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Measuring U-space Social and Environmental Impact

Session: Community Noise Impact, Engagement and Perception

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Abstract U-space will enable urban air mobility (UAM) on a wide scale, facilitating a variety of use cases (e.g., medical and emergency transport, delivery of goods, passenger transport services). Social acceptance and impact on citizens is not completely understood in this growing scenario. Current U-space performance frameworks include indicators to evaluate UAM's environmental impact. However, they are still too generic and aggregated to properly capture the broad variety of impacts of UAM operations. The goal of the MUSE (Measuring U-space Social and Environmental Impact) project is to develop a set of performance indicators (PIs), methods and tools for the assessment of the impact of UAM operations on the quality of life in European cities. The project is expected to establish the basis for a future U-space service that supports the minimisation of UAM's negative social and environmental externalities. This general goal can be translated into the following specific objectives: (i) to define a set of PIs able to capture the full range of UAM impacts on citizens' quality of life; (ii) to develop new tools for the measurement and forecasting of the proposed PIs; and (iii) to showcase and evaluate the capabilities of the new tools developed by MUSE through their application to a set of case studies in the city of Madrid.

Keywords: UAM, social acceptance, noise impact, population, environment

1. INTRODUCTION

The development and deployment of U-space holds great promise for unlocking the potential of the drone economy and enabling urban air mobility (UAM) on a wide scale (SESAR JU, 2020). Over the next 10 years, the implementation of U-space is expected to facilitate a variety of UAM use cases (e.g., medical and emergency transport, delivery of goods, passenger transport services), accelerating the development of new technologies

and leading to the creation of high-quality jobs. These opportunities, however, come with major challenges, especially in the case of UAM operations over densely populated areas.

In addition to the technical and regulatory developments required to realise the full potential of UAM, citizens' acceptance will be critical to success. As part of the preparation of an adequate regulatory framework for UAM, the European Union Aviation Safety Agency (EASA) recently conducted a comprehensive study on the societal acceptance of UAM across the EU (EASA, 2021). When asking EU citizens about their concerns regarding UAM operations in their city, safety and noise come first, but the range of concerns is much broader and includes other impacts such as visual pollution, induced stress due to traffic movements above one's head, security, privacy, and the occupation by take-off and landing facilities of urban spaces that would be better used for living or recreation.

In recent years, some studies have started to investigate the attitude of European citizens towards UAM, but the efforts to characterise and quantify UAM's impact on the quality of public spaces are still scarce (Biehle, 2022). The SESAR 2020 PJ19.04 project has begun to develop a U-space performance framework that includes a set of indicators to evaluate UAM's environmental impact. While this is a first step in the right direction, the proposed indicators (e.g., "number of people exposed to noise within an area during a period of time") are still too generic and aggregated to properly capture the broad variety of impacts of UAM operations on different population groups and urban contexts. In order to inform the design of the future UAM regulatory framework and enable new U-space services that help realise the full range of benefits of UAM without affecting the liveability of European cities, more advanced indicators and measurement mechanisms are urgently needed. More specifically, there is a need for a better understanding of the interplay between UAM's concept of operations (e.g., geofencing, route design, allowed traffic density), drones' visual and noise footprint, and citizens' spatial behaviour and use of public space. The work presented in this paper summarises the MUSE project approach and how it aims to address this pressing need.

This paper presents a high-level vision of the work performed in the context of the SESAR MUSE research project. The goal of the MUSE project is to develop a set of performance indicators (PIs), methods and tools for the assessment of the impact of UAM operations on the quality of life in European cities. The project is expected to establish the basis for a future U-space service that supports the minimisation of UAM's negative social and environmental externalities.

This general goal can be translated into the following specific objectives:

- To define a set of PIs able to capture the full range of UAM impacts on citizens' quality of life.
- To develop new tools for the measurement and forecasting of the proposed PIs.
- To showcase and evaluate the capabilities of the new tools developed by MUSE through their application to a set of case studies in the city of Madrid.

2. METHODOLOGY

The proposed research approach will be guided by the following principles:

- Combination of quantitative and qualitative methods.
- Interdisciplinarity, with the purpose of integrating the required technical expertise in drone operations, trajectory modelling, noise modelling and data analytics with the understanding of UAM impacts provided by experts from relevant fields such as sociology, psychology and public health.

- Stakeholder engagement and co-creation approaches that incorporate the expectations and concerns of relevant stakeholders throughout the full project lifecycle.
- Use of case studies to demonstrate the capabilities of the newly developed Solutions, stimulate stakeholder engagement and derive lessons learnt on practical implementation aspects.

Based on these general principles, we propose a research methodology that comprises the following stages:

1. Analysis of UAM impacts on citizens' quality of life and development of environmental and social PIs.
2. Development of the U-Space Environmental and Social Impact Assessment Toolset
3. Validation of the U-Space Environmental and Social Impact Assessment Toolset and application to case studies

2.1 Analysis of UAM impacts on citizens' quality of life and development of environmental and social PIs

The first step for the development of environmental and social PIs to measure the UAM impact on citizens consists on reviewing and analysing previous and ongoing research initiatives and studies addressing UAM's impacts on people's quality of life. This allows to identify the most relevant impacts and classify them according to their nature, distinguishing between noise-related impacts, impacts due to visual pollution, and other impacts. We will review existing evidence on the impact of noise on citizens' health and well-being, as well as existing surveys, focus group discussions and other experimentation aimed at characterising the relationship between the intervisibility surface of visual pollution objects and the perceived visual pollution, in order to identify meaningful noise exposure and visibility metrics. This literature review will be enriched with interviews and working sessions with the members of the EEAB, in particular urban planners, sociologists, psychologists, and environmental health specialists.

The next step consists in reviewing and summarising relevant research initiatives dealing with the development of a U-Space Performance Framework, analysing the available social and environmental PIs and the associated measurement methodologies, and identifying the main gaps and areas for improvement. This step mainly involves desk research, including the revision of current reports from ICAO, EASA and other institutions, as well as the work conducted in the frame of SESAR 2020 PJ19.04 project and SESAR projects such as DACUS (<https://dacus-research.eu/>).

Once the limitations and the needs for improving the current metrics are identified, a new Environmental and Social Performance Framework will be designed. The proposed performance framework shall meet the following requirements and general principles:

- To ensure consistency with SESAR's performance approach, we will adopt the definitions of KPIs and PIs adopted by SESAR, distinguishing between those indicators considered appropriate for target setting (KPIs) and those that may not have associated targets, but are still interesting to monitor and understand the performance of the system (PIs).
- The indicator system shall capture all the identified impacts of UAM operations on people's quality of life and/or the factors that determine the social aspects of U-Space operations.
- The proposed indicators shall be designed so as to enable the maximum possible level of geographical, temporal, demographic, and socioeconomic resolution. This

enables the analysis of the interaction between UAM impacts and factors such as age, gender, place of residence, level of income, occupational status, etc., as well as the aggregation and evaluation of UAM's impact at different spatial scales (e.g., neighbourhood, municipality, metropolitan area), for different time periods (e.g., daytime vs nighttime, working days vs weekends) and along different dimensions (e.g., impact on different population groups).

- For each proposed PI or KPI, a measurement mechanism shall be specified in a clear and unambiguous manner, including the required input data and the calculation methodology/algorithms.

2.2 Development of the U-Space Environmental and Social Impact Assessment Toolset

Development of trajectory generation engine

GEMMA is a trajectory generation engine developed by the UPC that generates realistic flight missions in any environment, including not only point-to-point flights but also complex missions involving scans, loitering, etc. The trajectory simulator is a kinematic simulator (i.e., it does not model the forces and moments that create the movement of the aircraft) and can use uniform movement or accelerated movement models. The turns for the moment are of type fly-over.

The software can be configured to include a variety of operational layers relevant for the drone operations, namely: operating schemes (e.g., visual line of sight, extended line of sight, beyond line of sights and point-to-point flights); airspace structure (e.g., altitude limits, restricted areas, geofence); fleet composition (drone types and their performances); types of operators (small, medium, large); and geographical location. GEMMA can be used for pre-ops assessment as well as in post-ops analyses, enabling the user to analyse historical trajectories. GEMMA has been used to generate the potential demand for business to business delivery and develop a management environment in which a undetermined number of drones could be piloted by several remote pilots, simulating concepts such as the hand-over of aircraft within pilots, and to develop the human interfaces with capabilities of multi-vehicle piloting (Bareas, 2017). GEMMA has also been used for validation urban air mobility capacity limits and for testing a strategic conflict detection service (Barrado et al. 2021).

GEMMA is being used in MUSE to build the drone urban traffic concept of operations, detailing the particularities of many drone operations, taking advantage of its capabilities for defining complex flight plans considering geofencing and other drone-related constraints.

Development of noise models

Noise modelling is based on ONERA's in-house tool CARMEN (Bertsch et al., 2021), a modular, parametric tool based on a chain of aircraft noise source emission models, calculation of acoustic installation effects, and noise propagation towards the ground. CARMEN has been extensively used for applications such as classical tube and wing aircraft, as well as helicopters and new aircraft concepts (e.g., blended wing) (Legriffon & Sanders, 2018; Legriffon, 2019; Legriffon et al., 2022). Its modular structure makes it possible to take into account several types of noise sources, at an arbitrary number and location on the aircraft. In the context of MUSE, CARMEN will be evolved to render it capable of calculating noise maps for a fleet of drones in an urban environment.

We expect the main noise source of the considered drones to be rotor/propeller noise. The semi-analytical models implemented in CARMEN (Reboul & Taghizad, 2012) are adapted to the drone specifications defined in MUSE. The input data required to calculate the noise radiated by these sources will be generated by the in-house flight mechanics tool DynaPyVTOL (Basset & Perret, 2022), which will be chained to CARMEN. For given drone characteristics and flight and mass objectives, DynaPyVTOL calculates the resulting

trajectories and blade and rotor dynamic data. In MUSE the trajectories will be delivered by the trajectory generation engine described in section 2.3, while the dynamic input data will be calculated using DynaPyVTOL. For complex drone architectures (e.g., with rotor fairing), simplifications of the geometrical characteristics might have to be considered.

So far, CARMEN has been used mostly for concept evaluation, so noise propagation is classically done in free field. While specific wind and temperature profiles can be taken into account, the presence of buildings in the propagation paths is not yet taken into account. To overcome this problem, in MUSE the open-source tool NoiseModelling (UGE France) (Bocher et al., 2019) will be connected to CARMEN so that, considering some simplifications of building characteristics, a realistic noise map is created for each single drone flyover, including reflection, masking and diffraction by buildings.

Finally, once the single flyover tool is operational, the aggregation of the noise impact of the whole fleet is necessary. Since CARMEN is a fast parametric tool, the calculation of a single drone noise emission along a given trajectory is relatively fast (typically less than 1 hour, depending on the flight duration and the number of configuration changes during the flight). In the context of MUSE, the chain of three tools will be automated to make it possible to calculate the noise footprint of a high number of drone movements above a city in a predetermined operation volume and time window.

Development of visual pollution models

Visual pollution is the compounded effect of disorder and excess of various objects in a landscape which population finds unattractive, ugly, intrusive or disturbing (Chmielewski, 2020; Nami et al., 2016). The term visual pollution objects is used to refer to the physical components that decrease the landscape's visual quality and/or obstruct the view of valuable elements of the natural or the built environment. The quantification of visual pollution is challenging because of its subjective nature and, unlike air or noise pollution, there are no standard methodologies and instruments to measure it.

MUSE will follow the systematic approach proposed by Wakil et al. (2019). For each area of the city and each temporal window a visibility analysis will be conducted, taking into account drone trajectories and physical characteristics; as in the case of noise, some simplifications of the drone geometrical characteristics are likely to be required. Visibility analysis takes into consideration what can be seen by an observer from a given location, in order to produce quantifiable metrics of visual perception (Sahraoui et al., 2018). The visibility analysis will combine planimetric analysis, which will characterise the sky viewshed (i.e., the portion of sky visible from a given viewpoint) by distinguishing the pixels in view from the pixels masked along each ray simulated from the viewpoint, and tangential analysis, which will involve weighting drones according to their size and to their distance from the viewpoint. The analysis is performed using the visibility analysis functionalities implemented in general purpose geographical information system (GIS) software (gdal for python) and a more specific tool for the purpose, PixScape (<https://sourcesup.renater.fr/www/pixscape/en.html>).

Development of methods and tools for dynamic population mapping, exposure assessment and PI calculation

The analysis of population exposure to UAM noise and visual pollution requires accurate and detailed information on the population's presence in different areas of the city at different moments in time. The main data source to generate this information will be anonymised mobile network data (MND). Traditionally, the analysis of population exposure to air contaminants, noise and other environmental hazards has been based on census data and other cross-sectional, static sources. Using census data implies the unrealistic assumption that people spend 24 hours at their residence area and ignores the dynamics of daytime activity, including routine travel and more occasional trips to perform activities at different locations, overlooking the fact that some residents spend a long time far from the

area which is supposed to represent their exposure, which can lead to significant biases in the estimation of exposure (Briggs et al., 2006). In recent years, the pervasive use of geolocated devices in our daily activities has enabled the collection of rich spatio-temporal data about human activity. The electronic traces generated by mobile devices provide an indication of the positions of the user along the day, enabling the regular or even continuous collection of fine-grained activity and mobility data and overcoming many of the limitations of traditional approaches to exposure assessment (Picornell et al., 2019). MND are particularly interesting for this purpose, thanks to the possibility of obtaining large samples of movement data with high spatio-temporal resolution for practically all population segments.

MND will be processed using Nommon's Population Insights tool. Population Insights is a state-of-the-art software platform that processes MND and blends them with other layers of information (e.g., land use and Pol, information on the transport network, sociodemographic statistics) to provide dynamic population maps, floating population statistics and other customisable presence and activity indicators segmented according to different criteria, such as sociodemographic profile, type of activity (home, work, education, pass-through traffic, etc.), length of stay and frequency of visits. The data includes passive events coming from network monitoring probes, which record the antenna to which the device is connected every few minutes/seconds, thus providing an indication of the user location through the day.

Within MUSE, the data processing pipeline of this tool will be evolved to implement two main improvements:

- Integration of GPS mobile apps data, pedestrian counts and EO data to distinguishing between indoor and outdoor activities. Except for particular cases (e.g., in-building microcells), MND do not allow the differentiation between indoor and outdoor activities, as the mobile devices in a certain area may connect to the same antennas regardless of whether the user is inside a building or outdoor. The classification of activities is thus based on a number of assumptions (land uses, time of the day, etc.). The distinction between indoor and outdoor activities is however important to assess exposure to noise and especially to visual pollution. Within MUSE, pedestrian counts available from footfall sensors (usually available as open data for many European cities) and GPS mobile apps data, available from data aggregator companies, will be leveraged to enrich the activity-travel diaries and adjust the expansion factors so as to obtain a more precise estimation of the time spent in outdoor activities. The recent advances in population mapping through very high resolution (VHR) satellite imagery (Wang et al., 2019) will be used to validate and calibrate the estimations of the indoor/outdoor differentiation. VHR EO images (Pleiade Neo, to obtain the highest resolution currently available from satellite imagery) will be acquired for various locations and temporal windows. Automated methods to extract pedestrian counts will be developed, profiting from recent advances in convolutional neural networks (CNN), a deep-learning architecture that has revolutionised the extraction of information from images (Froidevaux et al., 2020; Yao et al. 2021). This will allow us to build an algorithm to identify whether a remotely sensed target is a pedestrian or not, producing accurate pedestrian counts that will be used to calibrate the activity classification criteria and expansion factors implemented in the MND processing pipeline.
- Generation of exposure diaries. So far, most research efforts for population exposure assessment to environmental hazards based on mobile location data start by computing dynamic population maps that are then fused with air pollution levels, noise maps, etc. on an aggregated level (Picornell et al., 2019). In MUSE we will go beyond this approach by fusing population and noise and visual pollution data at the level of the individual activity-travel diaries (i.e., before any spatial or temporal

aggregation). This will allow us to compute exposure levels and duration of exposure with any arbitrary temporal resolution so that we can quantify not only the exposure to punctual thresholds, but cumulative effects due to continued exposure.

Once the individual exposure diaries are computed, they will be post-processed to generate the different environmental and social impact PIs.

2.3 Validation of the U-Space Environmental and Social Impact Assessment Toolset and application to case studies

Once the trajectory generation tools, the noise and visual impact models, the exposure assessment and PI calculation modules are developed, they will be jointly evaluated through a set of case studies. This will be done following a two-step approach. First, the workflow defined to chain the different models will be implemented for a limited number of simplified scenarios, in order to verify the functioning of the system as a whole. The results of different scenarios will be stored in a database and connected to a interactive visualisation tool to simulate the user acceptance testing. A first round of experiments conducted by the members of the MUSE project team will be followed by one or more working sessions with at least 5 external users, which will help us improve the functionalities of the system and its usability. Second, once the design of the system is frozen, it will be used to run a battery of case studies corresponding to more complex scenarios, with the aim to showcase and evaluate the capabilities of the tool, produce concrete policy recommendations for U-Space and UAM regulation.

The case studies will be specified in collaboration with relevant stakeholders and will aim at covering a variety of urban areas (e.g., residential, commercial, industrial, recreational, educational, etc.) and periods of study (e.g., daytime vs nighttime, working days vs weekends) for different combinations of UAM demand levels and fleet compositions, U-Space operational constraints and weather conditions. Depending on the complexity of the scenarios, some simplifications may have to be considered with regard to building characteristics, number of drone types, size of operation volume, etc.

The evidences gathered during the case studies processes will be consolidated into a detailed assessment of UAM's impacts for the scenarios under study and a set of policy recommendations. The results of the case studies will also serve to derive conclusions and lessons learnt on the requirements for the practical implementation of the MUSE Solution (e.g., regarding data collection, computational tractability, usability of the tool, etc.) and outline a roadmap for its transition to the next stages of the R&I cycle.

3. RESULTS AND DISCUSSION

The project is ongoing at the moment of the elaboration of this paper, this section will focus on preliminary results obtained, discussion of issues found, and next steps towards the achievement of the objectives of the project.

3.1 UAM impact and performance indicators

The analysis conducted on past and current studies, existing surveys, and discussions in focus groups has aided in identifying the most relevant impacts of UAM on the quality of life of citizens. These impacts have been classified based on their nature, distinguishing among noise-related effects, impacts arising from visual pollution, privacy concerns, equity, diversity, and inclusion (EDI), and Other (Accessibility, Trust, ConOps, Safety...).

A large number of studies and research papers are dealing with public perception of Urban Air Mobility (UAM) issues, through public surveys and questionnaires (e.g. Yedavalli and J. Mooberry, 2019; AiRMOUR, 2023) or by proposing and analysing different objective or

subjective measures to capture benefits and/or negative impacts of UAVs and eVTOLs flights.

The results of the conducted surveys show a high level of subjectivity and different perception among the individuals, but some consistencies are also observed. For example, results suggest that people generally become more open to drone usage with greater knowledge, understanding or personal experience with the use of drones (AiRMOUR, 2023).

Noise and visual pollution are the two most addressed negative effects, related to the implementation of UAVs and eVTOLs as part of UAM. Relevant research, related to those aspects, will be discussed in more detail.

The majority of the reviewed research, dealing with the assessment of UAM, points out the relevance of noise issues (Rizzi et al, 2020; Torija & Clark, 2021), or both visual pollution and noise issues (as negative effect) for public perception and UAM acceptance (Wang et al, 2023). Research conducted in the study Stolz & Laudien (2023) showed that experiencing drone flights in the virtual simulation changed the attitude and concerns of the participants, e.g. participants' worries about noise and privacy related to drones significantly decreased.

Performance framework

The proposed focus areas are mostly based on the SESAR performance framework provided in the PJ19-W2: SESAR Performance Framework - U-space Companion Document (PJ19-W2 CI, 2023) and in related projects (DACUS, AiRMOUR, etc.), while the indicators have been proposed based on a comprehensive literature review carried out.

The list of proposed Key Performance Areas (KPAs) is the following: Noise (NO), Visual pollution (VP), Privacy concerns (PC), Access and equity (AE), Economic aspects (EA), Emissions (EM), Wildlife (WL), and Security (SC).

The indicators to be proposed that represent the impacts in those areas focus on measuring the number of people affected by a certain effect, e.g., the number of people exposed to an equivalent noise level (L_{Aeq}) higher than a certain threshold in dB, for a fixed period of time, within an area. By doing this, the performance framework focuses on the social dimension of the negative effects, and weights them with the population presence. It is not the same, for example, a high noise level in a densely populated area than in an industrial area, where less people is affected.

All the indicators proposed can be combined with different cross-cutting areas in order to enable the analysis of the interaction between UAM impacts and factors such as age, gender, place of residence, level of income, occupational status, etc. Going back to the previous example, the number of people exposed to an equivalent noise level (L_{Aeq}) higher than a certain threshold in dB, for a fixed period of time, within an area, may be segmented into the different age groups considered.

3.2 Impact assessment toolset

This subsection summarises the developments completed in relation with the U-Space Environmental and Social Impact Assessment Toolset previously described.

Trajectory generation engine

GEMMA, the trajectory generation module, has been designed to support a variety of missions in mind. It assumes a U-space airspace is in place to support the high number of operations, specially from last-mile aerial delivery. With a smaller number of trajectories GEMMA also generates emergency medical samples transportation and security tasks as the ones performed by local police. Small air vehicles are used, with vertical take-off and

landing capabilities and operational performances obtained from current manufacturers specifications. Several operators are defined with a delivery centre hub and an owned fleet of drones. At any moment, multiple flights from multiple operators may be on air simultaneously.

Delivery operations depart from the operators' logistic hub, deliver at destination and return back for further operations. The destination of the drone deliveries is randomly selected, with more probability for those areas with higher population density. The city defines the hours when flights are allowed. A probabilistic function is used to simulate top business hours.

The high level of parametrisation permits the definition of the geographic area (U-space geocage, forbidden areas, surface model, hospitals, etc.) of the airspace, the number of operators, their location and the maximum flights per hour they can manage, the available fleet of aircraft to be used and the social events subject to security scrutiny by police. It is also configurable the airspace rules of the air for delivery flights, as free route or through an airspace network. To easily scale the traffic a multiplicative factor can be also defined to the base configuration ranging from 1 to 256.

An example of the flight initial routes generated in a simulation is shown in Figure 1, where delivery operations are depicted in blue, emergency in red and security operations in yellow. The purple area is the centre of the city.

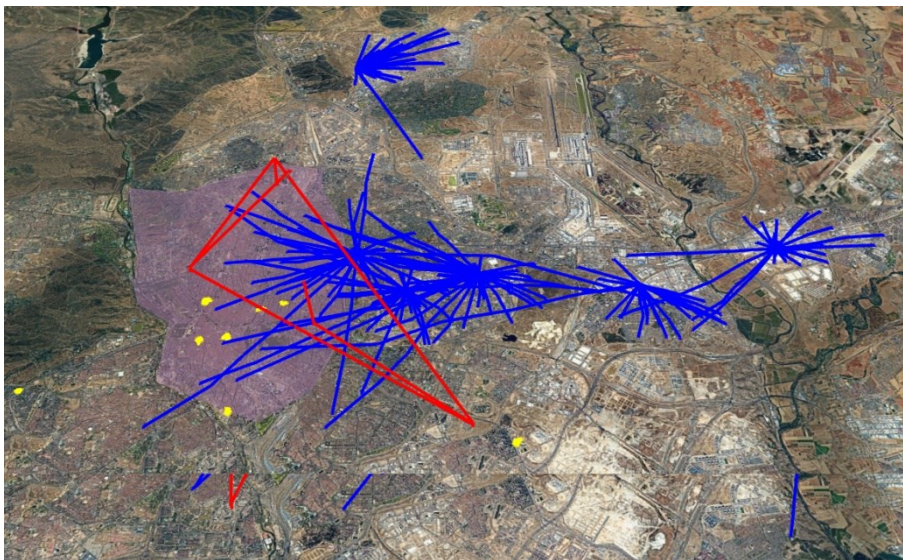


Figure 1: Free route traffic generated for one day in Madrid

To be more realistic the parcel delivery to be performed in the city centre, where open spaces to land are rare, we can also define the limits of the city centre and permit only to land at prepared premises or vertiports. Similar to the concept of operations that was already well established in the, Metropolis2 SESAR project the trajectory of drone delivery in the core city centre will follow a specific set of predefined aerial network. Several networks can be used when given to GEMMA in the form of a graph. Moreover, the graph can be replicated at different altitudes with a safety sliding distance between the different layers.

An example of a network created as a regular grid over the city and how the delivery trajectories follow the network is shown in Figure 2. The same colour code applies for the different type of operations, but in the centre of the city now one layer of the network is shown in green. Notice that security and emergency operations are allowed to not follow the network. Safety is possible thanks to the vertical separation between operation types. Routes are optimised with the A* algorithm, which penalises the number of turns.

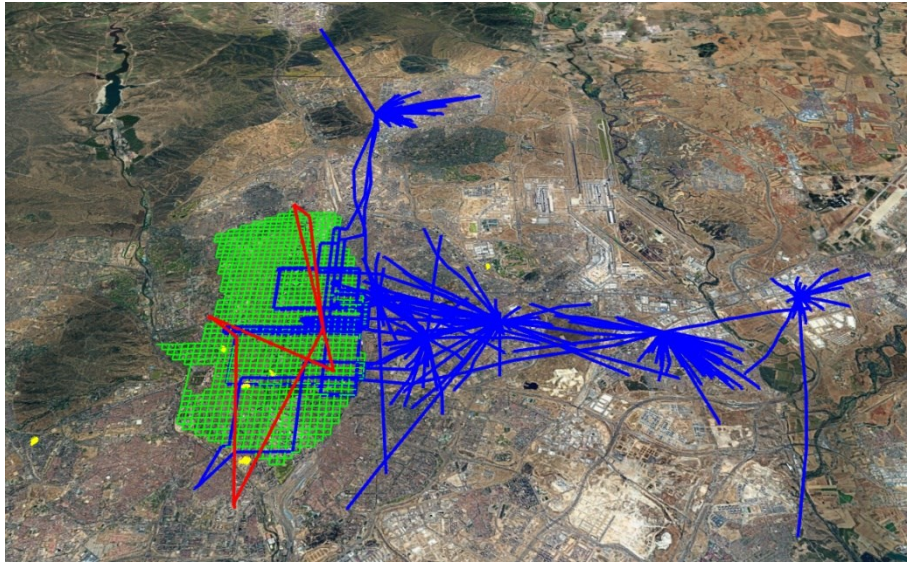


Figure 2: Route traffic generated for one day in Madrid through a regular grid network

Future simulations will include also vertical separation for North/South trajectories with respect to East/West ones. Also, a new aerial network to follow the city road network. Figure 3 shows an example of the A* optimisation on a grid-like tracks graph. Note that the resulting best path depicted in orange minimises the number of sharp turns.

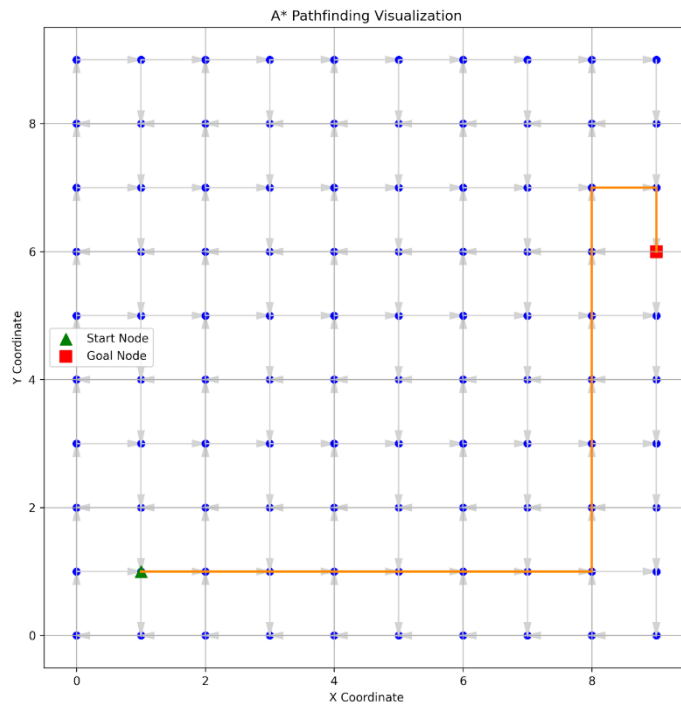


Figure 3: A* algorithm routing with the shortest path and minimising turns

Noise impact calculation

The noise module is composed of three tools: flight mechanics (DynaPyVTOL), noise source calculation (CARMEN) and noise propagation (NoiseModelling). While the two first are ONERA in-house tools, the latter is an open-source software. The three tools are used chronologically: DynaPyVTOL exploits the output of the trajectory generation module GEMMA and delivers dynamic vehicle and propeller data to CARMEN to calculate the noise emission at each time step. And finally, NoiseModelling aggregates all noise emission spheres, calculates the propagation and delivers noise maps with the noise indicators defined in the Performance Framework (3.2).

At the time of writing this paper, the flight mechanics tools have successfully been implemented and first drone types and missions have been calculated. It is able to deliver all necessary input for the CARMEN noise calculations along the whole trajectory of a single drone mission. All it needs is a drone geometry (number of propellers, number of blades etc.) and a targeted trajectory, translated by waypoints and targeted velocities at those waypoints. With this input it calculates whether the considered drone is able to fly the given trajectory and what settings are needed to achieve it.

Figure 4 shows an example of a drone visualisation and how a scenario input trajectory is successfully followed by the flight mechanics tool. Since we are aiming at an automated loop of calculations over a whole scenario (comprising several hundred missions), case specific fine tuning will not be manageable and generic behaviour laws will have to be considered.

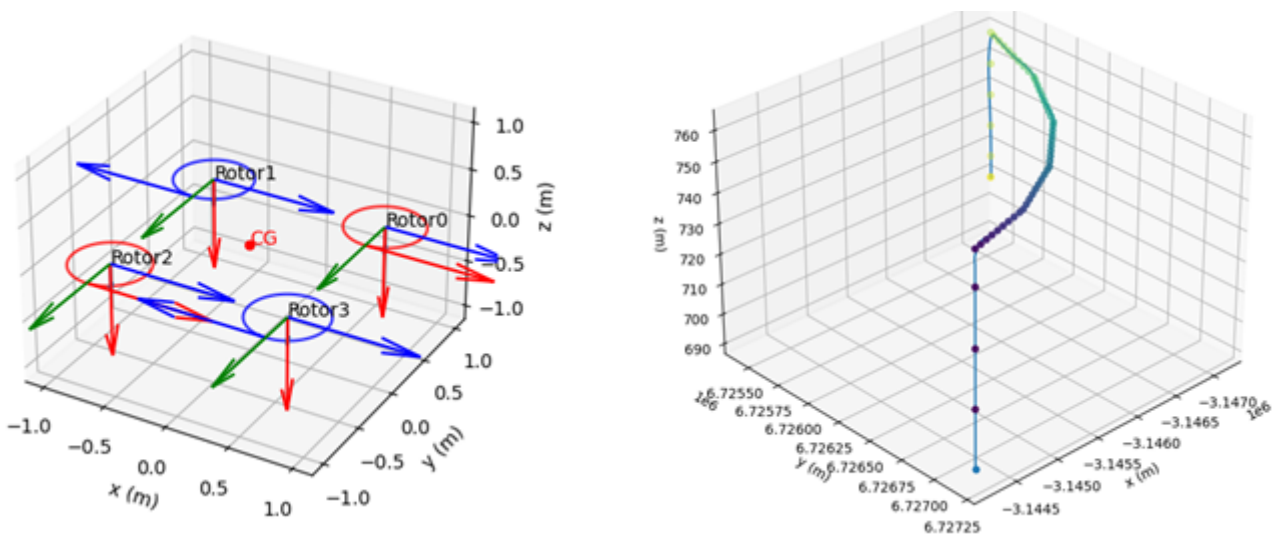


Figure 4: (Left) Quadcopter visualisation; (Right) Target mission (dots) and effective trajectory (line)

The output data, i.e. the exact flight trajectory, 3D vehicle orientation and dynamic drone parameters such as propeller thrust, torque, RPM etc., are successfully fed into the noise emission calculation tool which calculates the noise emission spheres at all time steps defined by the new realistic trajectory.

An important work was done on pre-processing to facilitate the automation process of DynaPyVTOL and CARMEN calculations. One calculation cycle can, now, be launched for a whole scenario including one drone type. It is, for now, limited to one drone type and has therefore to be concatenated afterwards with others to reach the whole scenario. This is due to the fact that drone parameters and behaviour laws cannot be made automatic in DynaPyVTOL, but are adapted manually in the code, based on experience and user knowledge.

The noise emission calculation is currently being optimised and limited to time steps only when significant drone parameter changes happen.

Finally, noise propagation is done based on a ray tracing method with the open-source software NoiseModelling (Bocher et al., 2019) which implements the CNOSSOS-EU (Anfosso-Lédée et al, 2012) directives on rail and road noise propagation. One can adapt all case specific input parameters about the sound sources (sound power level, directivity and positions), the characteristics of the city (buildings shape, type of ground, digital elevation model) and meteorological factors (temperature, hygrometry...). Noise source spectra are reduced to octave bands, neither upward-refraction conditions nor constructive interferences are considered, and aerology considerations are limited.

A Delaunay grid is chosen for the receiver positions for our application. The attenuation is calculated along the ray paths taking into account geometrical divergence, atmospheric absorption, ground characteristics and diffraction, leading to sound pressure levels in octave bands at every receiver position. An example for propagation paths visualisation and an example noise map are shown in Figure 5.

Currently, work focuses on the calculation of MUSE noise indicators with the NoiseModelling output.

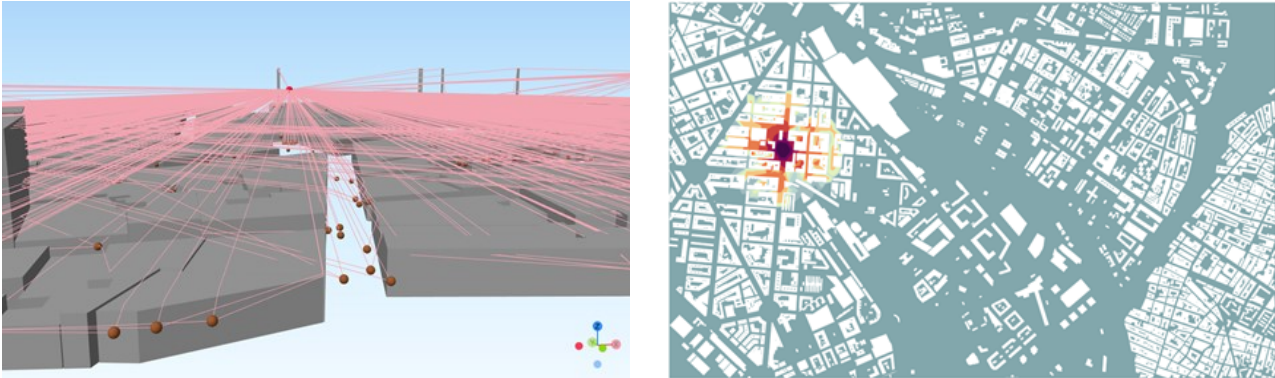


Figure 5: (Left) Propagation paths (diffractions and one order of specular reflections enabled), from a 20 m high source to receivers in a district of Madrid; (Right) Noise map representing a single omnidirectional noise source

The interface between CARMEN and NoiseModelling was successfully achieved. A dedicated publication on the work done on the three tools chain can be found at LeGriffon & Ruaud (2024).

Visual pollution modelling

The visual pollution module uses functionalities available in standard GIS software to perform analysis of the landscape visibility from raster data, coupled with a geometric analysis of the drones visible from the ground along their trajectories. The landscape raster data to be used are the Digital Surface Model (DSM) of the area to be studied, which includes not only terrain elevations but also buildings and other human constructions that affect visibility. Data defining the trajectories and the size of the drones are to be used to calculate the areas from where drones are observed and the severity of the impact on citizens.

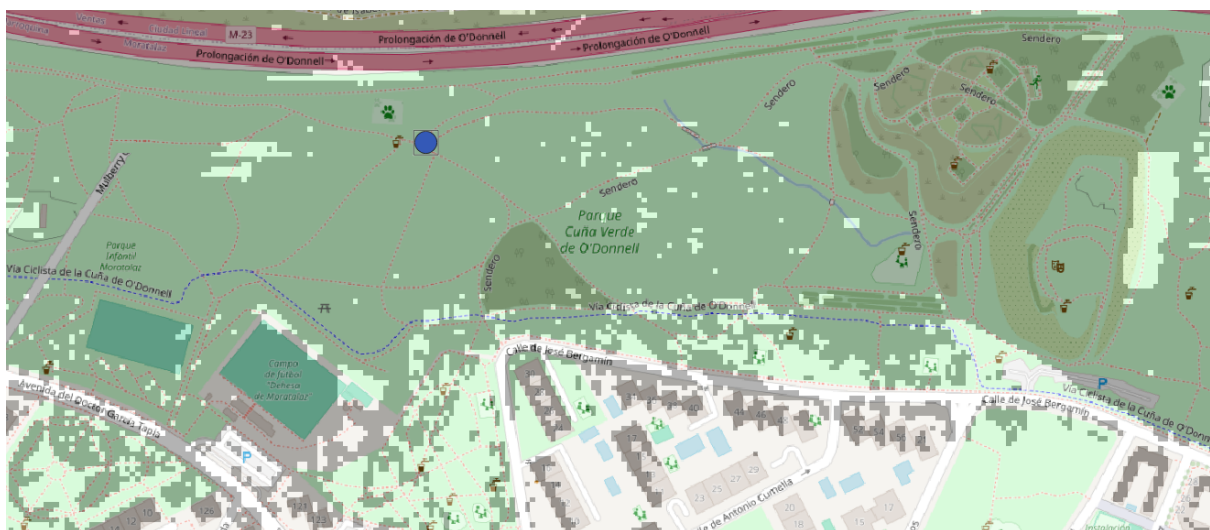


Figure 6: The shadow area represents the area where the drone (represented by the blue dot) is visible.

In order to quantify the visual pollution concentration (VPC), either from a single drone or from all drone traffic, the visible area occupied by the drone is used. The visual area occupied by the drone is compared to the visible area from the observation point, free of

urban objects (open sky). The goal is to measure the impact from the most conservative point of view, in which the drone blocks a line of sight that was previously unobstructed by other objects. This definition takes into account the distance and the drone's characteristics (width and length of the drone). To calculate the visible area occupied by urban elements in the absence of drones, we are going to use an open-source library that performs visibility studies, gdal viewsheed.

Finally, the visible area occupied by the drone, $\Omega(drone)$, is calculated using trigonometric formulas that take into account the distance at which the drone is, its width and length (a), see equation below.

$$\Omega(drone) = a/R^2 \quad (1)$$

Then, the visual pollution concentration is defined as the ratio between the area occupied by drones and the area free of urban objects:

$$VPC = \frac{\sum \Omega(drone_i)}{\Omega(open\ sky)} \quad (2)$$

Population presence and exposure calculation

The Mobile Network Data (MND) has a limitation on the geographical resolution of its indicators. To address this limitation, we combined the results with other source of data, GPS from mobile apps, and we have developed an algorithm to disaggregate the indicators to smaller areas (Gonzalez et al, 2024). In MUSE, visual and noise pollution vary greatly with distance, requiring a resolution of just a few meters. However, there is a constraint on the minimum size of the square grid for disaggregating population presence, as sufficient GPS data is needed in each grid square to obtain meaningful results.

This step consists of calculating the probability of being in the different parts of the square grid, for different times of the day. This heat map of probabilities is then applied to the Nommon Population Insights indicators, that are segmented in areas of several hundred meters of width and length, to a grid of a few meters.

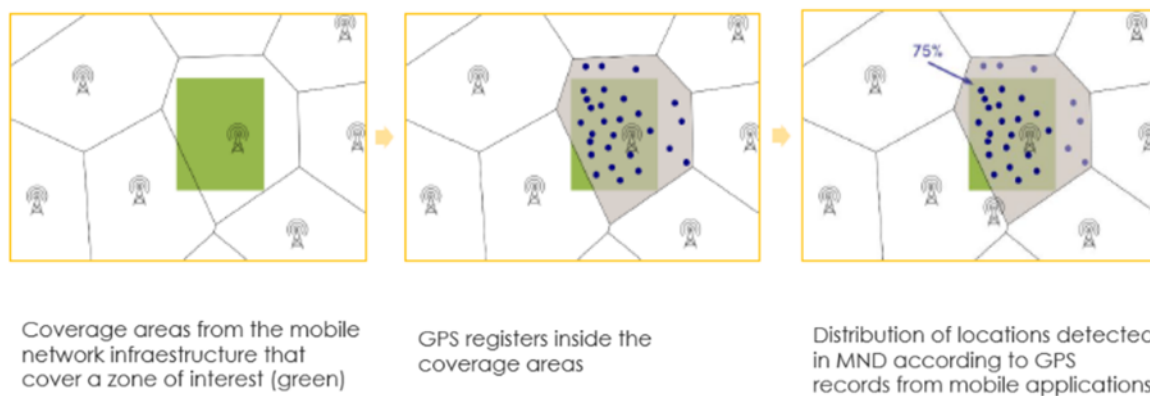


Figure 7: Disaggregation of population presence indicators from antenna coverage areas to smaller areas.

With this improved positioning, and considering other factors such as time of the day, activity performed, etc. the population location will be evolved to differentiate between indoor and outdoor activities.

The exposure calculation module will correlate noise and visual pollution indicators with population presence to obtain people exposure to UAM noise. At this moment, the development is ongoing to match the noise and population data.

3.3 Case studies

Our case studies will be based in the city of Madrid (Spain), due to variety of reasons: (i) most of the data required by the project are available as open data (e.g., land use, passenger sensor data, background noise), have previously been acquired by some consortium partners (e.g., 3D city models), or are available through specific agreements with data providers (e.g., Nommon's agreement with Orange Spain); (ii) the Madrid metropolitan area encompasses a wide variety of urban and peri-urban environments with very heterogeneous characteristics; (iii) the consortium Coordinator, Nommon, has a privileged relationship with the Mobility & Environment department of the Madrid city government and other local stakeholders, with which Nommon collaborates on a regular basis in the context of numerous consulting and research projects, which will ensure the relevance of the proposed case studies.

There are a variety of missions acknowledged in the relevant literature that are aimed to be covered by the UAM operations (e.g., parcel delivery, food deliveries, loitering missions, emergency mission). The definition of the initial case studies was performed in a close interaction with relevant experts in order to cover a range of realistic UAM applications. For this purpose, we created the survey which aimed to assess the most plausible scenarios with respect to two case studies that are envisioned to be performed during the course of the project, i.e., parcel delivery and emergency (medical) delivery. These two case studies are considered one of the most immediate UAM applications. The survey was distributed among the group of experts who attended the U-space Coordination Cell (UCC) meeting hosted by Castelldefels School of Telecommunications and Aerospace Engineering (EETAC-UPC) in April, 2024. The group of experts gathers the individuals from six different institutions that are prominent in the UAS field. Finally, the feedback from 14 respondents were collected and used for initial definition of the scenarios. However, the case studies will be consistent with the operational concept outlined, which assumes two different types of airspace, i.e., constrained airspace and open airspace.

The parcel delivery operations are mainly envisioned to be performed within the core of the city centre (it will eventually coincide with the perimeter of the M30 road) which is characterised as a densely populated area. It entails that we will need to follow the street-based network or alternatively, a grid-like structure, the concept which enables the deconfliction of the drone trajectories in an efficient way. However, the drone operations can be also performed from/to the outskirts of the city in which case we could follow the free route airspace structure. Consequently, the origin and destination selected for the parcel delivery of the route will determine the final route length. In this vein, we will try to be as realistic as possible adhering to the range capabilities of the current drone types, but also enabling some margins to encounter for further enhancement in the drone technology.

The definition of the characteristics of the drones considered for the study will be based on desk research. The members of the consortium already identified several drone types which characteristics can perfectly meet the given purpose. The drones which specifications are fully available in GEMMA tool are listed as follows: 3DR-Solo; DJI-3 Pro; DJI-4 Pro; DJI-4k; DJI-Advanced; DJI-FC40; DJI-Phantom 1; DJI-Phantom 2; DJI-Phantom 3; DJI-Phantom 4; DJI-Vision; Parrot-albris; Parrot-bebop 1; Parrot-bebop 2; Eurocopter EC135; DJI Matrice 600; Amazon octocopter; Matternet quadrocopter; DJI Matrice 100; DJI Matrice 200; DJI Mavic pro; Horsefly Gen 5.3.

Another important parameter that needs to be defined is the plausible future demand scenarios. For this purpose, we will use different input data (sociodemographic data, economic data, population activity-mobility patterns, official statistics and available reports on e-commerce and delivery services, etc.), building on the approach proposed by Doole et al. (2020). The demand will be distributed across vertical layers which will ensure the safe and efficient flow of the total traffic.

Taking all these elements into account, the results of the survey revealed two scenarios that will be initially tested in the case of drone parcel delivery.

Table 1: Case studies in parcel delivery mission

| ID | ConOps | Vehicle type | Origin of the route | Destination of the route | vertical layer occupied | route length | Capacity of distribution centre |
|-----------|---------------------|-----------------|-----------------------|------------------------------------|-------------------------|--------------|---------------------------------|
| CS01-SC01 | Grid-based network | DJI Matrice 600 | Outskirts of the city | Within the core of the city centre | 45m and 65m | Up to 10 km | Up to 20 ops/hour |
| CS01-SC02 | Free route airspace | DJI Matrice 600 | Outskirts of the city | Outskirts of the city | 45 and 65 m | Up to 15 km | Up to 20 ops/hour |

Given that the number of combinations can grow very quickly, the remaining scenarios to be analysed will be selected in a way that prioritises the questions proposed by stakeholders during one or more co-creation workshops (primarily the second MUSE Stakeholder Workshop planned). This selection will also focus on studying the impact of UAM on the population and evaluating the full range of functionalities of the MUSE Solution. The first series of bilateral meetings with relevant stakeholders is planned for late January or early February 2024, where consortium members will present initial ideas and assumptions on the definition of the case studies and discuss them with experts from different fields.

4. CONCLUSIONS AND FUTURE RESEARCH

The performance framework presented in this paper provides a holistic approach to analyse UAM impact on citizens, taking into account crucial aspects such as noise, visual pollution, privacy, equity, etc. and providing visibility on the effects to the different sociodemographic groups (differentiation per age, income, place of residence).

The preliminary results on the different developments conducted to measure those indicators show their potential to capture the mentioned impacts of UAM. However, we will need to wait until the different modules are integrated to showcase the benefits of the performance framework in the different case studies.

As the authors envision the toolset proposed, it may serve in the future to 3 main purposes related to their stakeholders involved:

- Drone operators: To assess the social and environmental impact of their individual UAM operations, ensuring that they are minimised.
- U-space traffic manager: To manage and/or approve UAM flights considering their social and environmental impact on citizens quality of life.
- Policy makers: To identify new policies and regulations aimed at preserving quality of life on the cities. This application is strategical, in contrast with the previous ones that aim at tackling operational problems.

In the cases mentioned, it has to be noted that a regulation should be in place setting limits to the UAM impacts, a measure that is likely to happen as there are currently noise restrictions for road traffic.

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