a minimum separation, the dimensions of the control volume are determinant, so the maximum capacity or the minimum separation can be established but not at the same time.

In the simulations carried out, the dimensions of the control volume are:

$$LENGTH_{CV} = 2500\ m$$

$$WIDTH_{CV} = 2500\ m$$

$$HEIGH_{CV} = 2500\ m$$

Therefore, the number of cells in each direction will be:

$$NUM_{CELLSx} = int\left(\frac{LENGTH_{VC}}{CELL_X}\right)$$

$$NUM_{CELLSy} = int\left(\frac{LENGTH_{VC}}{CELL_Y}\right)$$

$$NUM_{CELLSz} = int\left(\frac{HEIGTH_{VC}}{CELL_Z}\right)$$

where $CELL_X, CELL_Y, CELL_Z$ are the dimensions of the cells in each direction.

In case the aircraft are placed in the centre of the cells, the separation will be equal to the dimensions of the cells.

It is evident that the dimensions of the control volume will determine the maximum number of cells that can be placed, it is, the maximum number of aircraft that will be able to keep the minimum separation between them. On the other hand, to emplace a given number of aircraft keeping a determined minimum separation, a certain volume of airspace is needed.

$$NUM_{AC}(CELL_X CELL_Y CELL_Z) = L_{CV}, W_{CV}, H_{CV}$$

Since the objective is keeping the scenarios random, the separation is applied at t=0 but the aircraft can fly in all directions. The process followed to place the aircraft is the following:

- Each aircraft is placed in the centre of a cell so that there is only one aircraft per cell
- Starting from the centre of the cell, the position of aircraft will be a random position within the cube with dimensions: $\frac{CELL_X}{2}\frac{CELL_Y}{2}\frac{CELL_Z}{2}$ so the aircraft are not completely ordered but keeping a minimum distance.

Therefore, the **minimum separation** between the aircraft in direction x, y, z will be:

$$minimum\ SEP_X = \frac{CELL_X}{2}$$

$$minimum\ SEP_Y = \frac{CELL_Y}{2}$$

$$minimum\ SEP_Z = \frac{CELL_Z}{2}$$

Hereafter in Table 59, it is presented the results without separation and with different separations for 100 aircraft and 100000 simulations:

Separation (x,y,z)	**Number of conflicts**	**Number of conflicts in the first 30 seconds**	**Risk of conflict**	**Risk of conflicts in the first 30 seconds**
Without separation	57284	4539	0.15000175	0.011885656
25,25,25	57487	4567	0.15053331	0.011958976
50,50,25	56479	4119	0.1478938	0.01078586
50,50,50	60946	4684	0.15843847	0.012176776
100,100,25	54262	3647	0.14208845	0.009549898
100,100,50	57136	4058	0.1496142	0.010626127
250,250,25	49480	2634	0.12956648	0.006897294
250,250,50	50021	2519	0.13098312	0.006596159
500,500,25	45292	1658	0.11859994	0.004341577
500,500,50	42590	984	0.11152459	0.002576666

Table 59: Conflicts calculated for different separation values

In the table, several trends could be highlighted:

- As the horizontal distance increases, the overall collision risk decreases.
- However, for the same horizontal separation, when vertical separation increases too much, the collision risk increases. The reason is that, as the scenario is defined, horizontal trajectories ($\phi \leq 5°$) are more likely than vertical ones. Therefore, since the vertical separation is enough (provided that the minimum separation is higher than the safety margin), it is preferable to have more flight levels with less vertical separation but less congested.
- The trend presented before is reversed when the horizontal separation increases very much (500 m). This is because, even having less levels, the dimensions of the cells are bigger so there are less overlaps vertically.

After, the results for the best (500 m, 500 m, 50m) and the worst scenario (50 m, 50 m, 50 m) according to the previous table are presented and analysed. The results depicted are the distances between the aircraft which enter in conflict and the time it takes to the conflict are presented. These two outputs are represented for all the potential conflicts and for those which occur within the first 30 seconds. Several things could be appreciated in them:

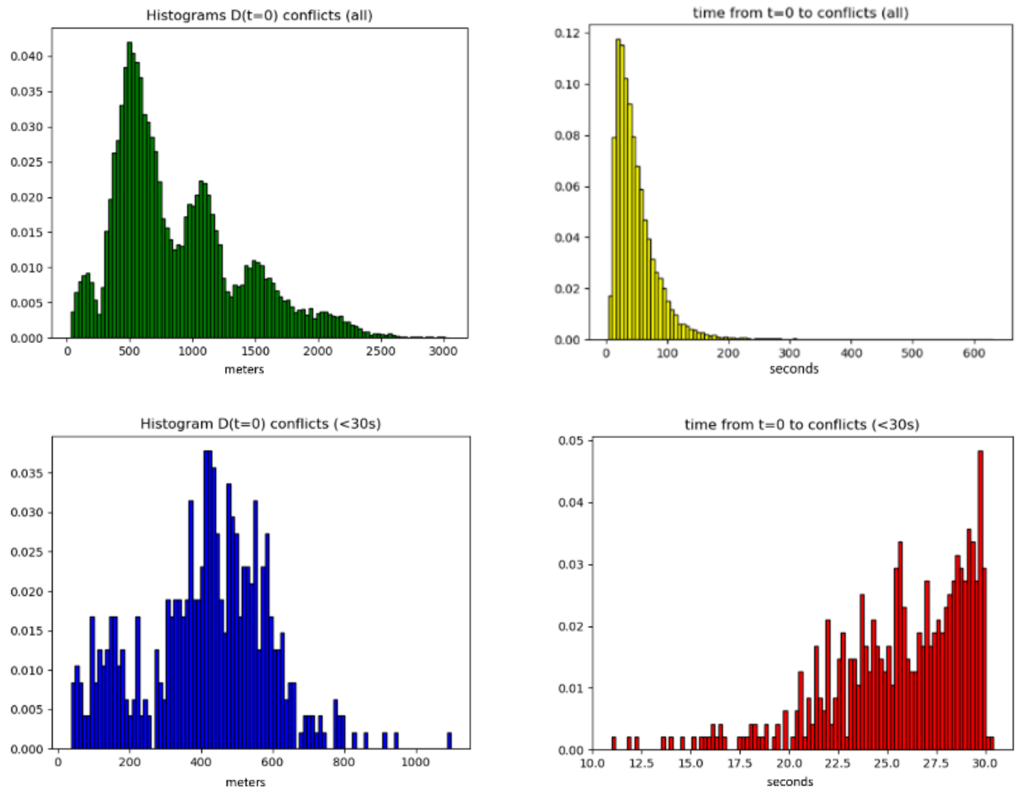


Figure 64. Results with initial separation of 500 m, 500 m and 50 m

Firstly, in the first graph, it is represented the distance at which the aircraft that have a conflict were in the beginning of the simulation. Since the dimensions of the cells were 500m, 500m, 50m, most of the aircraft were at distances multiple of minimum separation. The ones below 500m are these that enter in a conflict in the vertical direction.

Regarding the conflicts which occur before 30 s, most of them occur after 20 seconds, so it is a considerable time to react.

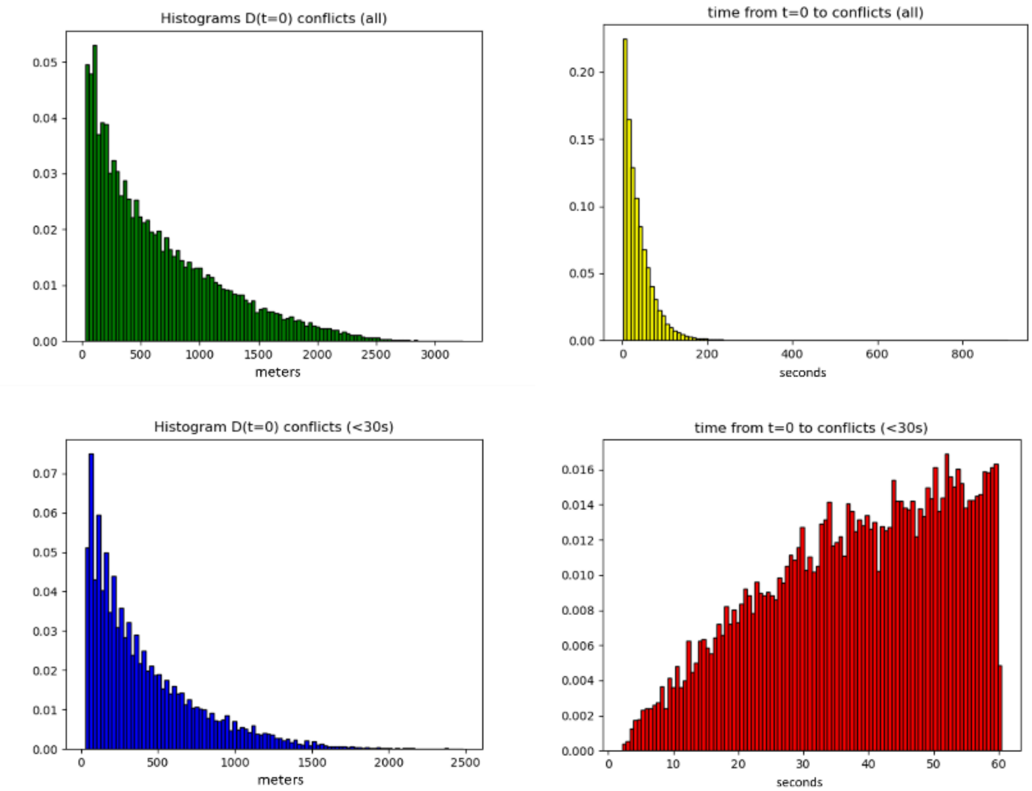


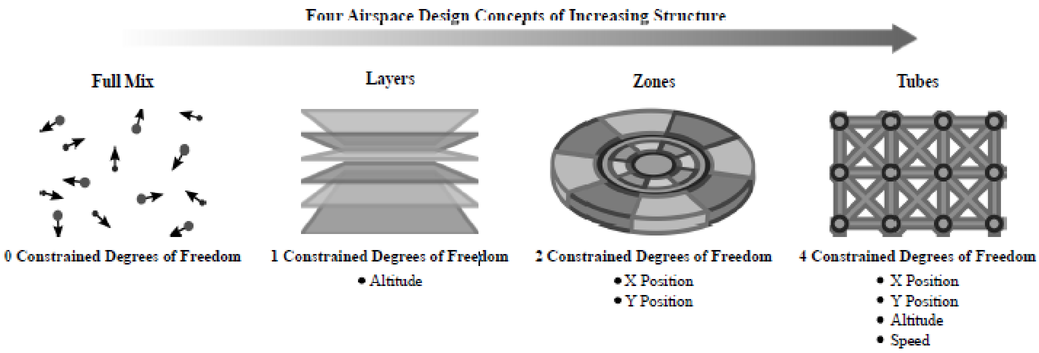
Figure 65. Results with initial separation of 50 m, 50 m and 50 m

It can be observed that these separations are not enough since most of the collisions occur in the first seconds of the simulation. The trend of the graphs is similar to the case without separation.

Additionally, as the acceptable capacity depends on the fatality risk and not directly on the conflict risk, different additional factors, beyond of separation, will have to be analysed to set the separation requirements. Depending on the evolution of these factors in a certain volume of airspace (dynamic population density, drones' size and equipage, CNS degradations), different separation requirements will be necessary to safely absorb the same capacity, so separation will have to be dynamically calculated and applied depending on these factors.

C.3.5 Scenario 5-Collision risk reduction introducing airspace structures

As it is stated before, the aim of introducing airspace structures is trying to accommodate the demand while maintaining an acceptable level of risk. In terms of airspace structures, the layers are the simplest one. Increasing the complexity, there are the structure of sectors and tubes.



There are two configurations for the layered airspace structure:

- **Two types of layers:**
    - Direction 1: $0° - 180°$
    - Direction 2: $180° - 360°$
- **Four types of layers:**
    - Direction 1: $0° - 90°$
    - Direction 2: $90° - 180°$
    - Direction 3: $180° - 270°$
    - Direction 4: $270° - 360°$

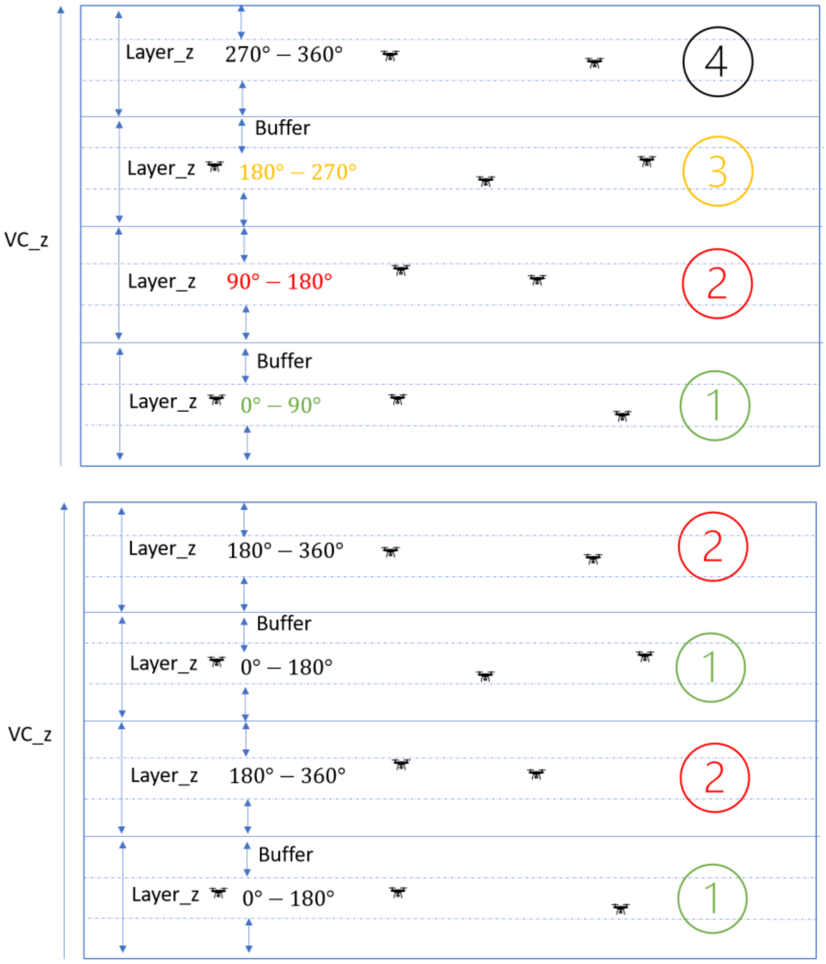


Figure 66. Layers concept

The results for two and four layers are presented below, showing that a 4 layers' structure produces a lower collision risk than a 2 layers' one. They also show that increasing the layer thickness reduces the collision risk, in a linear manner; however, as the thickness increases, a lower buffer is also preferable.

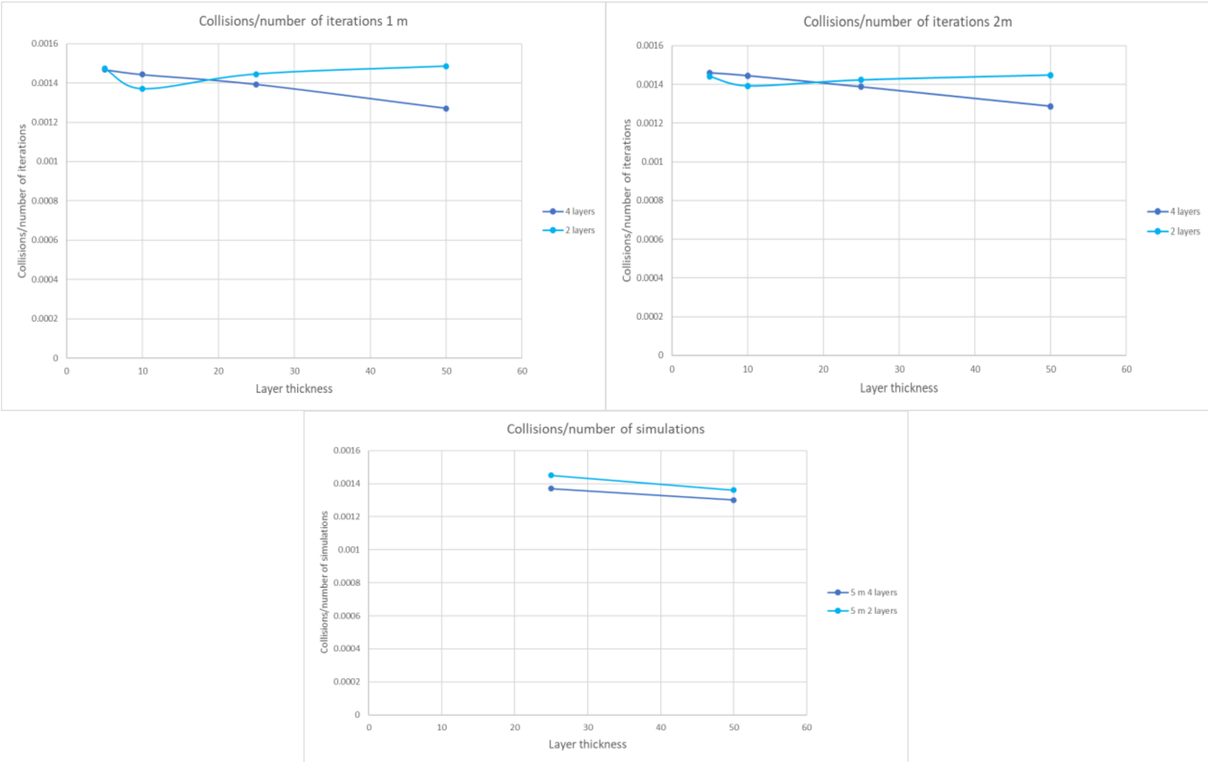


Figure 67. Collisions ratio per Layers' thickness with 2 and 4 layers, for different buffers

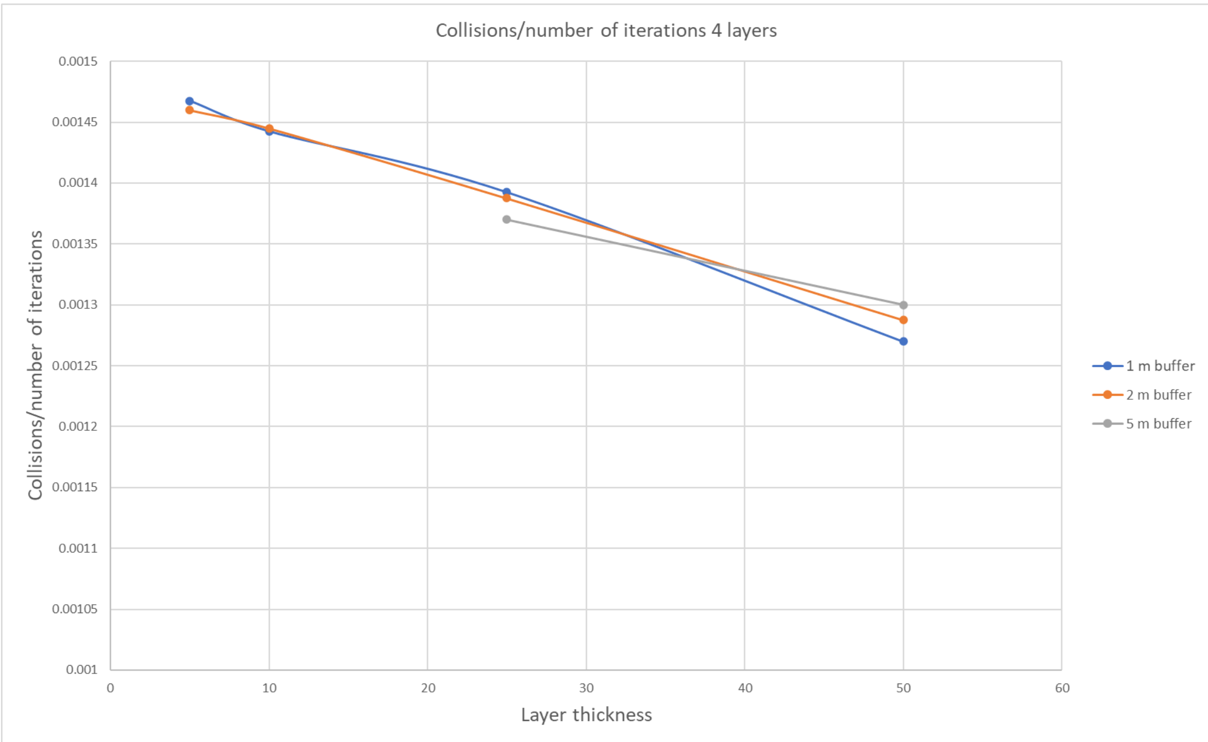


Figure 68. Collisions ratio per Layers' thickness with 4 layers, for different buffers

Finally, the impact of layers on the collision risk with regard to the free-flight environment has been compared for different drones' densities. The results show that as the drone density increases, the layers effect improvement decays, at least for small layer thicknesses

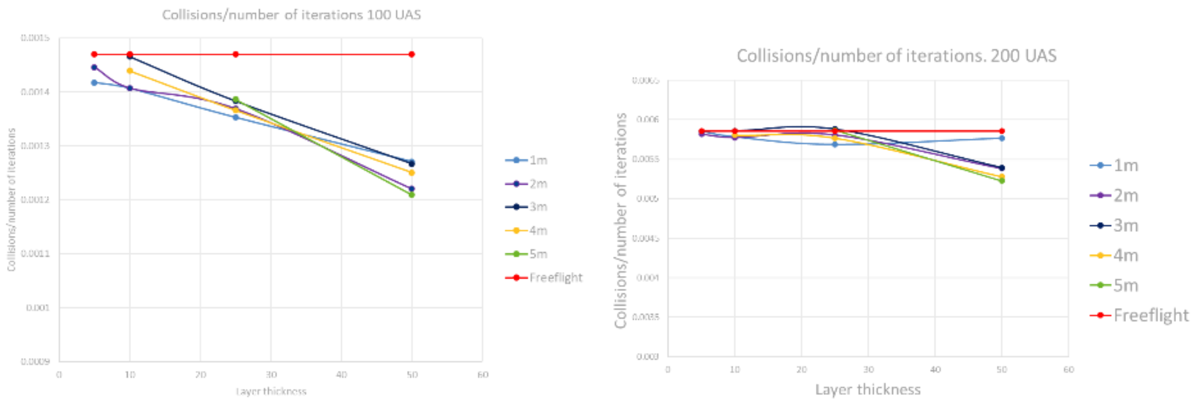


Figure 69. Collisions ratio per Layers' thickness with 4 layers, for different buffers and drones' densities

Additionally, Sectors have been also considered as a potential airspace structure.

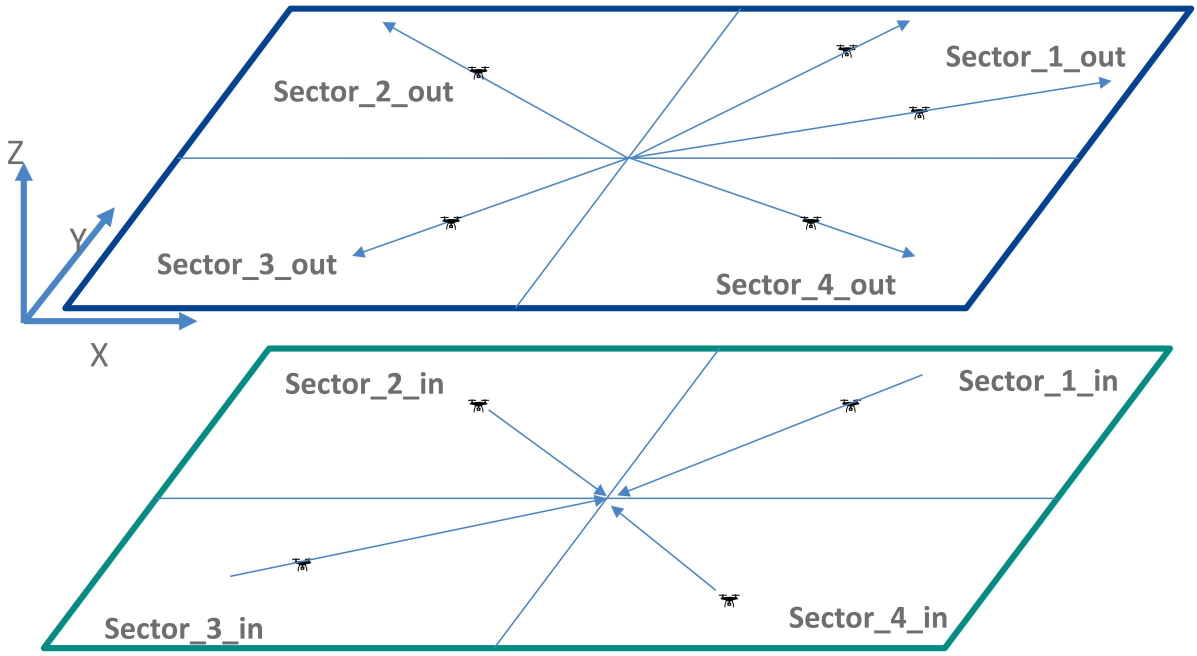


Figure 70. Sectors concept

The analysis considers a combination of layer and sectors: drones would fly in different horizontal sectors, depending on the direction from their origin point to the destination one, and then distributed in vertical layers depending on if their flying inbound or outbound. The results below show that the collision risk does not improve with respect to the 4-layers structure; on the contrary, as the thickness of the layers increases (less layers for inbound and outbound sectors), the collision risk also increases.

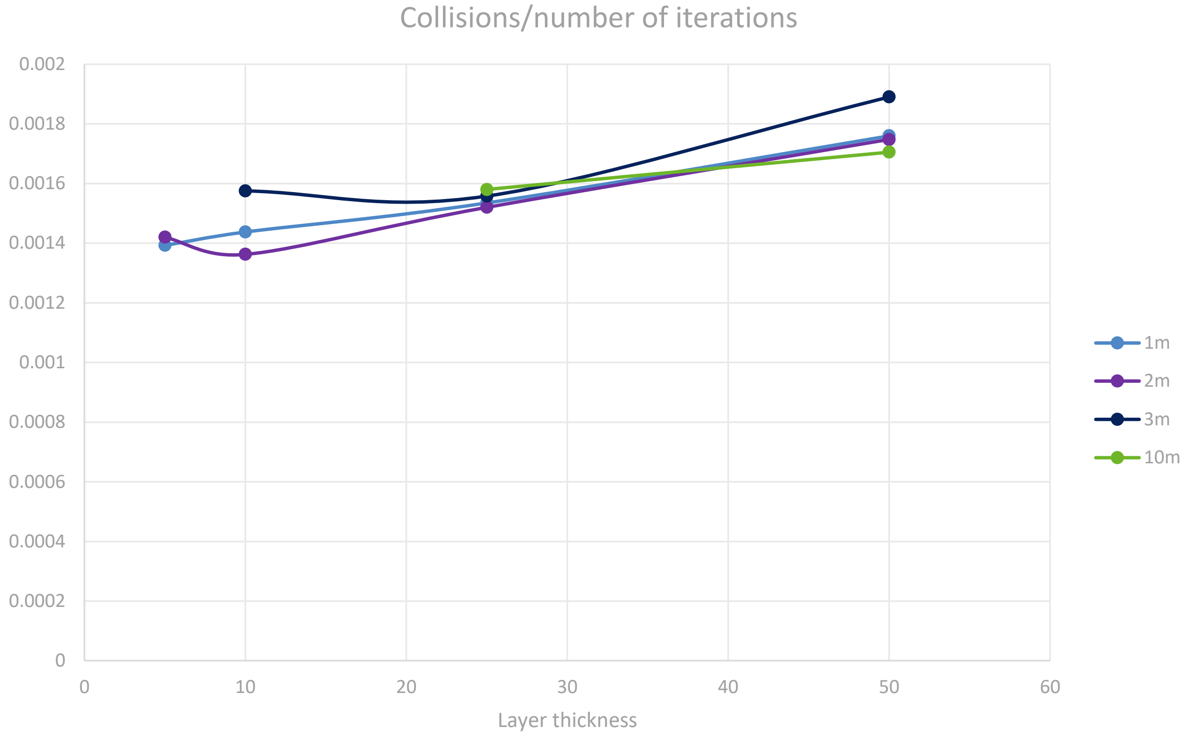


Figure 71. Collisions ratio per Layers' thickness with 4 layers, for different buffers

Appendix D Experiment #4 Detailed Report

This experiment aims to represent the drone traffic in Madrid city that is expected to take place in a typical day of the year 2035 and focuses on the effectiveness of DCB measures in the pre-tactical and tactical phases. The experiment uses the drone Traffic Characterization data that is forecasted in Europe for the horizon 2030-2050 and adapts these predictions to the characteristics of this European city.

A reference scenario is used to provide baseline metrics and hotspot measures using the DACUS DCM services and the RAMS Plus, *droneZone* variant which can model drone operations using a detailed commercial drone performance database with more than 2000 available vehicle types included.

Operations are concentrated within a 30Km x 30Km region covering the main part of the city. Noise, visual and collision risk services are used to analyse the impact of the initial 4D drone Operation plans for all the traffic that is planned to operate in a 24-hour period using 1Km x 1Km grid cells as illustrated in the screenshot below:

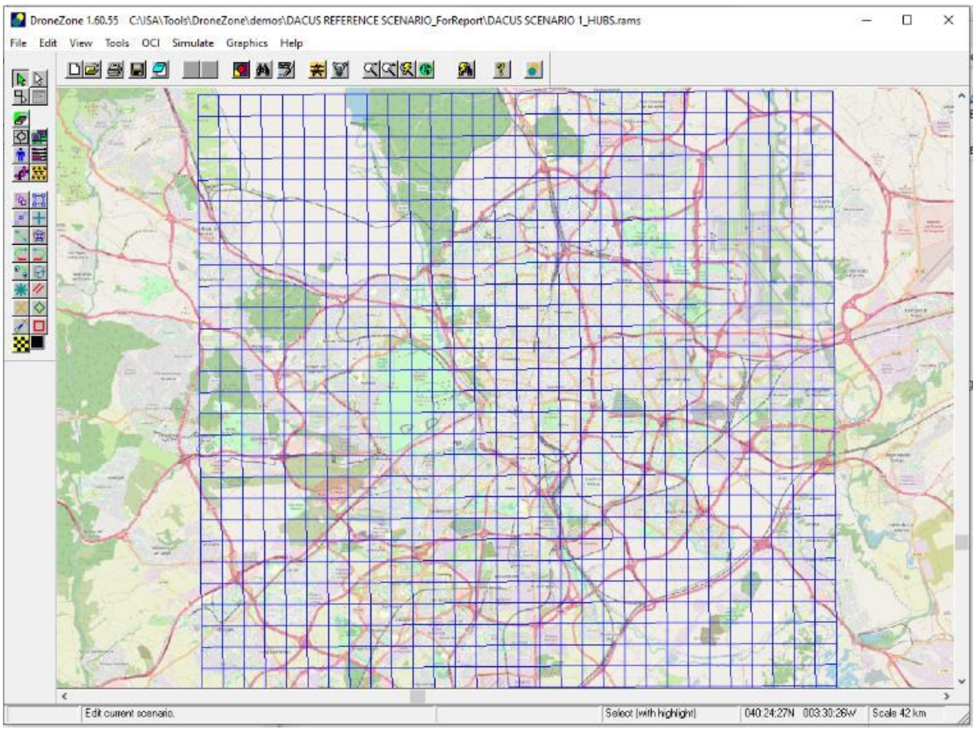


Figure 72: Madrid scenario analysis region

Drone traffic demand scenarios described in section D1.1 below are used to produce a baseline reference scenario and are re-used for each of several variant scenario in which DCB measures are introduced for a selected subset of DOP to help evaluate the effectiveness of those actions and the impacts on KPI related to the planned operations. Those predictions are based on the analysis of road traffic vehicle movement statistics available from the Madrid city council and the Spanish national institute for statistics [12] [13].

Additional surveys on the future urban environment answered by drone operators are also used to assist the traffic demand and mission characterisation, with resulting traffic characteristics for all scenarios being based on:

- A wide range of drone sizes ranging from very small surveillance drones (less than 1m in length and under 2kg weight) to large passenger carrying air taxis (up to 13m in length and 5600kg MTOW). Delivery drones of varying sizes are also included with MTOW up to 18Kg.All missions performed in a free-flight mode where feasible.

- Operations in the Madrid city and its immediate surroundings.

- Large vertiport for passenger/air taxi operations in key locations across the city (and at the airport).

- Multiple take-off and landing pads for drone delivery centres (e.g. Amazon warehouses).

- Variety of drone types and operating characteristics (VTOL, fixed wing …).

- Accurate 4D trajectories based on accurate drone performance characteristics for DOP publication in the pre-tactical planning phase and all phases of flight execution (climb, cruise, delivery, descent).

- Drone operations are conducted in a free-flight/free-route environment where operators are able to file and execute their own preferred trajectories in line with their business or mission objectives. In all scenarios tactical conflicts are identified and resolved based on the assumption that a Tactical Conflict Management service is in place which is optionally supported by on-board detect and avoid (DAA) capabilities.

- Strategic conflict management measures are built into the DCB measures when applicable and all DCB measures are activated dynamically in scenarios according to the time that they are required to solve specific hotspot issues in one or more airspace cells.

D.1 Summary of experiment and objectives

The experiment considers drone missions during pre-tactical and tactical phases and aims to test what happens when DCB measures are applied to regions where hotspots are identified and the impacts on a variety of KPI calculated when those missions are executed.

This experiment is based on the activation of restricted zones (hotspot cells that are affected by high social impact and/or collision risk values) where a subset drones must fly following different rules including:

- Speed controlled zones.
- Increase of operational ceiling (certain hours of the day when most hotspots take place).
- Altitude organization using directional flight layers to traverse hotspot cells.
- Organization using routes (organised per flight layers depending on the courses).
- Delays on ground to reduce hotspot counts.

Also, the experiment analyses the effectiveness of the tactical resolution strategies applied by attitude and type of conflict and determines the number of conflicts that are derived from these resolution manoeuvres.

The architecture followed is in line with the architecture defined in DACUS ConOps [3] and it is focussed on the Strategic, Pre-tactical and Tactical Conflict Resolution service.

The architecture followed is in line with the architecture defined in the DACUS ConOps [3] and it is focussed on the Strategic, Pre-tactical and Tactical Conflict Resolution service.

The objectives of these experiments, defined in the D4.1 Validation Plan document [1] are:

- Assess the effectiveness of DCB measures when unexpected events take place.
- Optimise decision making between on-board capabilities and U-space separation services.
- Evaluate and consolidate metrics in terms of capacity, efficiency, resilience and flexibility.
- Assess the usability of indicators defined in the SESAR U-space companion document for decision-making.
- Evaluate the impact of assigning "virtue points".
- Evaluate the impact of meteorology in drone trajectories.

D.1.1 Reference Scenario

For the Reference Scenario, all drones are executed in accordance with their published operational plans and the DOP generated by the *droneZone* simulator are provided to the DCM service models to determine a baseline set of hotspots using the specified 30x30 analysis grid shown previously in Figure 72.

Population density figures and sheltering factor information is also provided to the DCM service models for each of the analysis grid cells to support the noise, visual impact, and collision risk modelling requirements – which are population based.

To support the DCM process, DOPs are provided to each of the analysis models using the initial planned mission trajectory which is created prior to flight execution by the *droneZone* model using its internal 4D trajectory calculation algorithms and the associated performance data for each drone type.

The DOPs are analysed by the Collision Risk, Noise and Visual models and the resulting hotspots are added to the simulation scenario using the polygon structures capability provided by the FTS tool with the associated temporal details included. As shown in Figure 73 below, the hotspots are concentrated over the centre of the city.

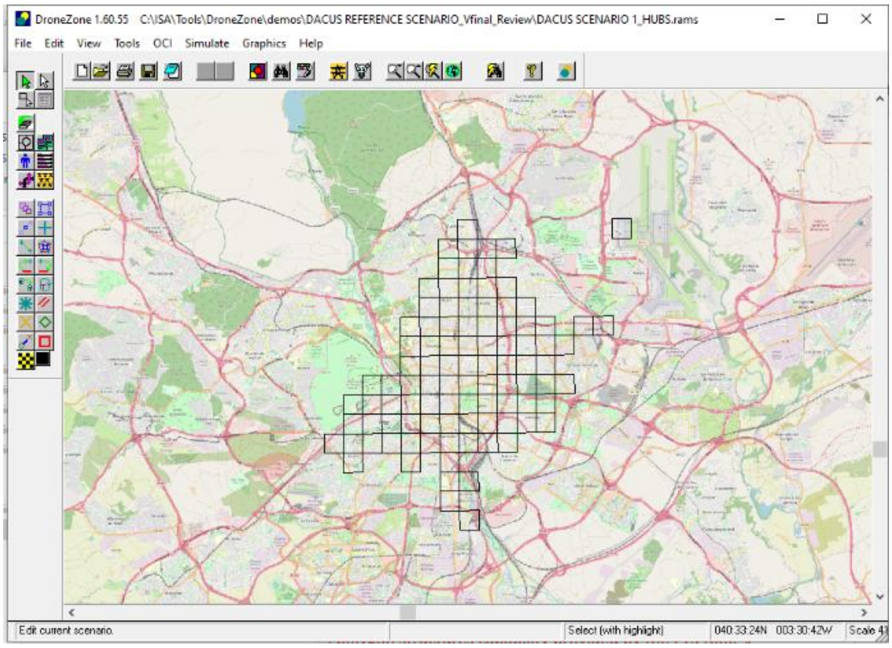


Figure 73: Hotspot cells identified for the reference traffic demand

No DCB actions are applied in the reference scenario, so that all the conflicts that would result from the proposed operations are identified during the simulation exercise and solved when the tactical resolution service is active by the resolution rules provide in the *droneZone* conflict resolution strategy rule tree that is included in the simulation tool.

The following missions are defined (adapted from the drone Traffic characterization):

Mission type	Number of missions	%
Food Delivery	1023	16,05
Emergency	4	0,06
Medicine delivery	396	6,21
Inspection	14	0,22
Aerial photography	32	0,50
Traffic Surveillance	1824	28,63
Events monitoring	2	0,03
Taxi	793	12,45
Package delivery	2284	35,84

Table D1.1: Traffic distribution

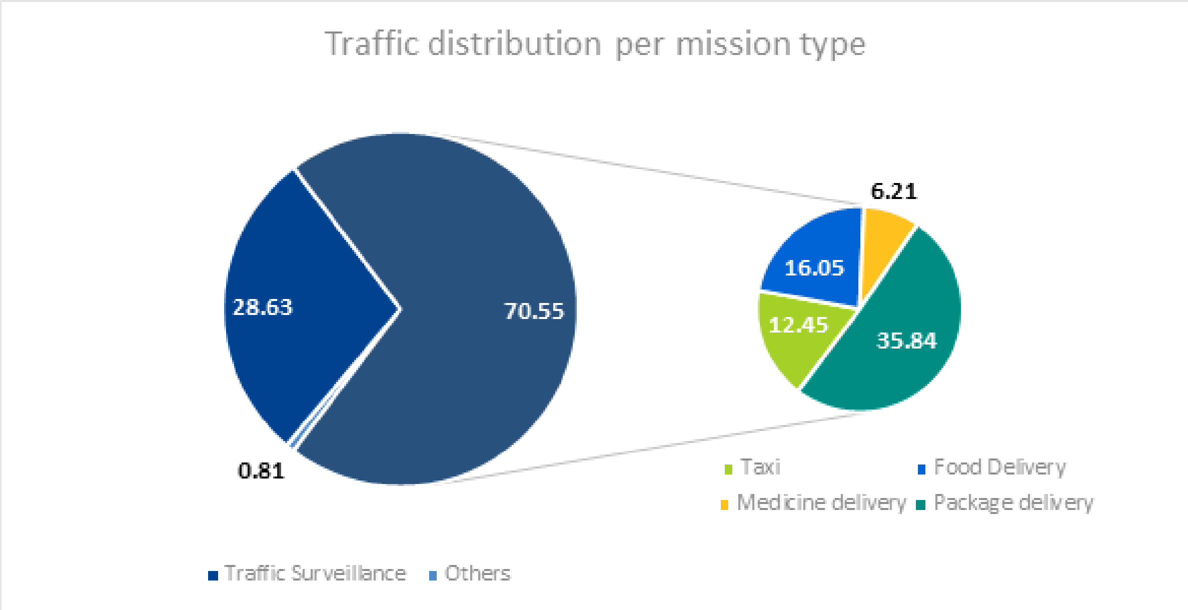


Figure D1.1: Traffic distribution

Food delivery is broken down into three different periods during the day, namely breakfast, lunch and dinner in line with local eating habits in the city. Different restaurant locations have missions based on a variety of statistical samples that are included in the *droneZone* scenario data (see section D2.1 below).

Package deliveries operate from assigned delivery warehouses based on the current locations of the major delivery firms in the city and are scheduled during business hours (07H00 – 22H00). Traffic surveillance missions are located above those parts of the road infrastructure where road traffic issues such as traffic jams occur in the present day.

Other mission types such as building inspections, aerial photography for real estate, security surveillance and sport event filming are included in accordance with locations that might require inspection/photography during daylight hours, and locations where major events take place (e.g. between 20H30 and 24:00 at the Bernabeu stadium for a football match).

Air taxi services, using large multi-copter drones that can transport up to 4 passengers are simulated between major locations in the city and at the airport where large scale vertiports are included in the scenarios.

The following graphic shows the hourly distribution of drone traffic departures over the 24-hour simulation analysis period:

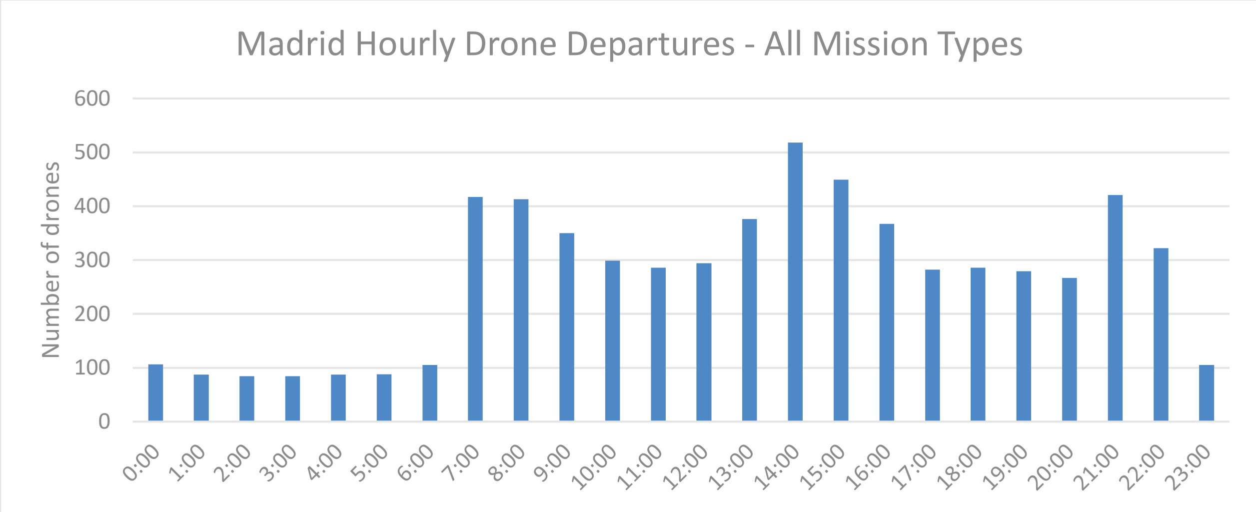


Figure D1.2: Hourly drone Departures

The baseline reference scenario is executed first in conflict detection only mode – to calculate metrics related to the number of unimpeded trajectories that would be flown with no intervention to resolve. Second, the scenario is run in full tactical conflict resolution mode to evaluate how the tactical conflict resolution service can solve airborne separation issues during the execution of the planned missions.

Thereafter each of the variant scenarios is created and DCB rules are added to implement operating restrictions in hotspot areas as described in the following sections.

D.1.2 Speed Controlled Zones

This scenario takes the baseline traffic demand and the identified Collision Risk and Social Impact hotspots due to the planned operations and assigns one hour speed restrictions to each of the zones where a hotspot is identified.

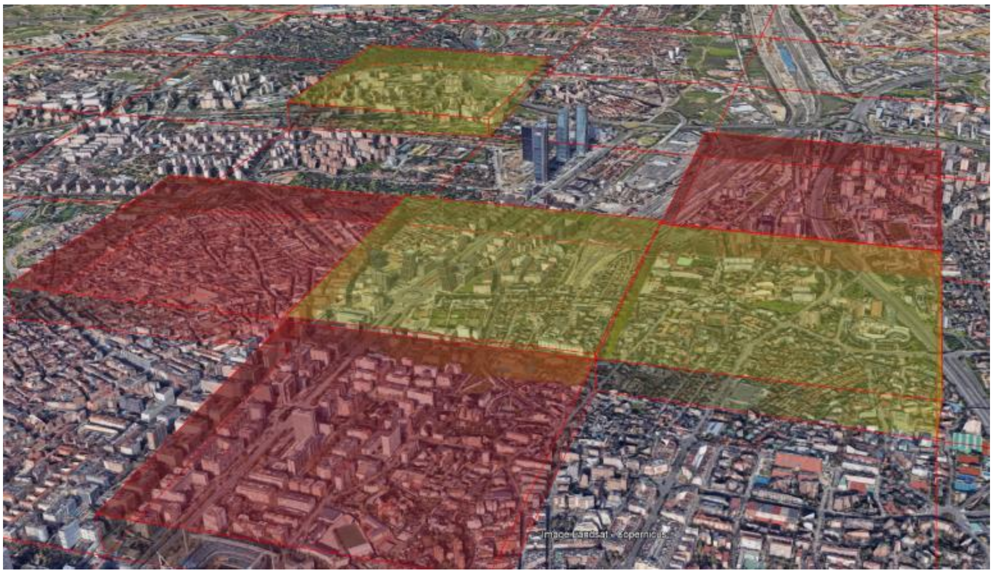


Figure 74: Snapshot of hotspots over Madrid

As shown in the screenshot below, each hotspot cell can be assigned vertical dimensions, a start/end time (when the assessed indicator for Noise, Visual or Collision Risk is above the target threshold), flight criteria that can be used to exclude subsets of traffic from any restrictions that are set for this cell and optional rules that apply for crossing the area.

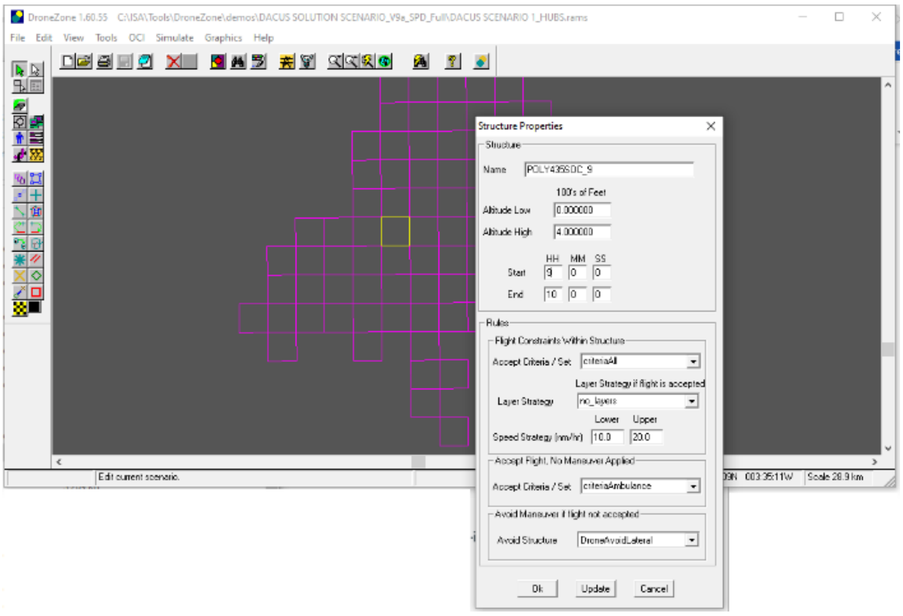


Figure 75: *droneZone* hotspot cell speed control assignment

Data related to the hotspot cell and the DCB rules that are applied to flights that qualify for mitigation actions are as follows:

- Name: Unique name used to identify the polygon cell
- Altitude Low: The lower altitude limit defined for the cell
- Altitude High: The upper altitude limit defined for the cell
- Start: The time that the cell starts to be active in the scenario
- End: The time that the cell stops being active in the scenario
- Rules: The assigned rule or rules that are applicable for flight operations in the cell:
    - Accept Criteria: Criteria to identify the sub-set of flights for which the rules apply.
    - Layer Strategy: Optional layer strategy that applies for flight operations in the cell.
    - Speed Strategy: Optional min and max operating speeds for flights in the cell.
    - Accept flights (No Manoeuvre Applied): Set of excluded flights that operate as planned in the cell.
    - Avoid Manoeuvre: avoidance manoeuvre to use for droned that are not allowed into the cell (options include lateral or vertical avoidance of the cell).

For the speed controlled DCB scenarios, each of the identified hotspot cells (from the DCM services) has been configured with no layer strategy and a minimum of 10 knots and a maximum of 20 knots speed when passing through areas with active hotspot cells. In this way all drones passing through the identified hotspots are required to adapt their current speed to remain within those defined limits. For the speed scenario selected operations (primarily emergency medical / ambulance missions) have been excluded from the constraints and are able to cross hotspot cells as per their original mission plan.

No operations are otherwise excluded so all the missions that were initially planned to pass through any hotspot cells will be subjected to speed constraints if not part of the excluded operation types.

D.1.3 Increase of Operational Ceiling

As DACUS is designed to consider DCM/DCB application in the urban environment, all of the planned missions that are used for the analysis scenarios are expected to take place up to a maximum height of 400 ft (i.e. they operate in the Very Low-Level Airspace, or VLL).

Figure 76: drone missions in the Madrid VLL airspace

When reviewing the baseline reference scenario, the majority of hotspots are identified between specific periods of the day (e.g. between 8 am and 9 pm) so the strategy considered for scenario #3 was to temporarily extend the maximum limit of the VLL airspace up to 1000 ft to allow traffic to operate at higher altitudes during periods when many hotspots were identified.

Figure 77: Madrid drone operations with increased operational ceiling

Increasing the operating ceiling was of particular interest when considering Noise and Visual impact hotspots (labelled as _SOC types in experiment #4) – since initial analysis in experiment #1 indicated that allowing some operations at higher altitudes that planned was able to reduce the societal impacts and reduce the number of hotspots being identified. For this reason, scenario #3 considered the baseline operations with an increase of the operational ceiling up to 1000 ft height for certain traffic during heavy hotspot periods.

D.1.4 Organization per Flight Layers

In scenario #4, a strategic DCB strategy was used which separates traffic in hotspot areas into different vertical layers, depending on the direction of flight for each operation as it crosses the hotspot region.

The initial analysis using directional layers to strategically separate traffic in a hotspot was one of the strategies that was tested as part of Experiment #3, when evaluating the Collision Risk model and potential methods of reducing the risk to remain within the Target Level of Safety (see Annex 3 section C3.3).

As the layer strategy approach used in Experiment #3 (where a set of four directional layers were used and flights were permitted to fly at different levels within the layer associated with the direction of travel) showed promising results in reducing collision risk, the *droneZone* simulator was adapted to include a flexible direction-based layer strategy that can be customised by users for any hotspot cell in a scenario.

As shown previously in Figure 75, for each hotspot polygon cell assigned in the simulation scenario, an optional level strategy can be included which is applied to all flights that match the specified criteria (and are not excluded from the rules of operation in the cell) according to the direction of travel. This is done using the flight level strategy definition in the tool as illustrated in the following figure:

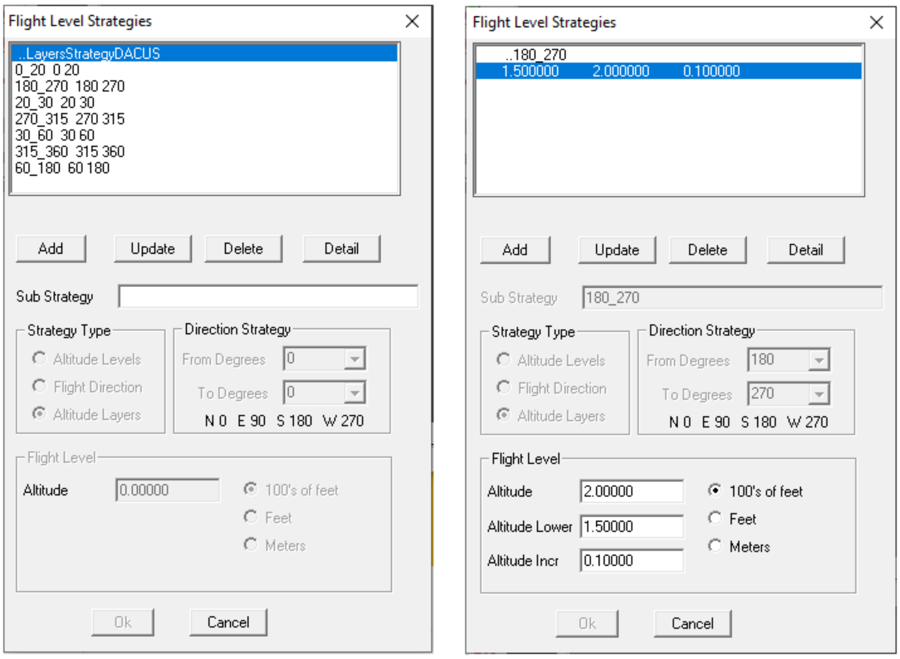


Figure 78: droneZone - setting directional flight level strategies

As illustrated above, directional layers can be assigned between any start and end heading in the simulation tool and cab be associated to one or more hotspot cells using the strategy name. For each directional layer, users can assign the minimum and maximum altitude for the directional layer in that segment within which drones must operate (if included in the assigned sub-set for the hotspot rule).

In addition, the Altitude Increment option (shown in the dialogue on the right above) can be used to assign a series of segregated sub-levels within the min/max altitude range at which traffic is allowed to operate.

If a flight that is subject to the operating rules is planned to cross the hotspot cell travelling in the specified direction, then one of the available altitudes from the min to max and including all available incremental levels will be randomly selected and that operation will be constrained to that altitude while crossing the cell.

Any flight that is planned to cross the cell in the given directional segment and which is already operating at a permitted altitude will not be modified. This includes any flight which was previously restricted in a neighbouring hotspot cell (i.e. the levels will not be modified a second time as long as the travel direction is the same in both cells and the available levels in consecutive cells are consistent).

If the drone flies through the hotspot in one direction, then later flies back through the hotspot in another direction, the level strategy for the second leg will be recalculated according to the new direction being used.

Finally, if a drone is expected to descend or change altitude as part of its flight plan, this is permitted within a level constrained cell (e.g. if a delivery is foreseen within that cell and the drone needs to descend to the ground to make that delivery).

For scenario #4, level constraints when crossing hotspot cells were assigned for a sub-set of the planned traffic. drones performing transport missions (package delivery, food delivery, air taxis and medicine delivery) are constrained to use layers that are between 25 and 50 ft wide (according to the level of traffic in the layer) depending on the heading they fly across the cell(s).

To determine suitable directional segments within which to apply segregated altitudes, the overall breakdown of traffic by direction was used and segments with similar amounts of traffic in them were identified as shown in the table below:

Course (DEG)	Missions (%)	Flight Layer
0<x<20	10,68%	**350-375 ft**
20<x<30	10,64%	**375-400 ft**
30<x<60	12,77%	**300-325 ft**
60<x<180	11,78%	**325-350 ft**
180 < x < 270	18,57%	**150-200 ft**
270<x<315	18,86%	**200-250 ft**
315<x<360	16,69%	**250-300 ft**

Table D1.2: Traffic distribution per courses and layer assignments

drones must operate between the top and bottom of the layer that applies to their direction of travel through the hotspot and may choose any layer in between as long as that level respect the minimum vertical separation defined (usually every 10 feet), depending on the amount of traffic that is crossing the adjacent layers at that moment.

Figure 79: Activation of directional layers in parts of the Madrid airspace

D.1.5 Organization per Routes

As part of experiment #3, the use of a formal route structure or set of 'tubes' was also considered as a method to reduce the collision risk in a region where hotspots were being identified.

To utilise this type of solution in the pre-tactical and tactical execution phase, the simulator tool was further enhanced to allow a grid of routes to be defined along which drones could operate (using a directional shortest path algorithm) to help reduce the impact when operating in free route mode.

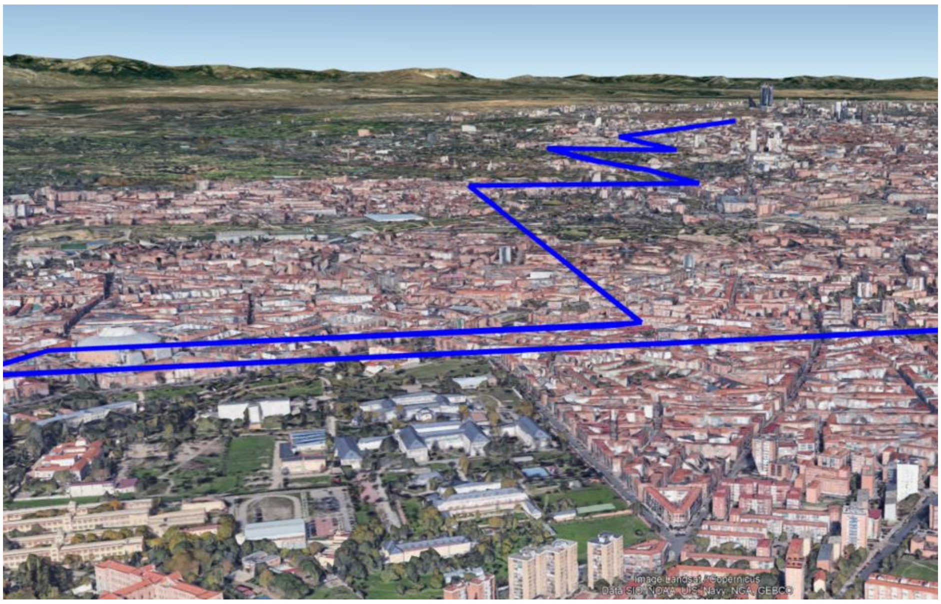


Figure 80: Implementation of route structure in parts of Madrid VLL airspace

Hence in scenario #5, each drone joined a flight layer based on their course and in addition to this, a route grid was defined over those zones where hotspots are identified.

The figure below shows the distribution of grid nodes that were used for the creation of route structures in the scenario, with yellow, orange, and red cells to indicate where the different types of hotspots have been identified:

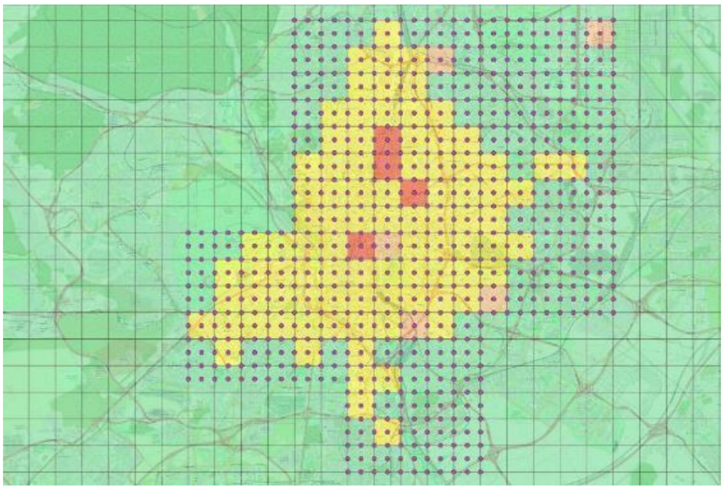


Figure 81: Route grid points assigned in scenario #5

These nodes were assigned to be part of North-South or West-East axis routes in the scenario. Transport missions (such as food and package delivery and air taxis) were then required to join the first navaid/node that was closest to their origin the reach their destination by following the directional route path using the shortest available path.

To determine that path, drones would operate along any available segment connecting one node to another and on which they are permitted to fly, until reaching the node which is closest to their delivery or destination point. Once there, the drone proceeds to the delivery/end point (as illustrated in figure below).

If required, the drone will go back to the grid to complete any return leg that is required – in the opposite sense.

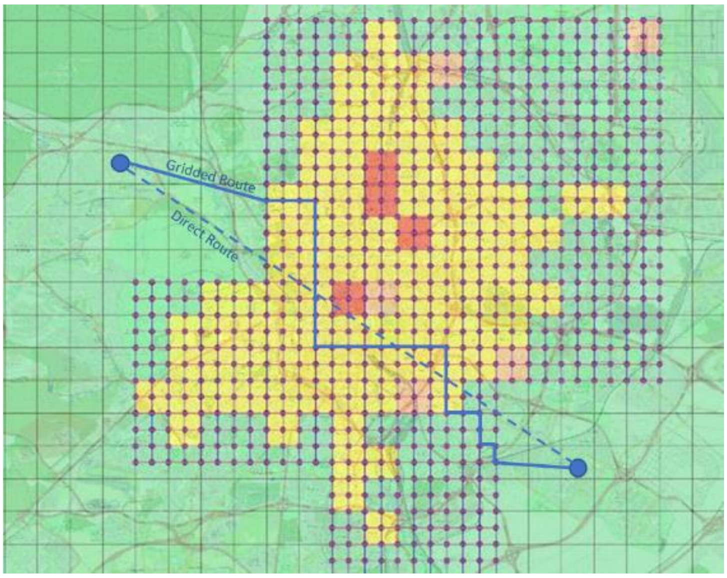


Figure 82: Example of shortest path using route grid points

D.1.6 Delays on Ground

In response to hotspots identified by the DCM service models, scenario #6 investigates a strategy of delaying the departure of a certain number of proposed missions for short periods of time can help to reduce the risks by constraining the number of active flights in hotspot cells during the time that they are active.

This strategy has been tested during the verification of the DCM models in both experiments #1 and #3 with promising results.

Scenario #6 of the DCB simulations therefore extended the use of departure-based mission delays for selected operations to see how the mitigation action could help reduce hotspots in the Madrid region and to assess the impact of this strategy on drone operations.

To determine the amount of delay that may be suitable to assist in the reduction of DCM indicators in hotspot cells, two methods were used – firstly, the variance used in the collision risk model Monte-Carlo simulation analysis is considered, since delaying a mission by a greater value than this variance will remove the vehicle from the pairwise collision risk counts if that delay is greater that the delta being used. Secondly, the typical crossing times for analysis grid cells (which are 1km x 1km in size) can be used since delaying more than the average or median crossing time will shift operations into a different 'set' of flights.

The collision risk model uses a time variance based on a normal distribution with a mean of 0 and a standard deviation of 60 seconds to create random demand trajectories during the Monte-Carlo analysis process.

Typical crossing times for polygons in the core Madrid area range from very small (for taxis) to 4-minutes or greater (specifically for traffic surveillance and other inspection/photography type missions that may hover or remain in the same (x,y) location for some minutes while sending pictures to observers on the ground for example).

As illustrated in the chart below, most operations remain in a single 1km x 1km polygon cell for considerably less than 2-minutes (85.6% of operations).

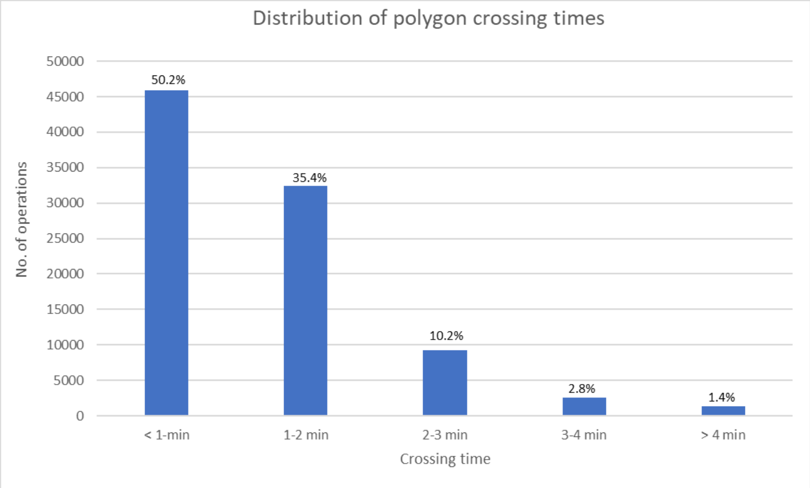


Figure 83: Typical hotspot cell crossing times

For this reason, departure delays were allocated in 'chunks' of 2 minutes as needed (i.e. a 2 min delay, a 4 min delay …etc).

Additionally, to help select candidate operations for which delays may be applied, the additional information provided by the collision risk model in its hotspot results was used:

Consider the following result (summary) for a hotspot identified by the collision risk model:

Timestamp	CxRisk Value	Coordinate X	Coordinate Y	Risk Pairs + Score
16:05:00	1.5105 e^{-6}	40.45652	-3.68803	{ (24, 36): 420, (35, 46): 252, (36, 46): 214, (36, 100): 214, (24, 35): 156, (8, 24): 22, (12, 30): 22, (8, 46): 10 }

This result indicates that there is a collision risk hotspot with a value of 1.5105e^{-6} (where the target TLS is 1e^{-6}) identified at 16:05 in the cell with the centre coordinates provided in the table and with 8 conflict pairs contributing to the risk score.

Each pair is identified using:

droneId1: the id of drone 1 in the conflict pair within the indicated count period.

droneIs2: the id of drone 2 in the conflict pair within the indicated count period.

Score: the number of times in 1000 monte-carlo executions that this pair has conflict.

Hence pairs with higher scores are contributing more to the risk than those with lower scores.

Using this information and calculating the total contribution to risk for each drone gives the following results for the 8 issues identified for this hotspot:

DroneId	Score1	Score2	Score3	Score4	Score5	Score6	Score7	Score8	Total
36	420		214	214					**848**
24	420				156	22			**598**
46		252	214					10	**476**
35		252			156				**408**
100				214					**214**
8						22		10	**32**
12							22		**22**
30							22		**22**
To delay:	**36**	**46**	**36**		**24**		**12**		

Using the total contribution for each drone in the pairs of conflicts reveals that four of them should be delayed:

- From the first pair, drone 36 is selected and allocated a 2-min delay since it has a higher overall contribution to the risk in this hotspot due to potential interactions with other drones (848 compared to 598)
- For score2 drone 46 is selected over drone 35 for the same reason.
- For score 3, both drones have already been delayed by 2 minutes each due to previous scores so an additional delay is required to one of them, otherwise they will continue to have potential interactions and they have not changed with respect to one another – drone 36 is therefore delayed for an additional 2 mins increasing its overall delay to 4 minutes.
- The pair of drones in score 4 includes one drone (36) which has already been delayed (currently 4 mins) and a new drone which has not previously been involved in a conflict. Since drone 36 is already delayed no additional delays are needed for this pair.
- Score 5 involves two drones which have not been delayed, therefore using the drone that contributes most would require a 2-minute delay to drone 24 with a score of 598. This drone was also involved in a previous issue but was not delayed, so adding a new delay may place it back into conflict with the previous drone (drone 36 from score 1). However, since the other drone (36) has already been further delayed (by score 3) to 4-mins, a 2-min delay to drone 24 is not going to put it back in conflict with drone 36 which is currently subject to a 4-min delay so 2-mins delay is applied to drone 24.
- Score 6 involves a drone which was already previously delayed (drone 24) and another which is not currently delayed. Due to the existing delay from the previous pairing no additional delays are required for this pair.
- Score 7 involves two new drones that have not been delayed. Therefore, the highest total contributor is delayed by 2-mins (drone 12 in this case).
- Score 8 involves a drone that is already delayed and one that is not so the existing delay can be maintained to solve this pair and no addition delay is needed.

At the end of processing this hotspot, four drones are delayed for a total of 10 minutes delay being applied.

This process is repeated for all the risk hotspots to assign suitable, but low delays in response to hotspot issues.

D.2 Development of the experiment

For the development of the exercise and the execution of the simulations, the *droneZone* simulation tool is used. This adaptation includes new features that permit the creation of drone mission plans, the polygon structures definition (that includes the strategies for the DCB measures implementation), high-fidelity navigation with separations/altitudes/navigation in feet/meters, use of an extensive catalogue of drone vehicle performance data and the simulation of different types of drones with hi-fidelity 4D modelling.

D.2.1 Scenario preparation and assumptions made

For the scenario preparation, the following points have been considered:

- Movements and vehicle counts at different points of Madrid city to estimate the number of missions in the projected reference scenario.
- Buildings shapes and their coordinates and heights to define cruise flight levels where drones could easily avoid the maximum number of obstacles.
- Meteorological data (this is available and included in scenarios but has not been activated in the analysis scenarios that were eventually performed for the study).
- Food delivery statistics from the main Spanish companies.
- Main locations for different events: sports, outdoor activities, protests, etc.
- Traffic surveillance cameras distribution.
- Locations of logistic centres and pick-up points for package delivery.
- Hospitals and chemists' locations throughout the city.
- Historical and more representative buildings for façade inspection.

For the calculation of the traffic, data has been obtained from the Madrid Council website. Information that has been taken into consideration includes the number of different types of vehicles that are moving at different locations of the city, the times when they cross through a traffic count station (set by the Council to calculate the share of traffic and estimates emissions and noise contours) and the direction of travel.

The times of each type of mission included in the analysis scenarios have been set as following:

Type of mission	Time distribution
Package delivery	From 7am to 10pm
Food delivery	Breakfast: from 8 am to 11am Lunch: from 1 pm to 4pm Dinner: from 8pm to 12am
Air Taxis	24 hours
Medicine delivery	From 7am to 9am and from 3pm to 5pm

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Table D1.3: Time distribution of transport missions

A “busy day” from the year 2019 (before the COVID19 pandemic) has been used to develop the traffic characteristics, in order to have a representative day of traffic in the city. The 17th of February was selected as a suitable date and data was extracted for all the years between 2013 to 2019 to create a historical traffic growth scenario.

Thereafter, data for the year 2035 has been forecasted by using a Holt Exponential Smoothing with Alpha and Beta parameters optimised and the results have been calibrated by means of econometric data (average annual salary and population density and expected growing per area).

For the traffic surveillance missions, traffic cameras’ locations data has been obtained from the *Dirección General de Tráfico* website (the Spanish road traffic authority). To adapt this to drone traffic, a set different surveillance points each located around 1 km apart along the main roads and motorways have been identified. Then each drone is planned to fly a given route over those point (with only one drone operating over each defined point at any time) and multiple missions fly in a synchronized way to the next point (one behind the other) so that every point will be covered by one single drone throughout the surveillance mission time (in this case, one hour duration).

The rest of surveillance type missions (e.g. when a protest or demonstration is taking place), drones are scheduled to repeat the same path in a synchronised manner to ensure that the entire area is covered for the event is which is taking place during the entire event duration.

Inspection missions which cover different sides of the buildings’ façades have a two-hour duration and are scheduled at different times of the day between 8am and 7pm (sunlight hours).

Finally, since not enough data has been found to estimate the number of emergency missions, these have been randomly created throughout the day.

For assigning feasible and obstacles free flight levels to the drone missions, data has been extracted for building information (shape, corners, height, and coordinates) from the Spanish Cadastral database:

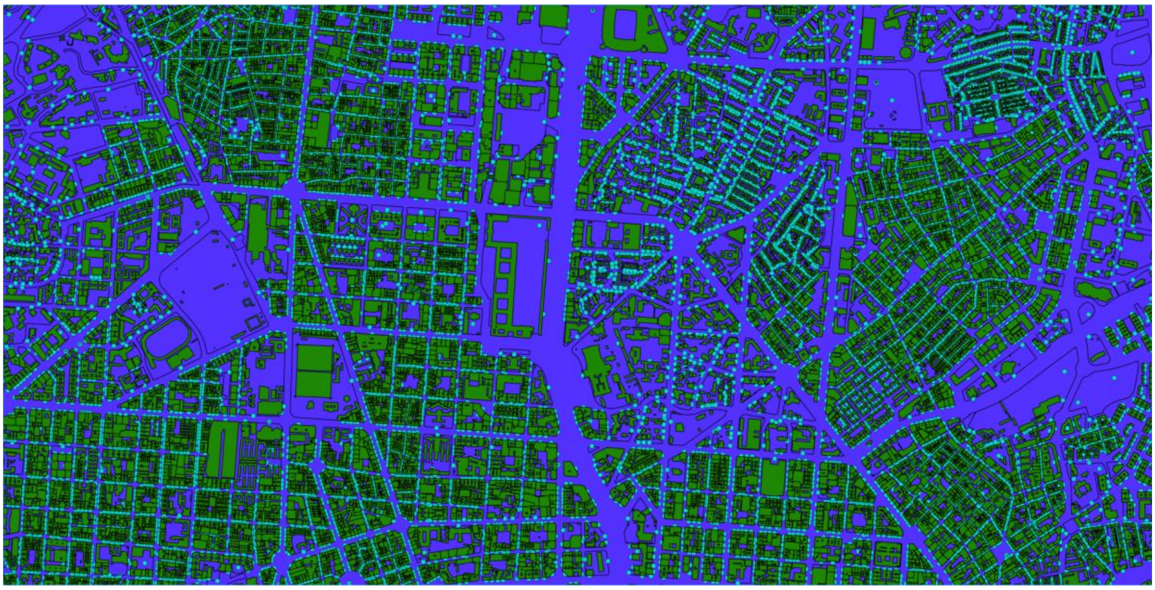

Figure 84: Excerpt of data from Spanish cadastral database

To simplify these geometries, GIS tools have been used to reduce the geometries (combine buildings that share the same location) and delete the holes (courtyards and other types that have no influence in the drone traffic) and a “Simplify” algorithm (that reduces the number of corners in complex geometries) has been executed.

Figure 80.2: Data from Spanish Cadastral database processed with GIS

Once completed. this data has been converted into RAMS data by defining the polygons as 3D restricted volumes as illustrated below:

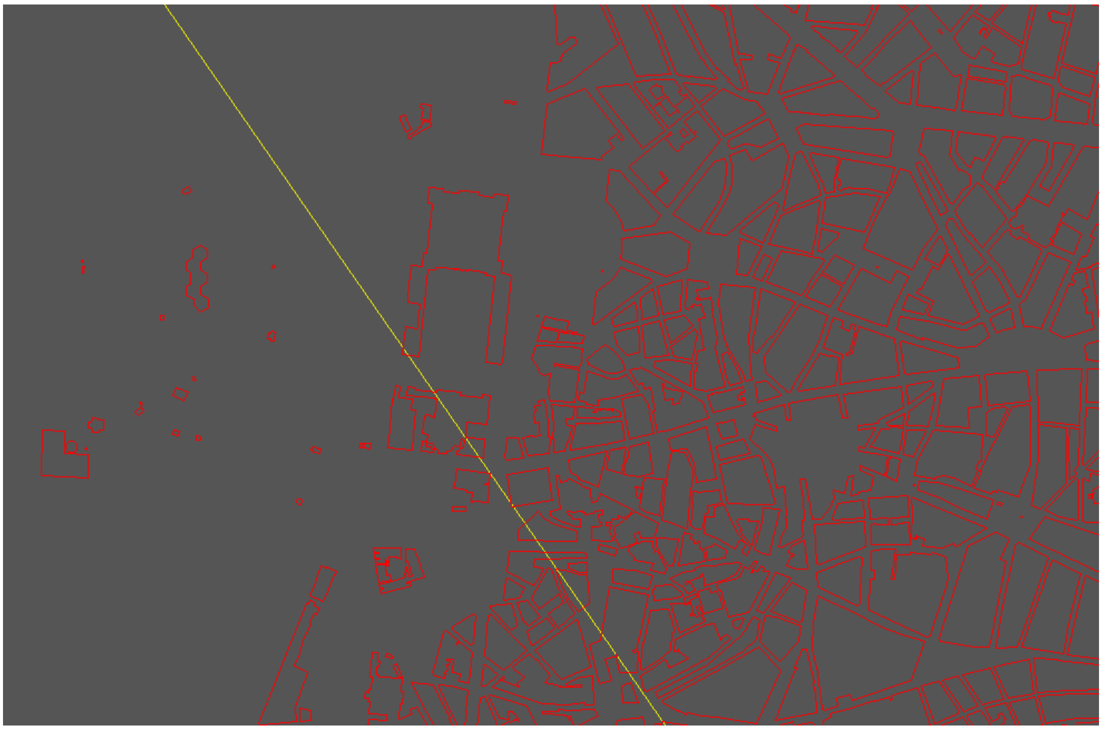

Figure 85: RAMS Plus/*droneZone* with 3D building data included

Finally, multiple landing and take-off areas in the form of vertiports have been added and grouped by sets in the simulator.

Drop points have been defined using navaids in the tool and they have been grouped by types to support randomisation of features such as restaurant locations or delivery drop points.

The operational ceiling has been set up to 400 ft (with the exception of Scenario #3, where an Increase of Operational Ceiling is included).

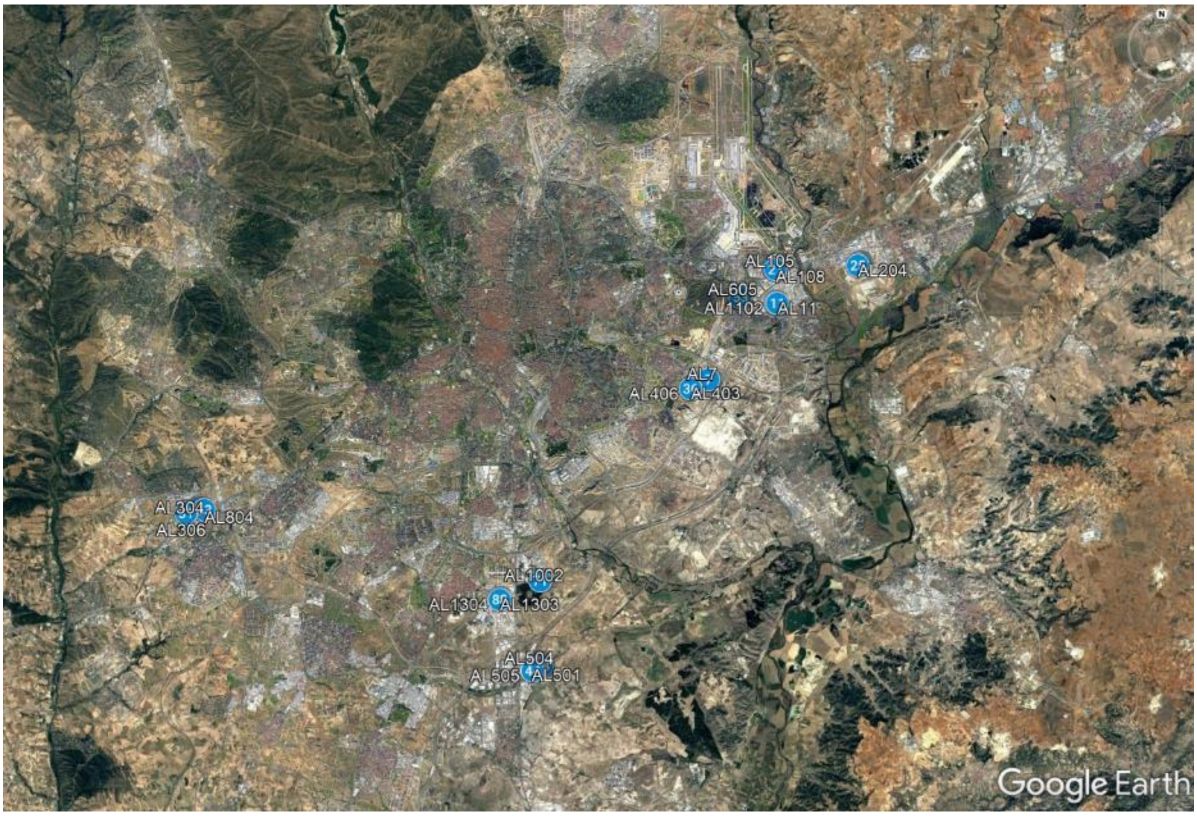

Figure 86: Location of vertiports

D.2.2 Execution of the simulations

As mentioned before in the document, simulations have been prepared and executed in drone Zone UTM Fast Time simulator.

All the missions that are planned and flown have been generated with the UAS Mission Generator tool which offers a great deal of flexibility to the user to create multiple mission profile in accordance with an unlimited set of statistical distributions as illustrated in the screenshot below:

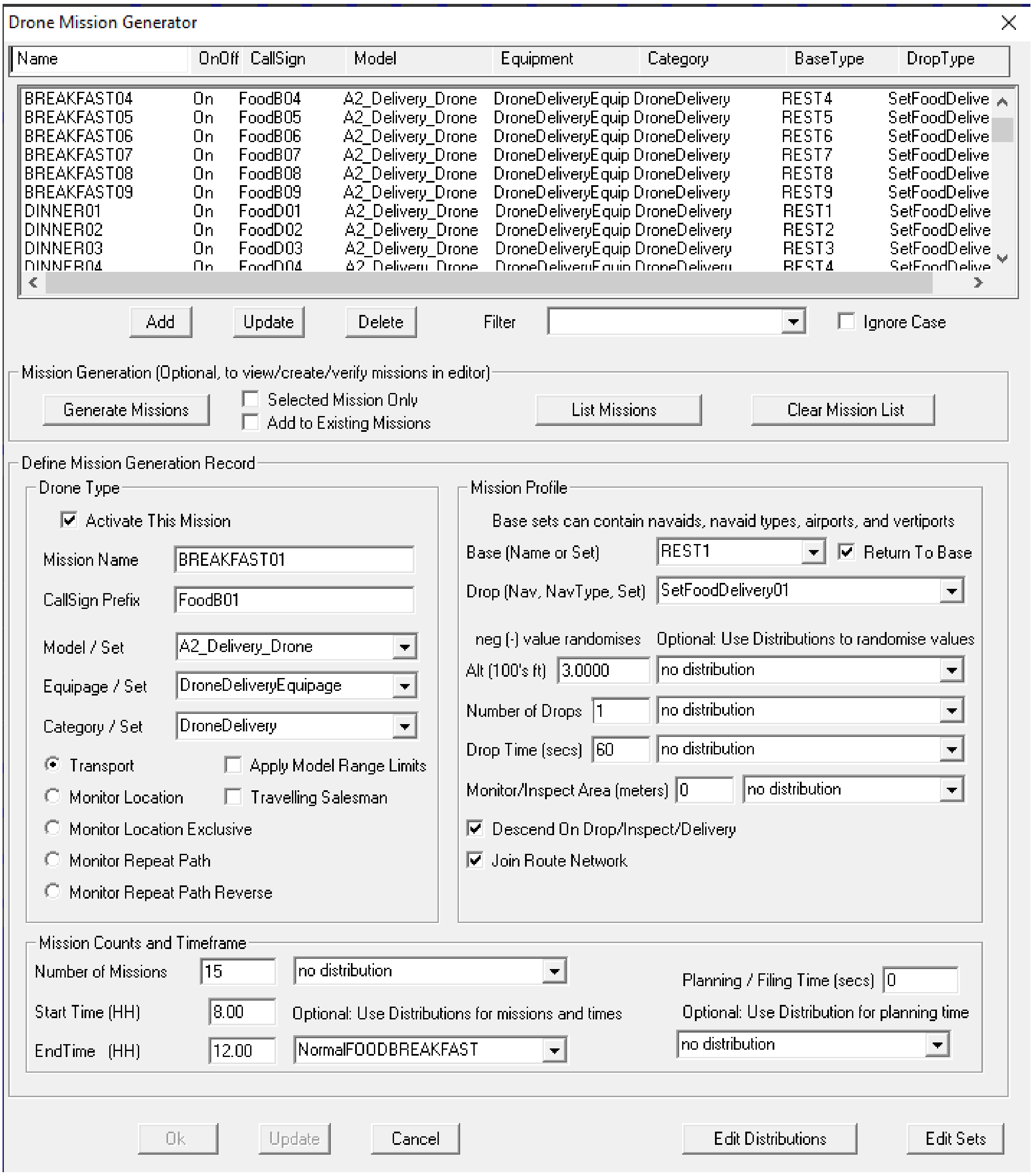

Figure D2.1: UAS Mission Generator Interface

Food delivery, package delivery, medicine delivery, air taxis and emergency missions have been set as transport missions, all of which originate from a vertiport or restaurant location and must descend on their delivery location/vertiport to release their payload.

Traffic surveillance missions have been set as monitor repeat paths (they each fly over an ordered set of points and may optionally loiter to monitor the traffic situation below).

Inspection, aerial photography and recording missions have been set as using a 3D monitoring location within which the drone will fly a random 4D path with regular stops to perform the required inspection operations (The 3D area is defined using a centre point and lateral dimensions to cover that area within which the drone will fly).

The number of missions and their duration have been defined by three different ways:

- Assigning a specific number of missions that will be randomly created during a concrete time period.
- Using Step distributions when the number of missions per hour is known.
- Using Normal distributions when the number of missions in a period is known and there is a peak at central hours.

Once the reference scenario was executed, DCM services have been consulted for the initially planned profiles to help identify cells where hotspots are predicted. For each of these time-based cells, different DCB measures were assigned using polygon structures with associated user supplied actions and rule to apply to candidate traffic wishing to fly through those cells:

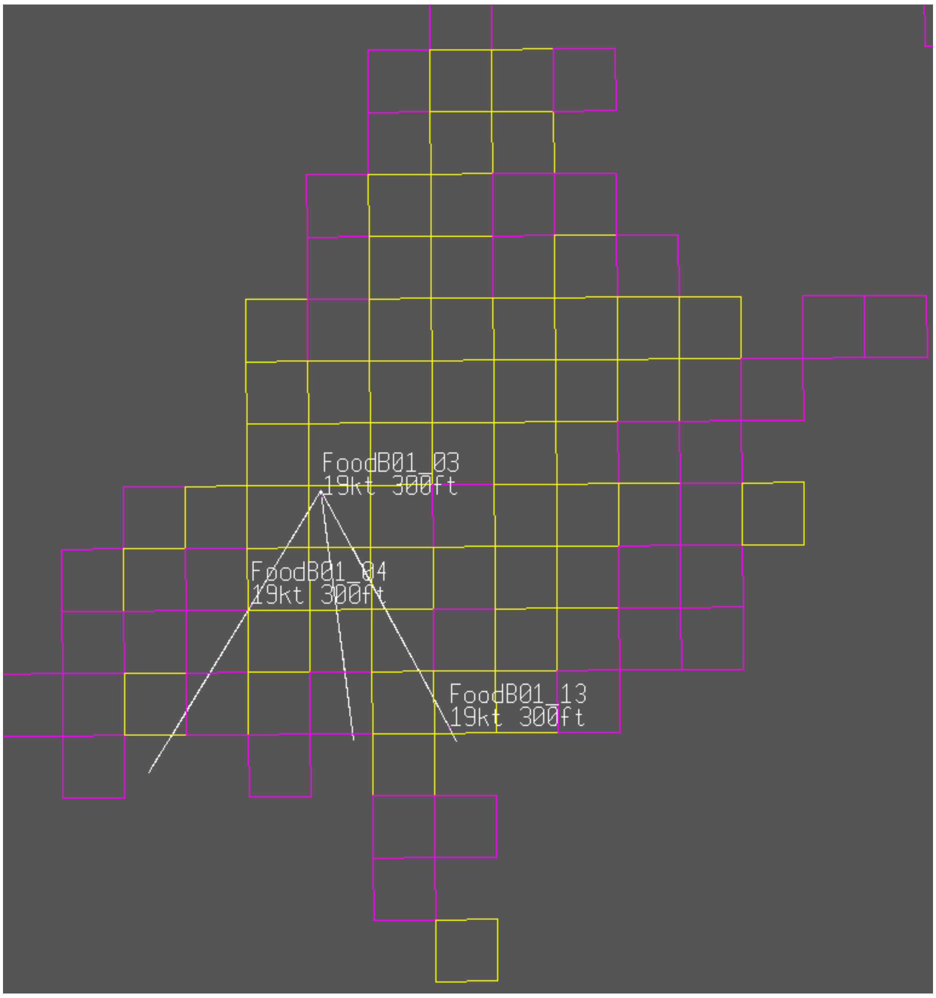

Figure 87: Example of hotspot polygon cells in the *droneZone* simulator

In Scenario #5 where traffic in the scenario is organised using a network of predefined route segments, drones had to follow the route grid to reach their destinations when inside the gridded area:

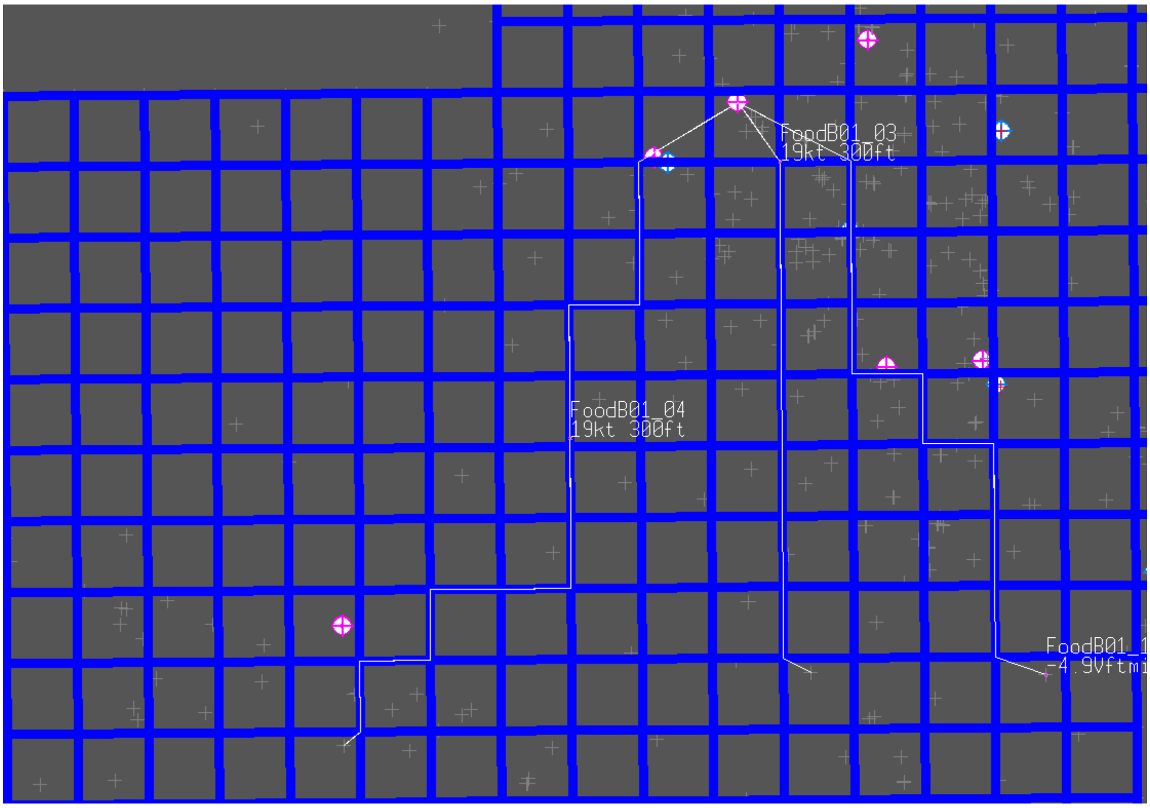

Figure 83.2: Example of the previous traffic organised per routes

Every simulation scenario has been executed both in detection only (the simulator detects conflicts but does not resolve them) and full tactical conflict resolution mode. For resolution mode, the simulator applies the following strategies depending on the type of conflict and (based on the attitudes of the two vehicles during the conflict):

- Hover in the Air.
- Perform lateral avoidance of the other vehicle.
- Perform vertical avoidance of the other vehicle.

If these strategies are not successful, then a drone is required to land (on either the nearest vertiport or by returning to base) and the mission is considered as a “not concluded mission”.

Once simulations are completed, a set of outputs is generated by the program. These output files are assessed using the ATM Analyser tool, which is bundled with the simulator, or using other methods to calculate the metrics for the experiment.

Moreover, these outputs have been used as an input for the Collision Risk and Social Impact models to identify the number of hotspots that have been generated in each scenario based on the predicted/recorded initial profiles for each operation.

D.2.3 Metrics definition and deviations from VALP

To test the effectiveness of the DCB measures, different metrics have been defined in terms of ***capacity***, ***efficiency***, ***resilience,*** and ***flexibility***. Most of these have been extracted from the DACUS D5.3 Performance Framework document and PJ19 ATM Performance Framework SESAR project and the methods used to calculate each of them are described below:

Capacity metrics

- **drone base throughput, in challenging airspace, per hour.** Defined as the hourly average number of drones that are departing or arriving to vertiports located in zones where hotspots have been identified.
- **Flying drones throughput, in challenging airspace, per hour.** The hourly average number of drones that are flying through hotspot zones.
- **Peak arrival throughput in drone bases.** The hourly maximum number of drones arriving to a vertiport.
- **Peak departure throughput in drone bases.** The hourly maximum number of drones departing from a vertiport.
- **Re-scheduled traffic reduction.** The difference between the number of delayed on ground or cancelled flights in the reference and various solution scenarios.
- **Number of hotspots.** The total number of hotspots that have been detected by the Collision Risk and Social Impact models.
- **Number of conflicts derived from other conflicts' resolution.** The number of conflicts that have been created between drones due to the conflict resolution strategy applied to resolve a previous conflict.
- **Number of Close Aircraft.** Number of aircraft that are at risk of collision (one of them could have time to do an avoidance manoeuvre) calculated as follows:

$$CAP3 = \frac{Number\ of\ aircraft\ at\ risk}{Total\ number\ of\ aircraft} * 100$$

- **Percentage of time doing avoidance manoeuvres.** Average for all aircraft in an area of the time doing avoidance manoeuvres calculated as follows:

$$CAP4 = \frac{Total\ time\ doing\ manoeuvres}{Total\ time\ in\ the\ scenario} * 100$$

- **Number of severe intrusions.** Number of aircraft that are at risk of collision without the possibility of doing an avoidance manoeuvre calculated as follows:

$$CAP5 = \frac{Number\ of\ aircraft\ at\ risk\ of\ severe\ intrusions}{Total\ number\ of\ aircraft} * 100$$

Resilience and Flexibility metrics

- **Average delay.** Difference between the actual arrival time and the scheduled arrival time, in average:

$$FLX1 = \frac{\sum_{i=1}^{N} Real\ Arrival\ Time(i)\ -\ Estimated\ Arrival\ Time(i)}{N}$$

- **Requirements respected.** Percentage of user mission requirements for flexibility respected:

$$FLX3 = (Total\ requirements\ -\ Unrespected\ requirements) * 100$$

- **Number of restrictions.** Number of restrictions on flight with mission plan changes or mission plan submission after RTTA (*Not used in the final analysis*).
- **Delayed flights > 3 min.** Number of flights that present a delay higher than 3 minutes.
- **Loss of airspace capacity avoided.** It has been defined as the difference between the percentage of demand not satisfied in reference scenario and the one not satisfied in solution scenarios.
- **Loss of drone base capacity avoided.** It has been defined as the difference between the percentage of demand not satisfied in a vertiport in reference scenario and the one not satisfied in solution scenarios.

Efficiency metrics

- **Horizontal drone Operation Efficiency.** Difference between the number of metres flown horizontally in the submitted Operation Plan and the metres that will be flown when a DCB measure is implemented:

$$EFF1 = \frac{Number\ of\ real\ flown\ meters - Number\ of\ flown\ meters\ in\ the\ Operational\ Plan}{Number\ of\ flown\ meters\ in\ the\ Operational\ Plan} * 100$$

- **Vertical drone Operation Efficiency.** Difference between the number of metres climbed in the submitted Operation Plan and the metres that will be climbed when a DCB measure is implemented:

$$EFF2 = \frac{Number\ of\ real\ flown\ meters - Number\ of\ flown\ meters\ in\ the\ Operational\ Plan}{Number\ of\ flown\ meters\ in\ the\ Operational\ Plan} * 100$$

- **Elapsed time airborne.** Difference between duration of the flight in the submitted Operation Plan and the duration when a DCB measure is implemented:

$$EFF3 = \frac{Real\ duration\ of\ the\ flight - Duration\ \ of\ the\ flight\ in\ the\ Operational\ Plan}{Duration\ of\ the\ flight\ in\ the\ Operational\ Plan} * 100$$

- **Arrival time.** Difference between the arrival time in the submitted Operation Plan and the arrival time when a DCB measure is implemented:

$$EFF4 = \frac{Real\ time\ of\ arrival - Arrival\ time\ in\ the\ Operational\ Plan}{Arrival\ time\ in\ the\ Operational\ Plan} * 100$$

- **Number of batteries consumed.** Number of batteries required to complete all missions based on drone models' autonomy. This metric is represented as a percentage of the increment with respect to the reference scenario.

- **Energy required.** Energy required to charge the batteries with the purpose of complete all the missions, expressed in kW. This metric is represented as a percentage of the increment with respect to the reference scenario.

Deviations from the Validation Plan

When designing and executing simulations, some of the objectives previously defined have been modified from VALP and/or assigned a new ID to allow them to be assessed in a more realistic way using the results from the simulations. Additionally, some of the scenarios that were defined in VALP document had to be adapted compared to what was planned to be measured in this experiment.

For this reason, some scenarios have not been able to be considered and their related objectives have not been achieved.

Objective in VALP	Objective in Experiment	Reason
EXP4-OBJ1.- Assess the effectiveness of DCB measures when unexpected events take place in the tactical phase.	**EXP4-OBJ1 NEW**.- Assess the effectiveness of DCB measures when unexpected events take place in the tactical phase.	Not covered in the final exercises
EXP4-OBJ2.- Optimise decision making between on-board capabilities and U-space separation services.	Covered in other experiments	Separation management and CNS capabilities has been studied inD5.2 [11]. Testing of CNS capabilities has been performed as part of Experiment #3 and is implicit in the collision risk model consulted in experiment #4 DOP to identify hotspots.
EXP4-OBJ3.- Evaluate and consolidate metrics in terms of capacity to determine the maximum number of UAS operations.	**EXP4-OBJ2 NEW.-** Comparison between the hotspots identified by each capacity metric and relevance.	The number of UAS operations has kept constant in each of the scenarios. This has been done to test the effectiveness of each DCB measure in terms of capacity.
EXP4-OBJ4.- Evaluate and consolidate metrics in terms of efficiency to determine the maximum number of UAS operations.	**EXP4-OBJ4 NEW.-** Analysis of efficiency metrics and relevance	The number of UAS operations has kept constant in each of the scenarios to allow testing of the effectiveness of each DCB measure in terms of efficiency.
EXP4-OBJ5.- Evaluate and consolidate metrics in terms of resilience and flexibility to determine the maximum number of UAS operations.	**EXP4-OBJ5 NEW.-** Feasibility of implementing resilience and flexibility metrics in DCB.	The number of UAS operations has kept constant in each of the scenarios to allow testing of the effectiveness of each DCB measure in terms of resilience and flexibility.

EXP4-OBJ6.- Evaluate how DCB measures act in scenario #3.	**EXP4-OBJ3 NEW.-** Comparison between the hotspots identified by the models in each scenario	Simulations have been focused on Scenario #3 and this scenario has been divided into 5 new scenarios (the ones defined in D.1 section).
EXP4-OBJ7.- Evaluate the effectiveness of the DCB measures in scenario #3.	**EXP4-OBJ3 NEW.-** Comparison between the hotspots identified by the models in each scenario	Simulations have been focused on Scenario #3 and this scenario has been divided into 5 new scenarios (the ones defined in D.1 section).
EXP4-OBJ8.- Determine which DCB measures are better in scenario #3.	**EXP4-OBJ6 NEW.-** Comparison between DCB measures, effectiveness and applicability.	-
EXP4-OBJ9.- Evaluate the possibility to assign "virtue points" to specific drones in order to prioritize their operations within the DCB process.	Not included in the final exercises	Due to some limitations in the way of assigning virtue points, it has not been feasible to address this objective in the experiment. It is expected to be tested in future projects by taking into account new variables such as environmental impact and safety requirements compliance in drone operations.
EXP4-OBJ10.- Evaluate the impact of assigning virtue points in the DCB process in terms of capacity, effectiveness and resilience.	Not included in the final exercises	Due to some limitations in the way of assigning virtue points, it has not been feasible to address this objective in the experiment. It is expected to be tested in future projects by taking into account new variables such as environmental impact and safety requirements compliance in drone operations.
EXP4-OBJ11.- Evaluate the impact of meteorology (strong wind gusts) in drone trajectories in terms of capacity, resilience and efficiency.	Tested in other experiments	Meteorology in Scenario #7 has not been finally addressed in this experiment. Impacts of weather have been tested in Experiment #2.

Table D2.3.1: Objectives deviations

For similar reasons, some of the Research Challenges that were originally planned to be assessed by the experiment #4 scenarios have not been fully addressed. These are summarised in the table below:

Research Challenge in VALP	Research covered in Exp.	Reason
OBJ4 - Optimise decision making between on-board capabilities and U-space separation services.	Not covered	This Research Challenge was supposed to be covered by EXP4-OBJ2. This objective has not been finally achieved in the experiment.
RC 3 - Consolidation of metrics to determine the maximum number of UAS operations	Partially covered	This experiment consolidates metrics in terms of capacity, efficiency and resilience and flexibility. However, these results only show variations when applying DCB measures and are not mature enough to determine the maximum number of UAS operations at this stage.
RC 4 - Applicable DCB measures and their effectiveness	Covered	-
RC 7 - Prioritization of drone operations within the DCB process	Partially covered	Some of the DCB measures have not been applied (or were only applied by giving priority to emergency missions and/or surveillance missions). However, prioritization based on a *virtue points* concept has not been finally implemented.
RC 12 - Impact of weather conditions in the DCB process	Not covered	This Research Challenge was supposed to be covered by EXP4-OBJ11. This objective has not been finally achieved in the experiment.

Table D2.3.2: Deviations in Research Challenges

The assumptions that have been made or modified for experiment #4 include:

- No effect of wind in trajectories is taken into consideration to simplify the scenario. For this reason, drones can fly without the need of changing their trajectory or flight level to avoid high wind speeds.
- All the conflict resolution manoeuvres are set before executing the simulation. These manoeuvres could vary depending on the drones' attitude but cannot be tactically changed during the simulation.
- If resolution manoeuvres do not successfully resolve the conflict, drones are required to land and abort their missions.

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- Although drone models' autonomy is known (as part of the performance data available in the simulation tool), it is not used as a constraint in any of the scenarios. Therefore, it is assumed that every mission has the required battery to be successfully completed.
- It is assumed that vertiports are properly managed and climb and descent operations are properly separated and do not cause conflicts in vertiports. Additional conflict resolution rules would need to be added to the simulation rule tree data to correctly manage vertiport operations in future analysis scenarios.
- There is not enough data to determine when an emergency mission takes part in the simulation. These missions are therefore randomly generated in the scope of the scenarios executed as part of experiment #4.

Finally, for metrics definitions, the following table shows the difference between the metrics that were defined in DACUS D4.1 document [1] and the ones that have been eventually calculated in the exercises:

Metric in VALP	Metric calculated	Reason
drone base throughput, in challenging airspace.	drone base throughput, in challenging airspace.	n/a
Flying drones throughput, in challenging airspace.	Flying drones throughput, in challenging airspace.	n/a
Peak arrival throughput in drone bases.	Peak arrival throughput in drone bases.	n/a
Peak departure throughput in drone bases.	Peak departure throughput in drone bases.	n/a
Re-scheduled traffic reduction.	Re-scheduled traffic reduction.	n/a
Number of hotspots	Number of hotspots	n/a
Number of conflicts derived from other conflicts' resolution.	Number of conflicts derived from other conflicts' resolution.	n/a
Number of impacted operations	FLX1 - Imposed Delay FLX3 – Requirements Respected	These two metrics define the previous metric and have been defined in the DACUS Performance Framework as "flexibility" metrics.
Lowest Closing Time	-	It has not been considered because drone Zone start the detection when a drone is entering the airspace. For this reason, the result is referred to the simulator performance and not to the exercise itself.
Percentage of time doing avoidance manoeuvres.	Percentage of time doing avoidance manoeuvres.	n/a

Number of severe intrusions	Number of severe intrusions	n/a
Time to recover from degraded to nominal conditions	-	Non nominal conditions have not been presented in the experiment. CNS capabilities are already tested in Experiment #3.
Minutes of delay	FLX1 - Imposed Delay FLX2 – Number of restrictions	These two metrics define the previous metric and have been defined in the DACUS Performance Framework as "flexibility" metrics.
Number of flights that have been cancelled	Number of flights delayed more than 10 minutes	drone Zone does not make automatic calculations. All missions have been executed. Metric has been replaced by the number of flights delayed more than 10 minutes (a 30% of the average flight duration).
Loss of airspace capacity avoided	Loss of airspace capacity avoided	n/a
Loss of drone capacity avoided	Loss of drone capacity avoided	n/a
Number of drones impacted by a contingency	-	Non nominal conditions have not been presented in the experiment.
Total number of meters flown	EFF1 – Horizontal drone Operation Efficiency EFF2 – Vertical drone Operation Efficiency	These two metrics define the previous metric and have been defined in the DACUS Performance Framework as "efficiency" metrics.
Arrival time to the drone base	Arrival time to the drone base	n/a
Number of batteries consumed	Number of batteries consumed	n/a
Energy required	Energy required	n/a
Elapsed time airborne	Elapsed time airborne	n/a

Table D2.3.3: Deviations in metrics

D.3 Scenarios and Results

Results from the models are represented in the figure below for the reference scenario:

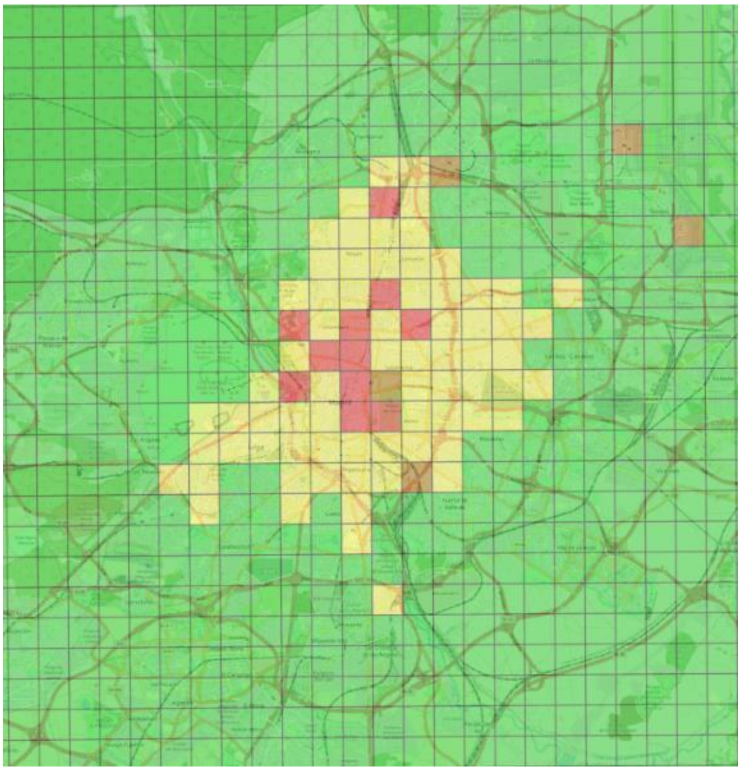

Figure 84: Results from the models for the reference scenario

These results have been used as a basis for the DCB measures application and solution scenarios definition. DCB measures have been applied to each cell that presents hotspots (yellow, red, and brown cells).

Reference

The results from the Collision Risk model are shown in the map below. It has been classified based on the number of hours when the hotspots are active in each cell. Most of the hotspots are located over the city centre, as it was expected.

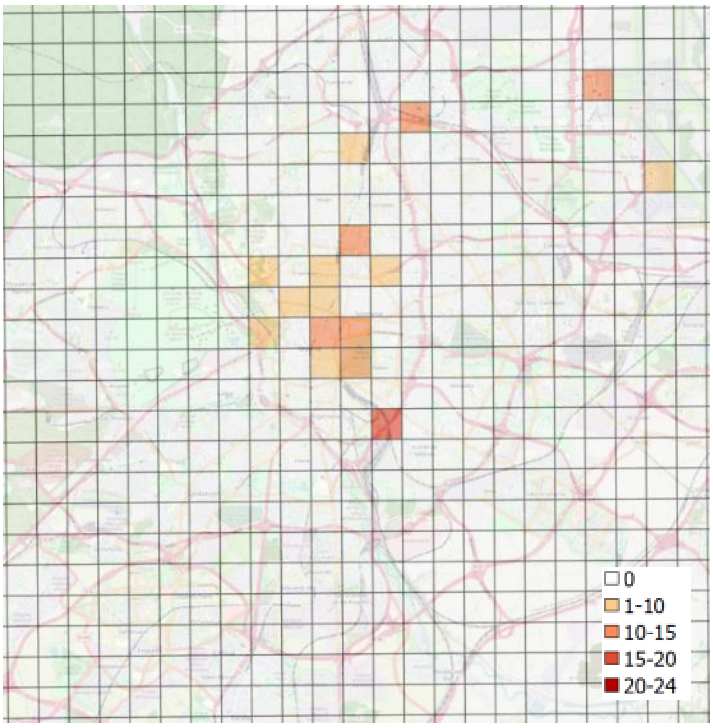

Figure 85: CR hotspots in Reference Scenario

Similar to the Collision risk model, visual impact hotspots are located at the centre of the grid.

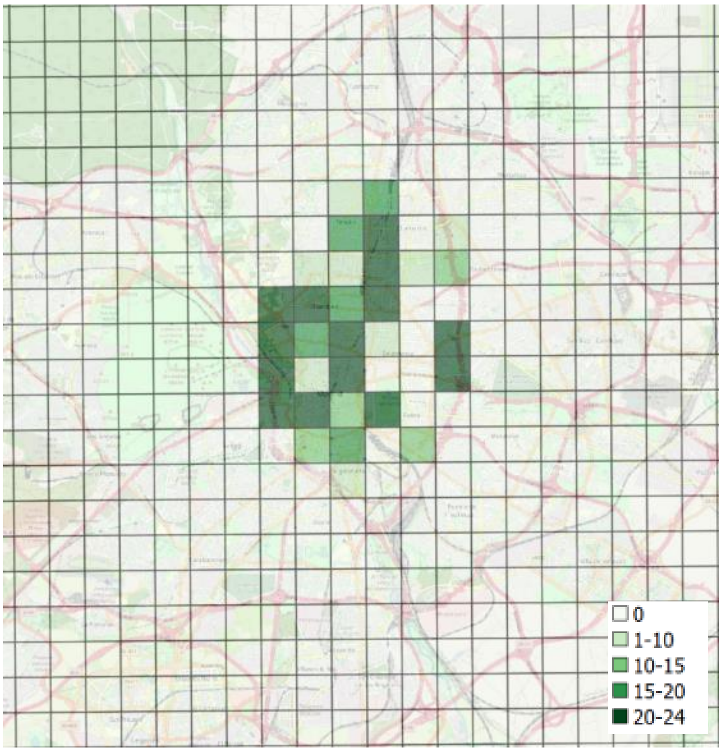

Figure 86: Visual impact hotspots in Reference Scenario

There is a wider coverage of noise hotspots, but as it can be observed below, most of them are located over the city centre:

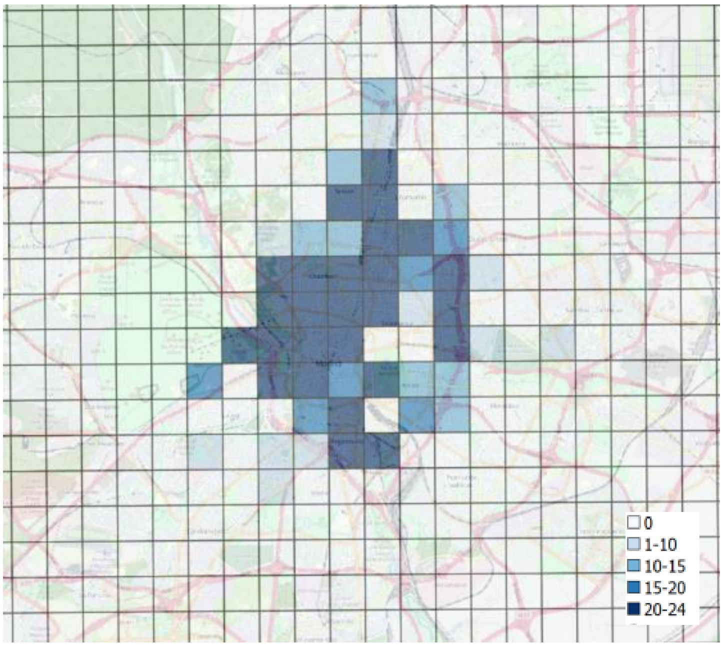

Figure 87: Noise impact hotspots in Reference Scenario

Speed

The number of Collision Risk hotspots is reduced in the speed-controlled scenario, but there are still a couple of them that present significant duration. It should be taken into consideration that the Collision Risk model does not consider current speed between drones, so many hotspots might have been solved with this measure and not been presented in the map:

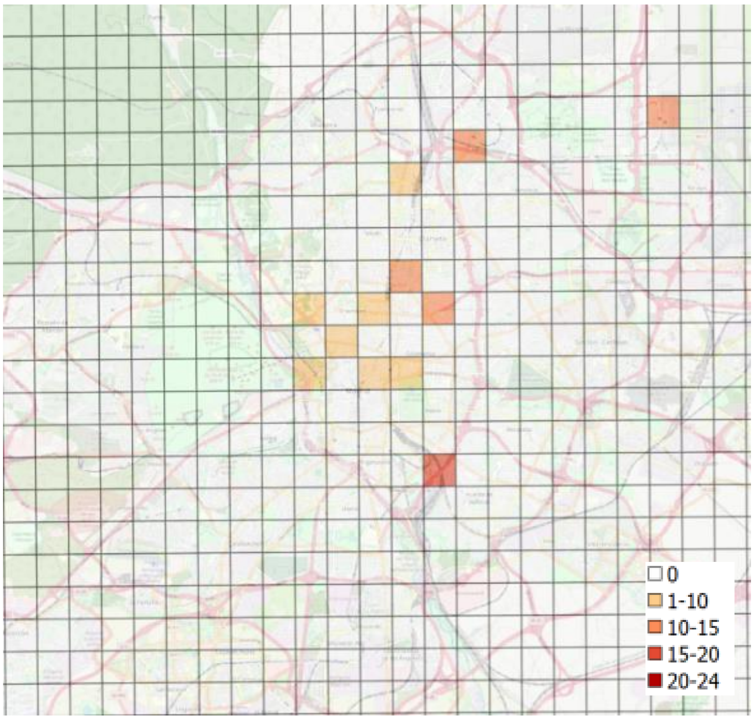

Figure 88: CR hotspots in Solution Speed Scenario

The number of visual impact hotspots has slightly increased but there are still concentrated in cells over the city centre. This is because drones modify their speed and therefore require more time to cross the cell, so the time of exposure is higher.

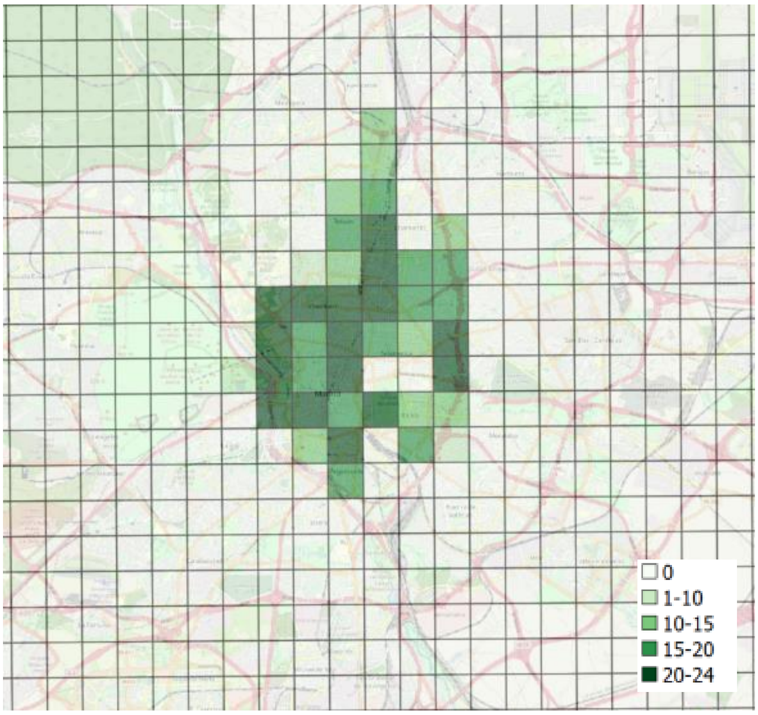

Figure 89: Visual impact hotspots in Reference Scenario

Similar to visual impact hotspots, the number of noise hotspots has increased:

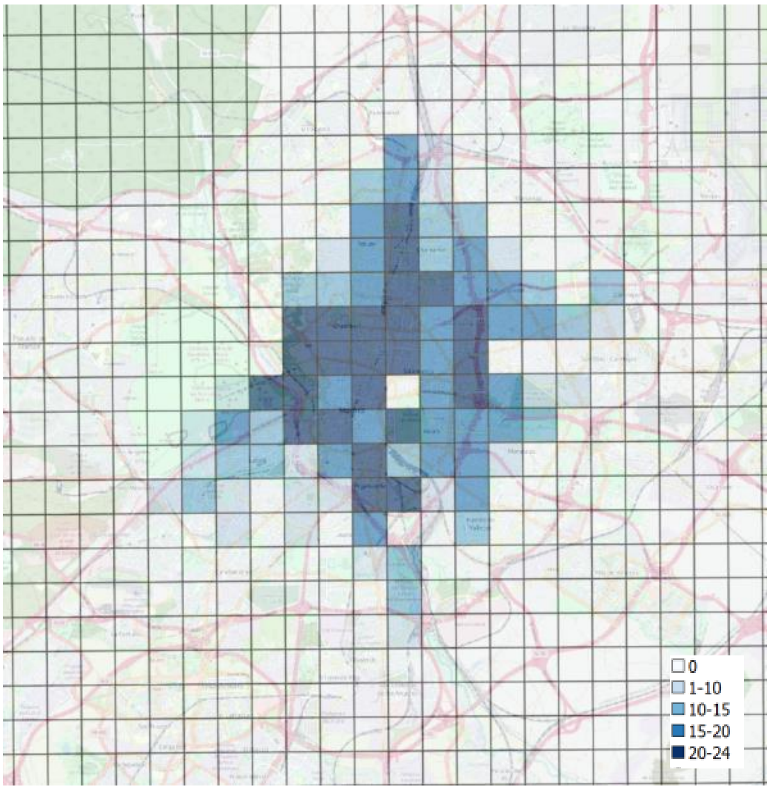

Figure 90: Noise impact hotspots in Reference Scenario

Ceiling

This is the only scenario in which both models present better results than the reference scenario.

It is shown that the number of cells with collision risk hotspots has decreased, and their duration is lower.

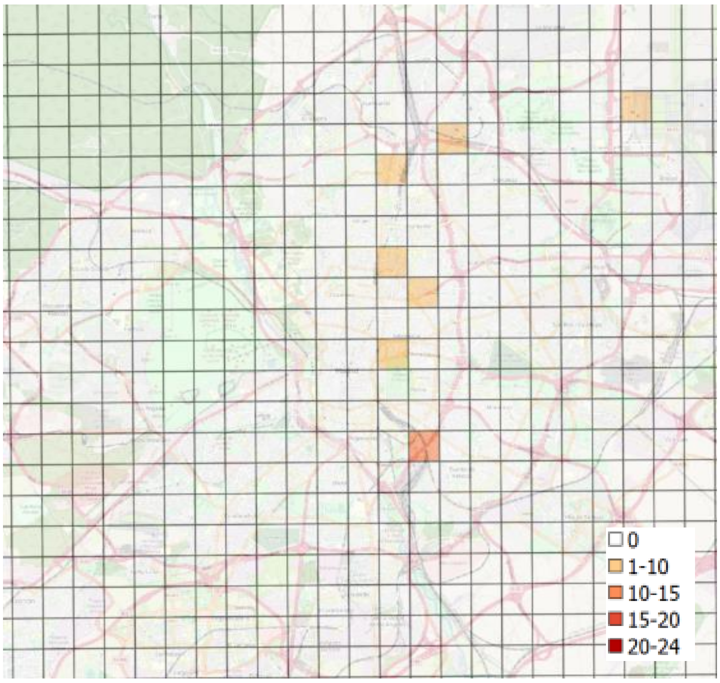

Figure 91: CR hotspots in Solution Ceiling Scenario

Visual impact hotspots have also decrease and the number of repetitions is significantly lower. This fact was expected because, in this case, drones are flying at higher altitudes and the distance to the exposed population has increased:

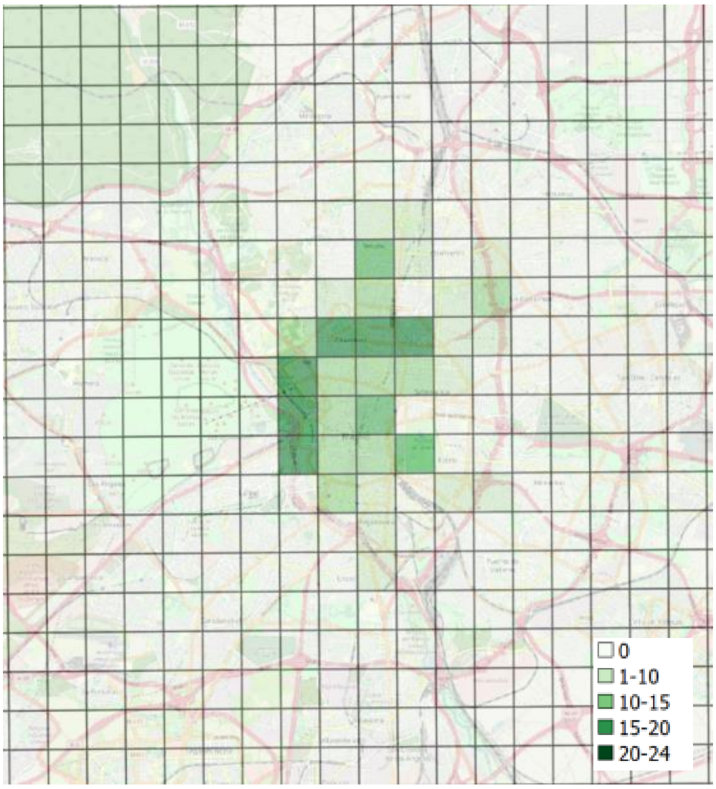

Figure 92: Visual impact hotspots in Solution Ceiling Scenario

Same tendency is shown with the noise impact hotspots. Noise exposure is lower because of the attenuation by distance:

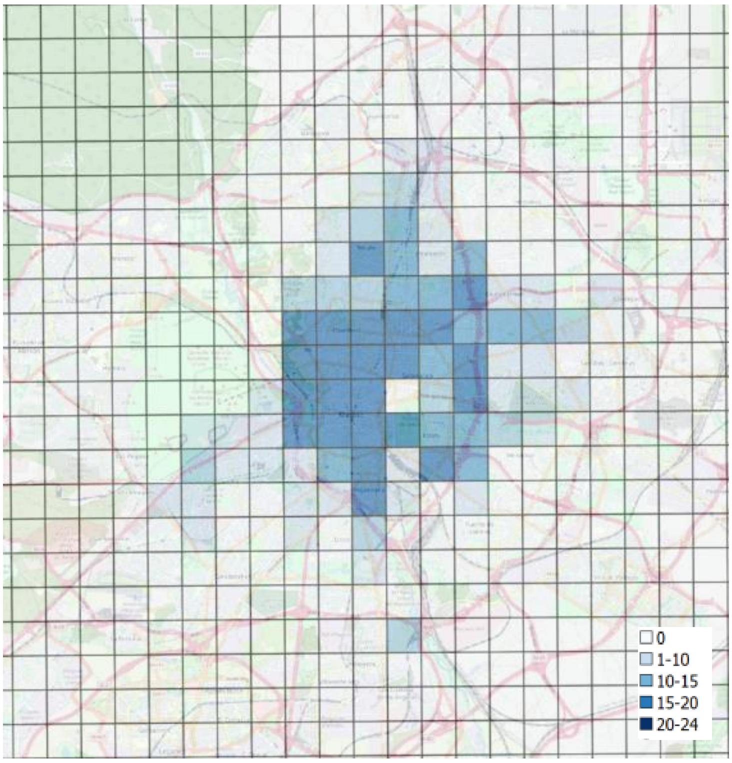

Figure 93: Noise impact hotspots in Solution Ceiling Scenario

Layers

This scenario presents the best results with regard to the Collision Risk hotspots:

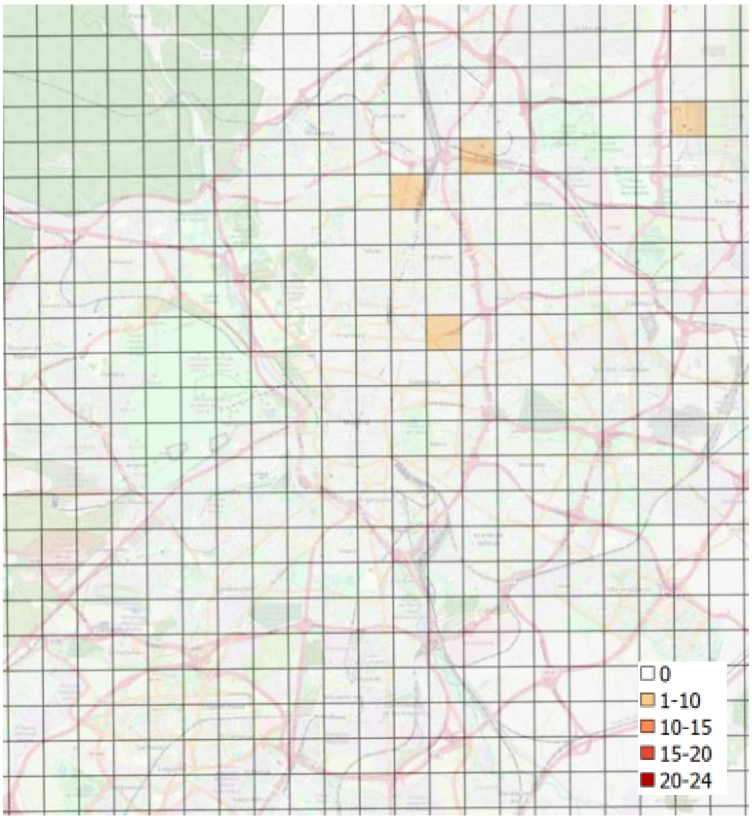

Figure 94: CR hotspots in Solution Layers Scenario

In contrast, the number of visual and noise impact hotspots is slightly higher in this scenario. Some drones have to change their flight level when crossing a hotspot cell based on their courses. drones that were flying at higher altitudes are imposed to fly at lower levels:

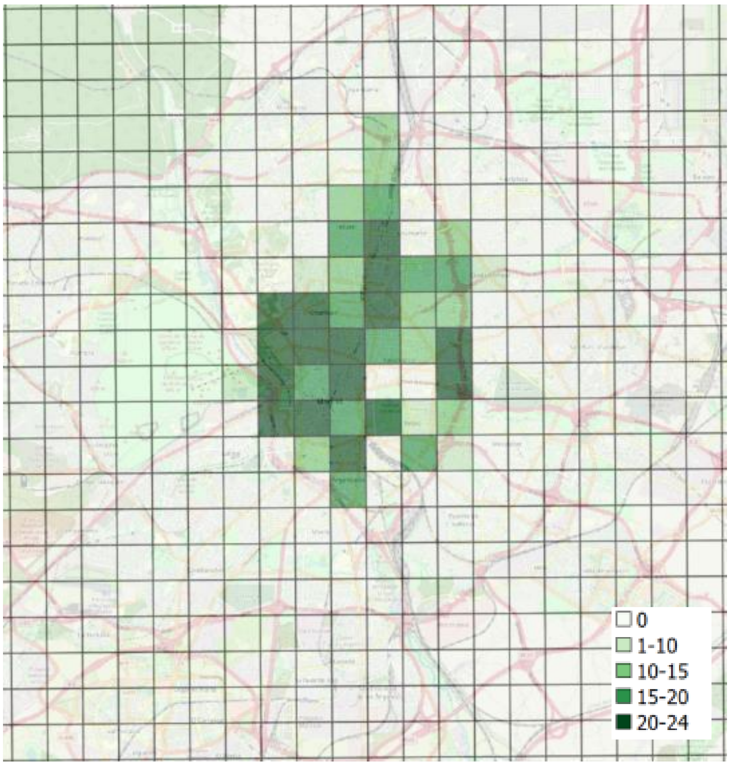

Figure 95: Visual impact hotspots in Solution Layers Scenario

These results show that the DCB measure is focused on separate drones' flows but does not increase the distance from the exposed population or assign higher altitude layers to heavier drones:

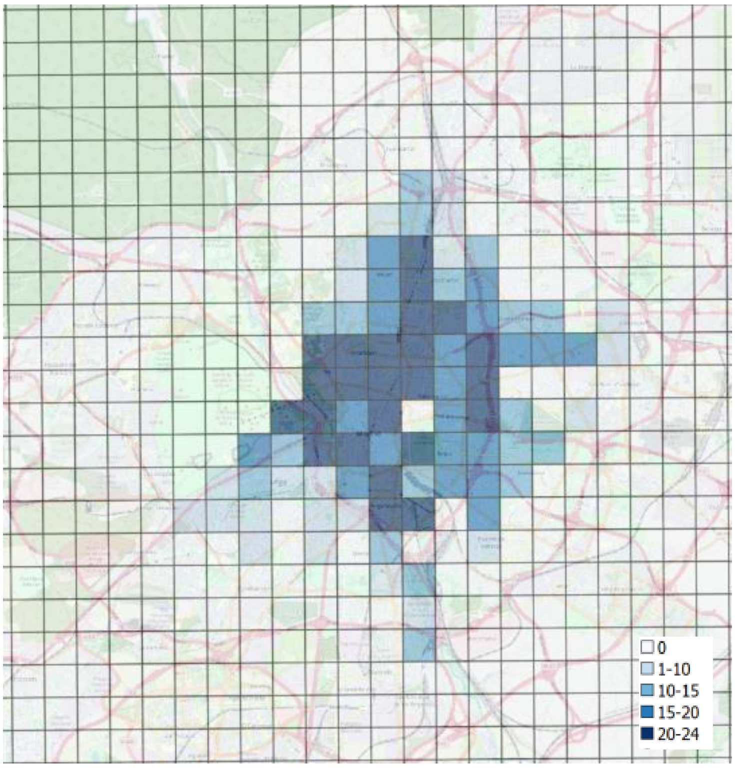

Figure 96: Noise impact hotspots in Solution Layers Scenario

Routes:

The number of cells that present Collision Risk hotspots has increased, but the duration of them is lower.

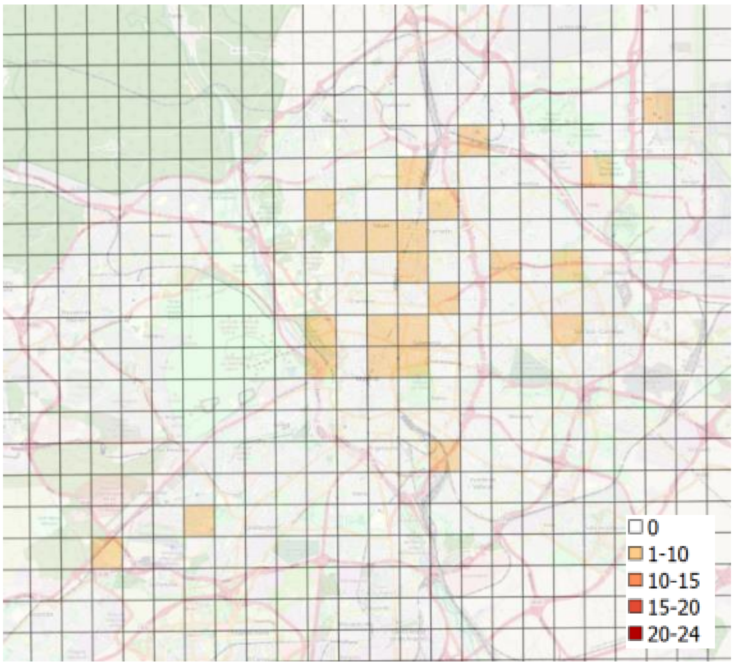

Figure 97: CR hotspots in Solution Routes Scenario

Visual impact hotspots have increased but it is not presented significant higher propagation than in the reference scenario:

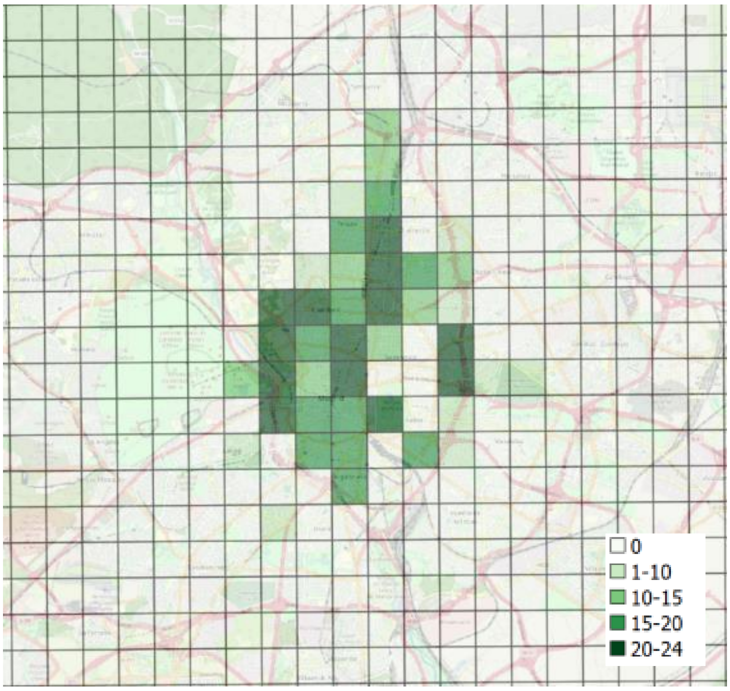

Figure 98: Visual impact hotspots in Solution Routes Scenario

Noise impact hotspots have increased and there are more cells that present these hotspots:

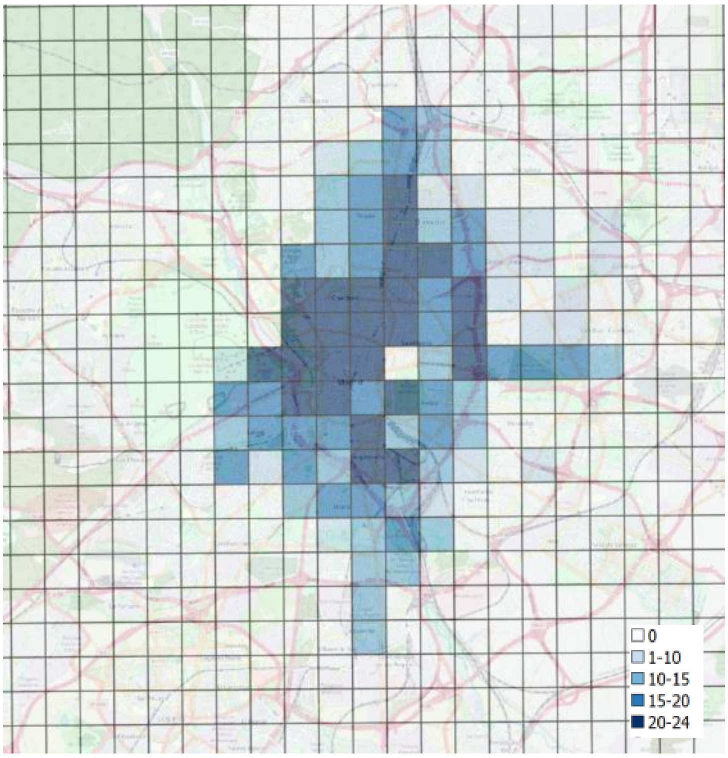

Figure 99: Noise impact hotspots in Solution Routes Scenario

Delays:

Because of the fact that most potential collision risk flights have been delayed on ground, some trajectories have been deconflicted before the take-off, so the number of collision risk hotspots is lower:

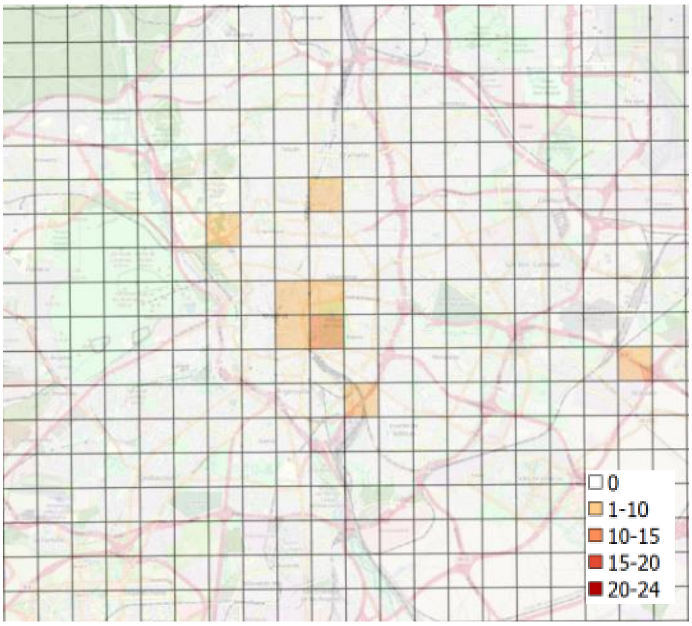

Figure 100: CR hotspots in Solution Delays Scenario

As it was expected, visual impact hotspots and their duration are similar to the reference scenario:

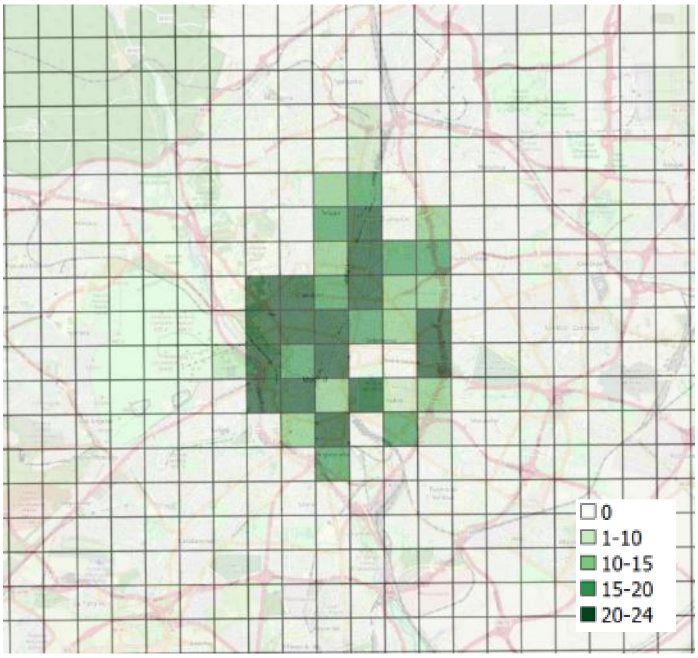

Figure 101: Visual impact hotspots in Solution Delays Scenario

The same case occurs with the noise impact hotspots:

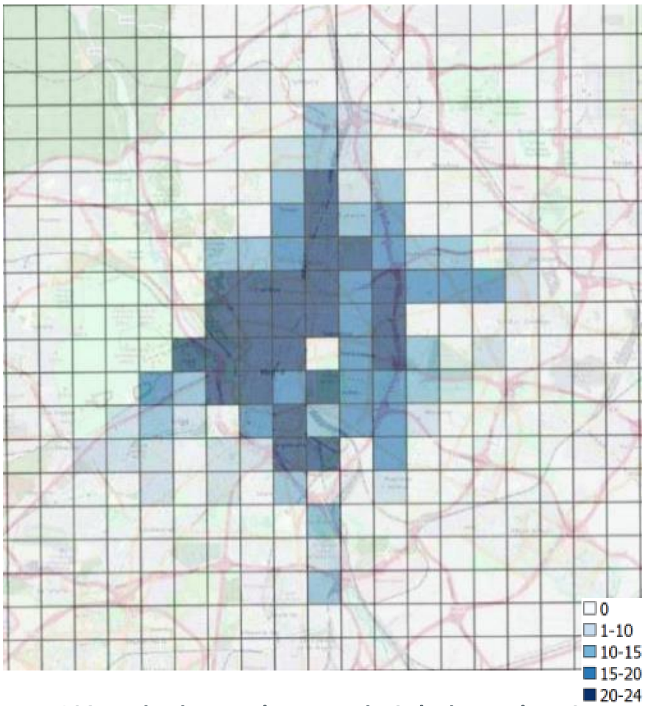

Figure 102: Noise impact hotspots in Solution Delays Scenario

Once scenarios have been executed and outputs processed, the results obtained for each set of metrics are as follows:

Capacity

The results of capacity metrics are presented in the following tables:

CAPACITY								
Metric	**Drone base throughput, in challenging airspace[2]**		**Flying drones throughput, in challenging airspace[2]**		**Peak arrival throughput in base**		**Peak departure throughput in base**	
Unit	drones/hour		drones/hour		drones/hour/base		drones/hour/base	
Reference	16		227		44		47	
Solution Speed	14	↑	136	↑	45	↑	48	↑
Solution Ceiling	15	↑	96	↑	52	↑	55	↑

[2] Challenging airspace refers to those areas where hotspots are identified and missions present higher risk of collision and/or the social impact of them is significant. A decrease of the drone throughput in these areas means that DCB measures are effective, and this does not affect to the demand satisfied (the number of missions is the same in all the scenarios).

Solution Layers	11	↑	72	↑	55	↑	53	↑
Solution Routes	17	↓	253	↓	37	↓	48	↑
Solution Delays	16	–	160	↑	42	↓	48	↑

Table D3.1: Capacity metrics (I)

This first set of metrics shows the variation of drone operations at vertiports. Some DCB measures such as delays on ground or the organization per routes cause higher mission durations, what is translated into a decrease of the arrival throughput at bases due to the delays. The increase of the operational ceiling and the organization per flight layers increase the vertical distance and time to reach the cruise level, so there is a slight increment of peak departure and arrival values.

The throughput in challenging airspace metric presents an improvement in all the scenarios with the exception of the organization per flight routes, where the increase of the number of hotspots and the rerouting of the drones' flight plans (with its corresponding increment of the flight duration) increases the number of drones flying in hotspots areas.

CAPACITY								
Metric	**Re-scheduled traffic**		**Number of CR hotspots**		**Hotspots with severe intrusions**		**Number of SI hotspots**	
Unit	Number of flights		Number of hotspots		Number of hotspots		Number of hotspots	
Reference	0		221		42		20161	
Solution Speed	0	–	175	↑	5	↑	25347	↓
Solution Ceiling	0	–	104	↑	14	↑	13759	↑
Solution Layers	0	–	61	↑	13	↑	21761	↓
Solution Routes	0	–	132	↑	31	↑	22047	↓
Solution Delays	24	↓	129	↑	29	↑	20326	–

Table D3.2: Capacity metrics (II)

The next set of metrics is related to the hotspots identified by the Collision Risk and Social Impact models and the traffic schedule. As described in the DACUS performance framework document [2], collision risk results have been calculated by considering the number of cells that register a maximum Target Level of Safety value higher than 1E-6, based on SORA (noting that new research is looking to adapt this threshold to be potentially more constrained in the future). Social Impact hotspots are identified in line with the approach described in the DACUS performance framework document section 6.2 [2]. Noise thresholds are defined based on a combination of the noise emission from each operation and the number of people exposed to that noise in each grid cell, based on the population within that cell, and the time of day that operations occur (e.g. daytime, evening, night). Visual impact

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values have been arbitrary assigned based on the visual impact of a typical drone of 1m-size, flying at 50 m distance and the population in the operating cell.

Results show that DCB measures are effective in Collision Risk reduction. However, only the increase of operational ceiling reduces the number of Social Impact hotspots. This is because the noise attenuation derived from the distance to the receptor; now drones are flying at higher altitudes, so the distance is higher and the impact on population so much lower. However, speed reduction and organization per routes increase the time of exposure to drone noise, so the number of hotspots is higher. Organization per flight layers permits a higher number of drones complete their missions (see “Number of not concluded missions” and “Percentage of loss of airspace capacity avoided” metrics) so the number of hotspots increase due to the higher number of drones that continue flying and complete their missions.

In addition, the reduction of the number of Collision Risk hotspots brings a reduction in the number of potential collisions that have been translated into severe conflicts (were drone separation is too small and resolution manoeuvres are not effective). This metric shows the benefits of implementing the DCB measures in terms of safety and capacity with respect to the reference (free flight) scenario.

In drone Zone tool, every mission starts at its scheduled time (the program does not automatically cancel missions). For this reason, only imposed delays on ground changes this value.

CAPACITY						
Metric	**Number of noise hotspots**		**Number of visual hotspots**		**Percentage of time doing avoidance manoeuvres**	
Unit	Number of hotspots		Number of hotspots		%	
Reference	17414		6700		5,3%	
Solution Speed	21880	↓	8127	↓	10,6%	↓
Solution Ceiling	10259	↑	4075	↑	6,9%	↓
Solution Layers	17672	↓	7394	↓	1,0%	↑
Solution Routes	18170	↓	6250	↑	< 1%	↑
Solution Delays	20326	↓	6322	↑	1,5%	↑

Table D3.3: Capacity metrics (III)

The number of noise hotspots is only better than the reference scenario when increasing the operational ceiling. This is because, in this case, drones are flying further from the exposed population at higher altitudes, so the distance attenuation is higher.

The number of visual hotspots also decrease in this scenario for the same reason, drones are flying at higher distance so the visual impact on population is reduced. This result has slightly decreased in the organization per routes and delays on ground scenarios. In these scenarios, drones’ flights are better organised and separated, so the visual perception and the reduction of the time in doing avoidance manoeuvres are improved.

As it has been mentioned, the percentage of time required for doing avoidance manoeuvres is reduced in the organization per layers, organization per routes and delays on ground scenarios. In these scenarios, flows are better organised, so drones do not require so much time to resolve them (especially for layer-based and delays scenarios, where conflict complexity is reduced). It is important to highlight that, although the best result is presented in the organization per routes scenario, this is because of the fact that the flight duration has significantly increased in this solution (see Efficiency metrics in this section), and this reduces the percentage of time for resolution manoeuvres.

CAPACITY								
Metric	**Total number of conflicts**		**Number of conflicts derived from other conflicts' resolution**		**Average delay**		**Percentage of delay respect to total mission duration**	
Unit	Number of conflicts		Number of derived conflicts		Minutes		%	
Reference	2364		178		0,05		0,69%	
Solution Speed	2656	↓	38	↑	0,45	↓	2,41%	↓
Solution Ceiling	1317	↑	29	↑	0,22	↓	1,79%	↓
Solution Layers	1732	↑	10	↑	0,01	↑	0,21%	↑
Solution Routes	3641	↓	54	↑	0,5	↓	3,95%	↓
Solution Delays	2245	↑	38	↑	0,41	↓	3,51%	↓

Table D3.4: Capacity metrics (IV)

This set of metrics is referred to the number of conflicts and those that are derived from other conflicts resolution, that is, those that are generating after the execution of an avoidance manoeuvre.

The increase of ceiling and the organization per layers reduce the total number of conflicts. The first one separates the drone operation and the second one reduces the conflict types (only parallel or small angle same direction conflicts are generated). Delays on ground resolve conflicts between drones that are in conflict before entering the airspace or overfly the same point at the same time.

In contrast, the speed reduction increases the number of conflict because present new coincidences that could not have happened before because one of the drones had abandoned the airspace before the other one entered.

Route structure reduces the degrees of freedom in drone operations, so a higher number of conflicts is generated (but the organization per layers in routes brings the possibility of easily perform an avoidance manoeuvre to resolve the conflict and not to generate another new one).

All the DCB measures improve the airspace organization and, therefore, reduce the number of derived conflicts. Nevertheless, that increases the flight duration, and a higher number of missions reach their destination with higher delay.

Only the organization per flight layers presents an improvement in delay metrics because of the reduced number of conflicts that it generates, and the smaller percentage of time drones expend in doing avoidance manoeuvres.

CAPACITY								
Metric	**Maximum delay**		**Requirements respected**		**Number of close aircraft**		**Number of severe intrusions**	
Unit	Minutes		%		%		%	
Reference	3,82		71,30%		37%		6%	
Solution Speed	1,65	↑	73,95%	↑	42%	↓	2%	↑
Solution Ceiling	2,58	↑	88,61%	↑	21%	↑	4%	↑
Solution Layers	1,02	↑	84,95%	↑	43%	↓	4%	↑
Solution Routes	9,86	↓	60,39%	↓	57%	↓	10%	↓
Solution Delays	12,22	↓	74,53%	↑	38%	-	5%	↑

Table D3.5: Capacity metrics (V)

This last set of capacity metrics shows the maximum delay, the percentage of drone operational plan requirements respected, the number of close aircraft and the percentage of severe intrusions (those conflicts at risk of imminent collision).

As shown in the previous set, the organization per flight layers is the most efficient measure to prevent delays. Although the increase of operational ceiling and the speed control increases the average delay, there are few drones in reference scenarios that require more time to perform an avoidance manoeuvre (that could generate an additional conflict) to resolve the conflict due to its complexity. These DCB measures reduces conflict complexity and, therefore, the maximum time to resolve them is lower. Organization per routes reduces the degrees of freedom in drone operations (it is not allowed to get out of the route until reaching their destination) so the flight distance and duration is higher because drones cannot fly direct from the vertiport to the drop point. In case of the delays on ground, this delay is mainly due to the imposed delay before starting the mission.

Most DCB measures facilitate drones to fulfil drone operation plan requirements (time of arrival, speed, optimum cruise level, trajectories followed, etc.). Only organization per routes reduces the percentage of requirements respected. This is because drones must change their flight plan and join the routes that are assigned, adapt their flight level to the layer that allows their courses and spend more time to reach their destination.

Finally, the number of close aircraft is higher in all solution scenarios, with the exception of the one when operational ceiling is increased (which separated drones in a higher airspace volume). But the conflicts generated are easier to resolve and the number of severe intrusions is lower (mainly in the speed reduction scenario where drones have more time to perform the avoidance manoeuvre thanks to this reduction).

The only scenario that increases these values is the organization per flight routes. The number of close aircraft is higher because they follow defined paths and many trajectories converge. Moreover, the reduction of degrees of freedom restricts the possibility of performing a lateral avoidance manoeuvre, so drones only can hover (with the risk of another conflict with a drone that is flying behind) or perform a vertical avoidance manoeuvre. In contrast, the organization per layers combined with route structures reduces the number of conflicts only to parallel same direction types, so drones can avoid a higher number of conflicts due to the lower complexity of the conflicts and conclude their missions (see "number of not concluded missions" metric) and reduce the number of derived conflicts.

Resilience and Flexibility

The results of resilience and flexibility metrics are presented in the following tables:

RESILIENCE AND FLEXIBILITY								
Metric	Percentage of not concluded missions		Delayed flights > 3 min		%Loss of airspace capacity avoided		% Loss of vertiport capacity	
Unit	%		%		%		%	
Reference	4,32%		0,02%		-		-	
Solution Speed	0,85%	↑	0,00%	↑	10,37%	↑	0,00%	-
Solution Ceiling	0,50%	↑	0,02%	-	77,98%	↑	0,00%	-
Solution Layers	0,66%	↑	0,00%	↑	80,80%	↑	0,00%	-
Solution Routes	1,66%	↑	3,10%	↓	69,16%	↑	0,00%	-
Solution Delays	2,28%	↑	0,41%	↓	58,90%	↑	4,17%	↓

Table D3.6: Resilience and Flexibility metrics (I)

All DCB measures reduce the number of not concluded missions (those when the drone has to land because it does not find a feasible avoidance manoeuvre to resolve the conflict). This is because they contribute to organize the traffic flows and deconflict some flight plans by reducing the complexity of conflicts and traffic distribution, so when a conflict is detected, it is easier to resolve it and the resilience of the system increases.

The number of flights that are delayed more than 3 minutes (around a 10% of the average mission duration) is lower in speed controlled, increase of operational ceiling and organization per layers scenarios. As it has previously mentioned, organization per flight routes increases flight distance and duration so a higher number of delayed flights is presented. With regard to the delays on ground scenario, this delay is mainly imposed before taking off, but it is balanced with the reduction of conflicts so this number it is slightly higher than reference scenario.

Moreover, all DCB measures increases system resilience and airspace capacity. As it has been mentioned before, the number of not concluded missions is lower than the one in reference scenario (see "percentage of not concluded missions" metric) so there are more missions that have been successfully completed and a higher percentage of traffic demand satisfied.

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Similar to "re-scheduled traffic" metric, all missions start at their programmed time because drone Zone simulator does not automatically cancel or delay missions, so only the solution scenario based on delays on ground shows a reduction of vertiport capacity due to the imposed delays on some flights.

RESILIENCE AND FLEXIBILITY				
Metric	**Number of restrictions**		**Average number of restrictions per flight**	
Unit	Number of flights with restrictions		Number of restrictions per flight	
Reference	0		0	
Solution Speed	4027	↓	4	↓
Solution Ceiling	4474	↓	< 1	–
Solution Layers	4249	↓	5	↓
Solution Routes	4103	↓	< 1	–
Solution Delays	27	↓	< 1	–

Table D3.7: Resilience and Flexibility metrics (II)

With regard to the flexibility metrics, every DCB measure implies that a restriction is applied to a drone that flies through the zone where it is applied (or the imposed delay flight in case of delays on ground).

The most restrictive metric is the organization per flight layers, where a drone has to change its flight level every time it changes its course.

Similar to flight layers, drones have to change their current speed every time they fly through a speed-controlled zone.

The rest of metrics are applied maximum once per flight (they are only once delayed or forced to join a route).

Efficiency

The results of efficiency metrics are presented in the following tables:

EFFICIENCY								
Metric	**Horizontal drone Operation Efficiency**		**Vertical drone Operation Efficiency**		**Arrival Time**		**Elapsed time airborne**	
Unit	%		%		Min		%	
Reference	-		-		-		-	
Solution Speed	0,56%	↓	-20,80%	↑	0,47	↓	1,02%	↓

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Solution Ceiling	-0,05%		363%		1,35		5,85%	
Solution Layers	0,25%		46,80%		0,80		3,75%	
Solution Routes	18,20%		-10,18%		11,45		56,95%	
Solution Delays	0,57%		-20,24%		1,87		-1,08%	

Table D3.8: Efficiency metrics (I)

It is shown a general decrease in the efficiency of the system when DCB measures are applied. With regard to the horizontal efficiency, drones follow similar trajectories than the ones in reference scenario (the small increase is due to the higher number of conflicts resolved that require extra distance to perform the avoidance manoeuvres), with the exception of the organization per routes, where they are forced to follow the route structure. Vertical efficiency is significantly lower in the increase of operational ceiling and organization per layers scenarios because flights can reach higher cruise levels in the first one and are forced to change their actual flight level as many times as they change their course in the second one.

As mentioned in previous metrics, DCB measures increase the flight duration (with the exception of the delays on ground scenario, where delays are mainly caused by the imposed delay before taking off). That is because the arrival time is later than the one in reference scenario and the elapsed time airborne is higher in all scenarios with the exception of the delays on ground one, where some conflicts are prevented and do not cause the delay they caused in reference scenario.

EFFICIENCY				
Metric	**Number of batteries required**		**Energy required**	
Unit	Number of batteries		%	
Reference	-		-	
Solution Speed	3,16%		2,52%	
Solution Ceiling	3,36%		21,37%	
Solution Layers	1,58%		0,23%	
Solution Routes	83,26%		60,79%	
Solution Delays	-1,09%		-1,06%	

Table D3.9: Efficiency metrics (II)

Finally, the number of batteries required to complete all the mission is higher in solution scenarios, because of the increase of flight distance and duration (except in ground delays scenarios, where these parameters are lower than the ones in reference scenario).

Energy required is also higher in solution scenarios, except in delays on ground scenario. The relation between the number of batteries and energy required is similar in all scenarios, with the exception of the increase of operational ceiling one. In this scenario, drones need more energy to reach higher flight levels. Moreover, these flight levels are mainly flown by air taxis (that have their optimal flight level between 700 and 900 ft above ground level) that require more energy to fly, that is because the increment of batteries is so much lower than the extra energy required.

These parameters have been calculated by considering an unlimited number of batteries and energy available. drone Zone does not interrupt the mission if its duration is higher than the drone autonomy, so in the reality, some drones could not have been able to complete their missions due to this fact. Nevertheless, these metrics might be useful for operators to estimate the extra number of energy and batteries that would be required if some of these DCB measures were applied.

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