MUSE

WHITE PAPER

MEASURING U-SPACE SOCIAL AND ENVIRONMENTAL IMPACT

LESSONS LEARNT FROM MUSE AND WAY FORWARD

Funded by the European Union

SESAR JOINT UNDERTAKING

Legal disclaimer

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Editors and contributors

Manon Coyne (POLIS)

Miguel Baena Botana (NOMMON)

Cristina Barrado and Jovana Kuljanin (UNIVERSITAT POLITECNICA DE CATALUNYA)

Emir Ganic and Tatjana Krstic (FACULTY OF TRANSPORT & TRAFFIC ENGINEERING, UNIVERSITY OF BELGRADE)

Ingrid Legriffon and Elise Ruaud (ONERA)

Antoine Masse and An Vo Quang (IGN FI)

Editing and layout: POLIS

MUSE Objective

The MUSE project developed a set of key performance indicators, methods, and tools for the comprehensive and rigorous assessment of the impact of UAM operations on the liveability and quality of life in European cities, with a particular focus on drone-generated noise and visual pollution.

Read more: https://musesesarproject.eu/

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IGN FI

Introduction

Setting the context

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 [1]. U-space is defined as a set of new services relying on a high level of digitalisation and automation of functions and specific procedures designed to support safe, efficient and secure access to airspace for large numbers of drones.

Over the next 10 years, the implementation of U-space is expected to facilitate a variety of UAM use cases, such as medical and emergency transport, delivery of goods, passenger transport services, etc. The deployment of these use cases will, in turn, accelerate the development of new technologies and lead 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 European Union [2]. 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 [3]. The project SESAR 2020 PJ19.04, and now the SESAR project PEARL have begun to develop a U-space performance framework [4] that includes a set of indicators to evaluate UAM's environmental impact.

While this is a first step in the right direction, their 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. 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 MUSE project aims to address this pressing need by developing a comprehensive framework to assess U-space Environmental and Social Impacts, intended to serve as a basis for a future U-space service focused on optimising the social and environmental performance of UAM operations.

The White Paper's purpose and structure

The MUSE White Paper provides a high-level view of the main results and conclusions of the EU-funded project MUSE. It targets decision-makers at an executive level, with the aim of promoting the project results and fostering their adoption and further development. It also launches a debate on the impacts of aerial mobility in urban environments, bringing relevant inputs to assess use cases and define priorities.

It is intended for the following readers with specific objectives:

- Drone manufacturers and operators with information on criteria to measure the performance of their products and activities (and UAM service users, such as logistics, health, or police services, to make informed choices on the service they use);
- U-space service providers and Unmanned traffic managers with new solutions to integrate into their operations, and criteria to define priorities and rules for unmanned aerial operations’ systems;
- Aviation authorities with input supporting the definition of standards for registration, certification and homologation of unmanned aircraft and pilots;
- Insurance stakeholders financially supporting the market development;
- National and European authorities with data to support market regulation and procurement of research and service development;

- Local and regional decision makers responsible for citizens' health, services of general interest, transport and logistics services, and urban planning, with inputs to better answer citizens' needs and increase local and regional quality of life;
- Researchers and the SESAR 3 JU with inputs for further research and developments;
- Health and Citizen representatives with information on existing means to improve their quality of life and support further reflection and action on the topic.

The White Paper focuses firstly on the context around the development of the MUSE solutions, the objectives behind the work conducted, and the outcomes resulting from this, to be exploited further. In a second part, the MUSE White Paper investigates the assumptions used in the project to discuss the social and environmental role of unmanned aerial services in urban areas. Proposed flight routes and features are presented, their expected advantages and the risks anticipated in the project are highlighted, and the challenges for decision-makers are explained. In the final part, concrete recommendations towards the target audiences are defined, based on the conclusions of the project. The conclusion proposes a future outlook in the perspective of exploiting the MUSE results in further research, aiming for later-stage implementation.

The role of MUSE in U-space and UAM

The main role of the solutions developed in the MUSE project is to assess the impacts of U-space on citizens' quality of life. But what is U-space, and what is quality of life? Definitions are needed to identify the object of measures (U-space) and the object of analyses (quality of life).

Definitions

Using generic definitions from recognised institutions framing the topic, the MUSE partners have defined more precisely the elements at the heart of their research and development process: U-space and UAM, citizens' quality of life, and expected impacts.

- **U-space and UAM**

U-space is the digital and regulatory system that enables the safe, efficient, and automated management of drone traffic in European airspace, as described by the SESAR Joint Undertaking. UAM is defined as the safe, secure and sustainable air transport of passengers and cargo in urban environments, enabled by new-generation technologies integrated into a multimodal transportation system, according to EASA. U-space is then the system enabling UAM. In the MUSE project, the proposed performance assessment targeted UAM operations – not solely the system enabling them.

- **Citizens' Quality of Life**

Quality of life refers to the 'overall well-being and satisfaction that individuals or communities perceive of their position in life in the context of the culture and value systems in which they live, and in relation to their goals, expectations, standards and concerns' [5]. It is a multidimensional concept that encompasses physical health, mental and emotional well-being, social relationships, economic status, education, and the environment (OECD, Eurofound, Eurostat).
It is often assessed through surveys and indices that consider a range of indicators to measure and compare the well-being of individuals or communities. Policymakers, researchers, and healthcare professionals often use these assessments to inform decisions and interventions aimed at improving overall quality of life.

To reflect on that and provide a rigorous assessment of UAM's social and environmental impacts, the MUSE partners have developed a comprehensive indicator system that provides the highest possible level of spatial, temporal, demographic, socioeconomic and behavioural resolution. All the indicators proposed can be combined with different cross-cutting areas (Table 1) 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. Such an approach can generate hundreds of different indicators that could be tailored to the specific challenges and needs of the various communities.

Cross-cutting area	Sub-area	Factor
Geographical	Level of urbanisation	Urban, Sub-urban, Rural
	Land use	Recreational, Residential, Industrial, Commercial
	Purpose of use of the facility	Hospital, School, Sport venue, Military, Industry, Governance
Temporal	Time	Morning, Evening, Night, School time, Work time
	Day	Weekday, Weekend
	Season	Winter, Spring, Summer, Autumn
Purpose of flying	Purpose of flying	Delivery of goods, Medical, Infrastructure surveying, Emergency transport, Passenger transport
Demographic	Age	Age groups (<25, 25-44, 45-64, >65)
	Gender	Female, Male, Other
Socio-economic	Occupational status	Employed, Unemployed, Student, Pupil, Retired
	Income level	Low, Average, High
Phase of flight	Phase of flight	Take-off, Landing, Cruise
Activity type	Activity type	Home, Work, Education, Other

Table 1: MUSE Cross-cutting areas

- **Considered impacts**

The impacts assessed relate to the externalities of these operations that affect citizens and the environment in urban areas. They have been categorised into 8 focus areas based on the European ATM Master Plan, 2025 Edition [6]. Using previous project research, a literature review, and stakeholder feedback from several workshops, the identified focus areas included noise, visual pollution, privacy concerns, access and equity, economic aspects, emissions, wildlife, and public safety. Within these areas, 41 indicators were defined (Annex 2). Their extended definition and computational methods are detailed in the MUSE deliverable 3.1 U-space Environmental and Social Performance Framework [7].

MUSE purpose

Measuring UAM social and environmental performance comes down to assessing the externalities of air transport of cargo in urban areas on the overall well-being and satisfaction of citizens, focusing on noise, visual pollution, privacy concerns, access and equity, economic aspects, emissions, wildlife, and public safety. This includes four specific objectives, which are detailed below.

- **Define a set of U-Space social and environmental Performance Indicators (PIs)**

The MUSE framework aims to accurately capture the impacts on citizens' quality of life with the highest possible level of geographical, temporal, demographic, socioeconomic, and behavioural detail. This process specifically validates the relevance and comprehensiveness of the proposed focus areas related to UAM's environmental and societal impacts on citizens' quality of life, the relevance of the proposed indicators to these focus areas, the measurability of the proposed indicators and the availability of necessary input data, and the usability and influence of cross-cutting factors (geographical, temporal, demographic, socioeconomic, and behavioural) on the proposed indicators.

- **Develop new methods and tools for the measurement and forecasting of the proposed PIs**

After validating the PIs and ensuring they reflect the variations of citizens' quality of life depending on their confrontation with air transport in cities, the MUSE project intends to develop methods and tools to collect data on these indicators, to achieve their exploitation. Since assessing impacts also means to anticipate them, a calculation of indicators should be possible ahead of flight operations, in their planning phase.

In addition, as air transport operations in urban environments are not frequent enough to collect data on existing services in the required quantity and of sufficient quality, modelling of potential services is necessary.

Considering this, the purpose of MUSE was also to enable the generation of trajectories corresponding to realistic potential flights in urban environments, and the calculation of defined indicators on these virtually generated flights. This includes the modelling of the emitted noise, the perceived visual pollution on the ground, or the distribution of population across the streets at any time, among other aspects.

Finally, the project framework and toolset are intended to support a prioritisation of the development and deployment of the most performant aircraft and air transport services, improving their integration into urban ecosystems and networks. These developments and deployments require collaboration with multiple stakeholders, whose coordination and decisions could then rely on facts and data providing clear indications on service and technology priorities in view of public health and social well-being. In this regard, the results of calculations should be understandable and easy to visualise by decision makers on these topics.

- **Showcase and evaluate the capabilities of the new methods and tools**

To ensure the exploitation of the developed toolset beyond the project lifetime, it should be tested and validated. To this end, the third specific objective of the MUSE project is to apply the toolset to defined case studies in a European city, which are relevant for the target audiences of the results.

- **Create the conditions for the transfer of the project results**

Finally, in addition to validating the toolset developed, all results of the MUSE project (including the framework and the validation results) require dissemination to the subsequent stages of the R&I cycle by outlining a new SESAR Solution. Dissemination is also intended towards other target audiences than the SESAR community and researchers, which entails the development of dissemination material in the form of clear and efficiently promoted recommendations.

Outcomes of the MUSE project

To fulfil the extensive purpose described above, the MUSE partners have developed a framework that comprises three main components, intended to serve as a basis for a future U-space service focused on optimising the social and environmental performance of UAM operations:

- A **Performance Framework**, which enhances the measurement and understanding capabilities in the proposed focus areas by providing indicators of UAM impact on the population depending on factors such as age, gender, place of residence, level of income, and occupational status, among others. All the indicators are included in Appendix B.

- A **Decision Support Framework**, which includes: (i) a set of models and simulation tools to generate trajectories and calculate the indicators of the performance framework, using state-of-the-art noise and visual pollution modelling and dynamic population mapping methods [8]; (ii) a visualisation tool that enables users to analyse the indicators through an interactive dashboard for supporting decision making (https://muse.ext.nommon.es/).

- A **set of lessons learnt and recommendations** on how the Decision Support Framework can support the minimisation of the environmental impact of different types of UAM operations, based on the results of specific demonstrations conducted with the developed solutions.

The use and impacts of U-space and UAM in society

To better understand the impact on quality of life, collecting data on running UAM services is necessary. But the current scarce number of operations to collect data from, and missing data collecting tools and methods in that sector [9], are an important obstacle to overcome.

Therefore, defining the scenario of operations is key to enabling impact assessment. This process requires a **selection of case studies**, which are analyses of specific use cases (description of use of a system [10]); the **description of a potential concept of operations**, identifying the characteristics of the proposed system from the viewpoint of an individual who will use it; and the **specification of the scenario**, setting conditions and parameters of operation of the selected case studies (urban area and day time of operation, UAM demand levels, vehicle types, etc.). This specification was based on practical considerations and assumptions proposed by the MUSE partners and validated with external stakeholders to facilitate the scenario execution.

Defining a relevant scenario to anticipate UAM service characteristics

Beyond identifying existing trends and flight characteristics, the case studies' selection also underlined which UAM operations might be happening in urban environments and how, based on the needs of citizens, businesses, and local and regional authorities. Addressing dense urban structures, where apartment buildings are standard, the project partners used Madrid as the case studies' location. For cost-benefit purposes, the study focused on a predefined zone within the city centre that includes key elements such as residential areas, recreational zones, restricted locations (e.g., the Royal Palace), and hospitals.

Parcel delivery case study description

Parcel delivery Context: Over the past decade, shopping habits in Europe have significantly evolved, with a substantial number of consumers now preferring online shopping [11]. Unmanned Aerial Vehicles (UAVs), or drones, are increasingly becoming popular for delivering small packages in urban areas.

Major players in the retail and logistics industries, including Amazon, Google, UPS, DHL, and Alibaba, have capitalised on this promising concept, making significant investments in large-scale experiments with delivery drone systems.

Parcel delivery ConOps: Parcel delivery operations are mainly envisioned to be performed within the core of the city centre of Madrid (M30 road perimeter), characterised as a densely populated area. Two models were considered: a free route model, where the flights go on a direct route from origin to destination; and a constrained model, which entails that the drones need to follow the street-based network, or, alternatively, a grid-like structure, enabling deconfliction of drone trajectories in an efficient way. Outside this densely populated area, flights have no restrictions on airspace structure.

Parcel delivery Scenario: To ensure the realism of the scenario, replication of the existing network of facilities established by prominent distribution companies is chosen. Hubs are distinguished from lockers: hubs serve as distribution centres (DC), while lockers function as vertiports for drone operations. A realistic expectation is a maximum of 10 distribution centres within the core of the city, and a considerably larger number of vertiports, in alignment with the findings of numerous studies in this field (Table 2).

Parcel delivery expected benefits: Drones offer operational advantages such as shorter delivery times, higher accuracy, and environmentally friendly operations. These elements enhance the positive impacts of drones and UAM services in general on urban traffic, air quality, and commercial services. Finally, lower infrastructure requirements support a wider outreach of delivery services through UAM solutions, which improves the connectivity of society and citizens in larger geographical areas.

ConOps	Vehicle type	Origin	Destination	Flight Altitude	DC Capacity
Free route	DJI Matrice 600	Any DC	Any place	[45m ~ 90m]	60 ops/hour
Grid-based	DJI Matrice 600	Any DC	Vertiport	45m, 60m, 75m and 90m from highest terrain point	60 ops/hour

Table 2: Final scenarios for parcel delivery prioritised based on experts' feedback

Emergency delivery case study description

Emergency delivery Context: The medical sector is one of the most relevant and promising uses of drone technology, likely to gain higher public confidence and acceptance. It typically covers two distinctive missions: routine healthcare deliveries, which assume the transportation of medical supplies such as blood and plasma [12], vaccines [13], medication and other essential medical equipment; or transportation in emergency responses.

Emergency delivery ConOps: In the context of MUSE, the medical sample transportation is envisioned to be performed as an emergency service in the area of Madrid. This type of mission will typically follow the shortest path (direct) between the origin and destination hospitals. Due to the urgent nature of the mission, they will be allowed to overfly the forbidden zones and will be segregated from other UAM traffic, taking place at the upper boundaries of low-level airspace defined by the regulation.

Emergency delivery Scenario: The scenario establishes routes between pairs of hospitals, with flights within layers at altitudes of 105m and 120m. The case study involves simulating drone flights across six hospital pairs in Madrid, with up to 12 drone flights per hour. The number and distribution of operations were based on available emergency intervention statistics for the city of Madrid in 2024 (Table 3).

Emergency delivery Benefits: Aside from the time-saving aspect, drones' relevance for healthcare routine missions, such as the transport of blood samples and organs, also relates to reliability, due to a higher level of predictability of the delivery time. Safe and precautionary transport, avoiding busy areas and completed by agile vehicles easy to pilot even beyond visual line of sight and in areas difficult to access, is a key benefit for citizens' healthcare, thus contributing to higher levels of quality of life.

Characteristic	DJI Matrice 600	RigiTech Eiger	Total
Total flights	87	93	180
Mean distance (m)	5808	8256	7073
Mean time (min)	8.2	7.5	7.8
Peak hour traffic	7	10	12

Table 3: Scenario for emergency delivery

Results of the case studies and recommendations

The data gathered from these scenario runs provide valuable insights and an example of how a solid base for setting the policy recommendation could be calculated, ensuring that drone operations are efficient, safe, and well-integrated into the broader airspace management framework. The complete results can be found in the MUSE deliverable 5.1 Case Study Report [14].

Parcel delivery case study results

1- Parcel delivery: Impacts assessed

Indicators related to noise, visual pollution, access and equity, and privacy concerns were calculated and used to draw conclusions and recommendations on UAM operations to favour for this case study.

2- Parcel delivery: Performance results

- **Population mapping**

Since population presence is crucial to assessing population impacts, the analysis started with a population presence evaluation throughout the day in the areas of interest with the MUSE population mapping tools. The tool developed is based on Mobile Network Data (MND), which has proven highly effective in reflecting population presence and movement patterns (https://www.nommon.es/products/population-insights/), enriched with GPS inputs for finer spatial resolution and validated through pedestrians detected with satellite Very High Resolution (VHR) images [15]. This approach enabled a robust methodology for identifying indoor and outdoor population distribution, showing substantial promise for capturing human activity in motion, paving the way for near real-time monitoring of street-level population presence.

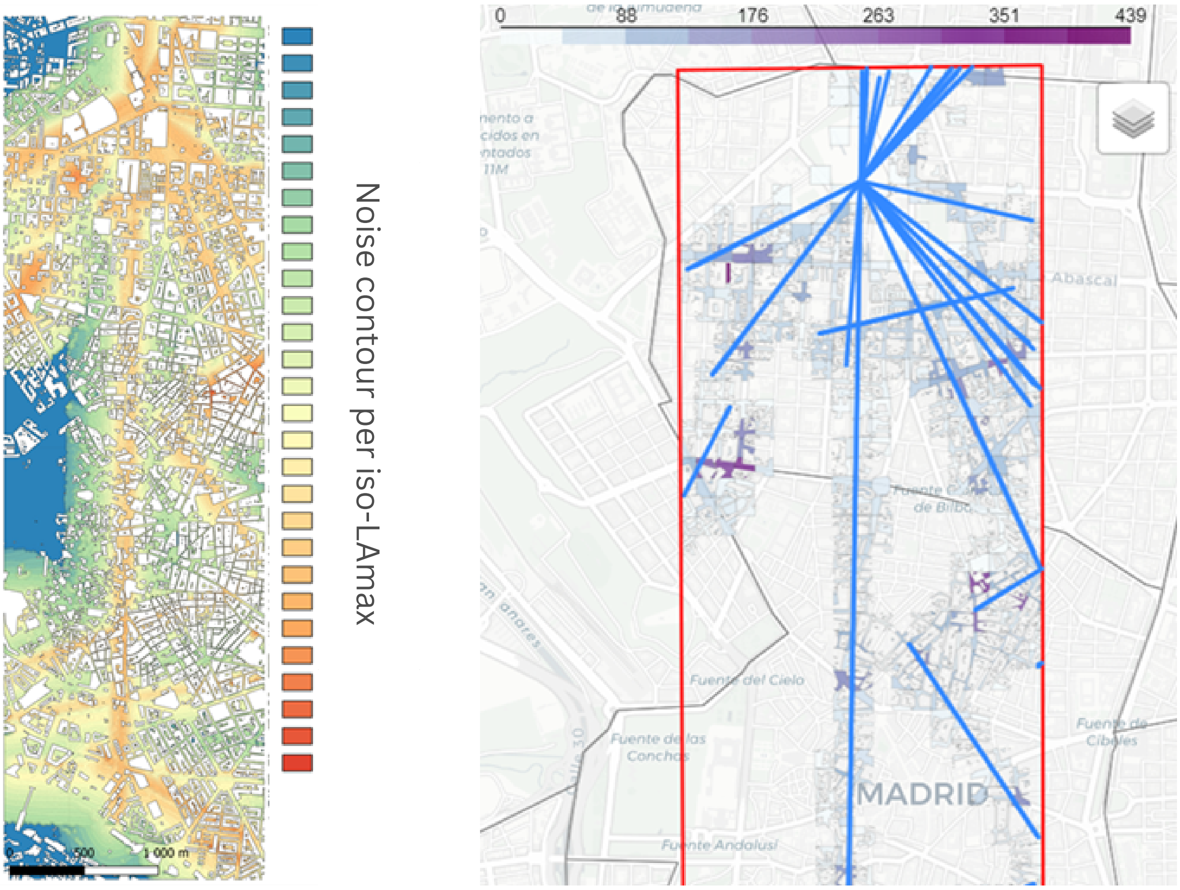
This evaluation showed a peak population presence in early afternoon hours, while the peak hour of UAM operations based on scenario definitions is the end of the afternoon. Indicators were calculated for the UAM operations' peak hours.

- **Noise impact assessment**

The MUSE tools enabled a calculation of noise maps around UAM parcel deliveries [16] for each airspace structure (free route and grid-based).

The noise levels obtained in the course of the project should not be used as absolute values, due to specific hypotheses used in the simulations, but should provide relative data for scenario comparisons, so as to contribute to informed decisions on the most adequate airspace structure. For example, scenario calculations showed that, because of higher altitudes, UAM parcel deliveries operated in a grid-based airspace structure affect a lower number of people when it comes to noise above a certain level than UAM parcel deliveries operated in a free route airspace structure (Figures 1 and 2).

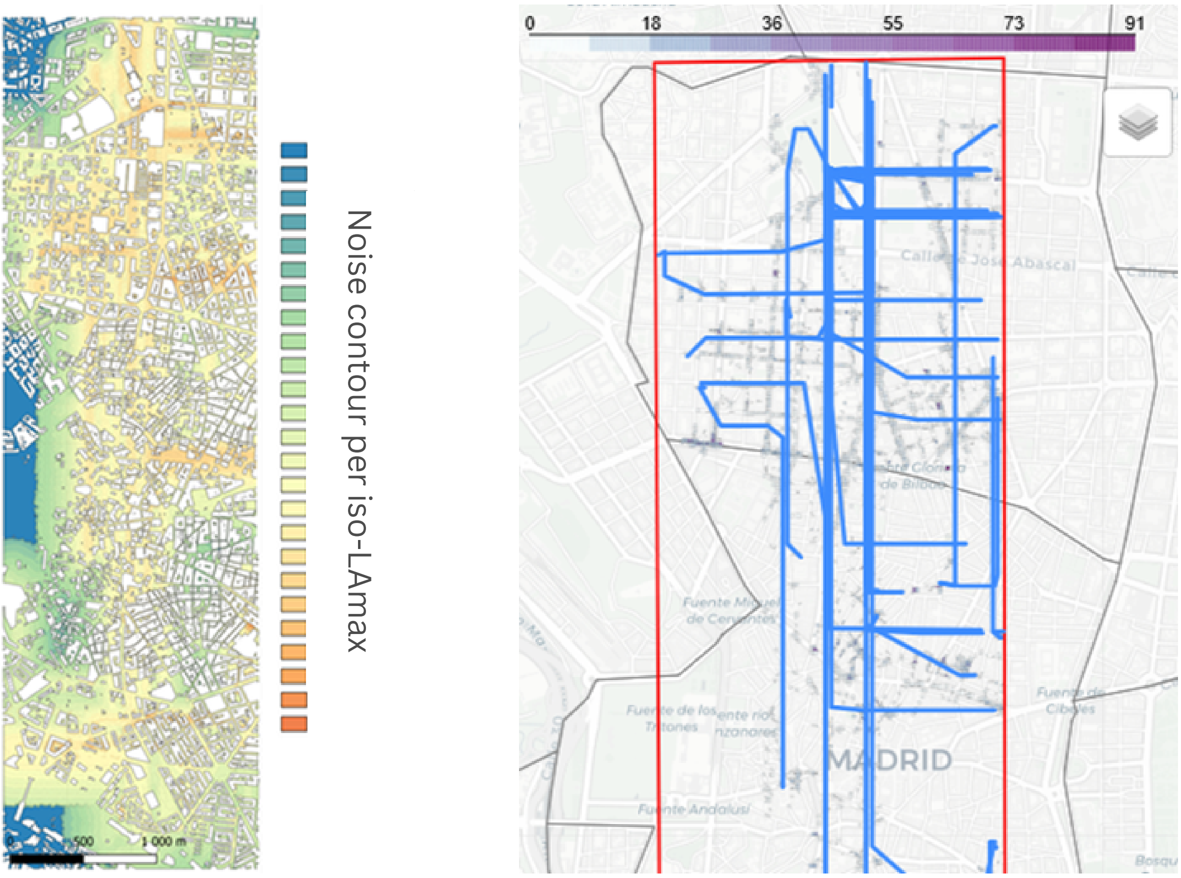
This conclusion was obtained with the calculation of indicators NO-1 (amount of people exposed to an **A-weighted equivalent noise level** ($L_{A,\,eq}$) higher than a certain threshold [30 dBA], for a fixed period of time [15 min], within an area) and NO-8 (amount of people exposed to an **A-weighted maximum sound level** (L_{Amax}) higher than a certain threshold [40 dBA], for a fixed period of time [15 min], within an area). This calculation combined noise and population maps obtained with the MUSE tools.



a) Noise map for NO-8: LAmax [dBA]

b) NO-8 result (threshold 40 dBA, 18.683 persons impacted)

Figure 1: NO-8 results with corresponding noise map at 5-5.15 p.m. in free route network



a) Noise map for NO-8: LAmax [dBA]

b) NO-8 result (threshold 40 dBA, 13.717 persons impacted)

Figure 2: NO-8 results with corresponding noise map at 5-5.15 p.m. in grid-based network

An observation deriving from the noise indicators and the used traffic data is that the main reason for the lower values in the grid-based network is the difference in operational flight altitudes between the free-route network, which roughly follows the terrain, and the grid-based network, flying at constant and hence always higher altitudes (see trajectory in red at Figure 3).

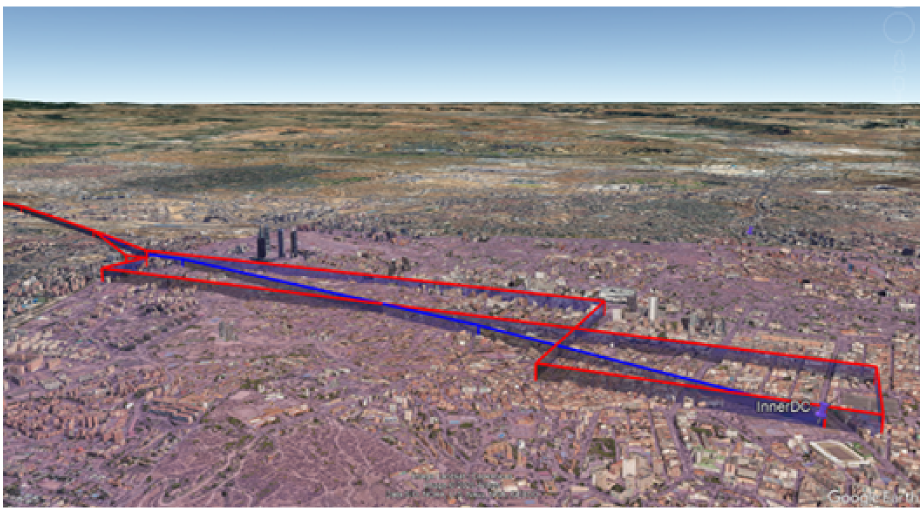


Figure 3: Same mission performed at grid-based (in red) and free route network (in blue)

- **Visual pollution impact assessment**

The MUSE tools and methods enabled the calculation of both the visual impact of a single drone and the number of individuals exposed to a visual pollution concentration exceeding a predefined threshold.

Analysing visual impact requires a definition of visual pollution and its measurement process. We considered two metrics to give an objective answer to this subjective matter, which depends on the compounded effect of disorder and excess of various objects in a landscape that the population finds unattractive, ugly, intrusive or disturbing. First, the total visual area occupied by the drone and second, an empirical metric calibrated with surveys [17]. Those metrics are used to calculate some of the proposed PIs from the given focus area.

As part of the results, we analysed the influence of departing and arriving operations, finding that arriving operations produce a longer effect, captured by indicators such as the VP-4 indicator, incorporating not only the visual pollution concentration but also the number of people exposed and the duration of the exposure. In addition, here again, the different airspace structures have been compared: the grid-based network has led to greater exposure than the free-route flights, which is mainly due to the fact that flights in this network are operated at higher altitudes, so the drone becomes visible to a larger number of people.

- **Access & Equity impact assessment**

The MUSE method to calculate access and equity is to assess the relative numbers of people affected in different areas. It is measured based on relative inequity. Figure 4 below shows the calculation used to obtain relative inequity between different areas.

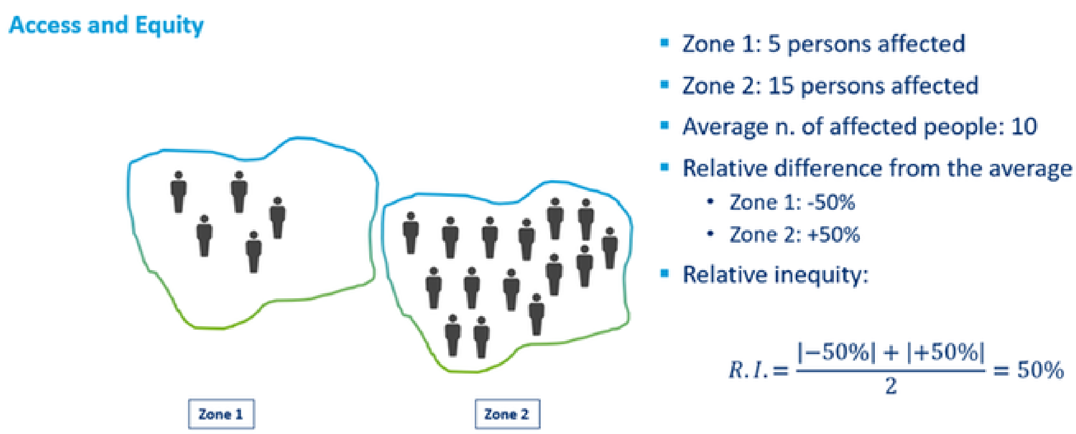


Figure 4: Relative inequity calculation method

The number of people affected is measured through noise and visual pollution indicators. The AE-3 indicator depends on noise PIs' results, assessing relative inequity of exposure to different noise levels, while the AE-4 indicator depends on visual exposure, assessed by the proposed visual pollution PIs.

- **Privacy Concern impact assessment**

Privacy concern is measured based on annoyance sensitivity values related to the land use (residential, industrial, commercial area) in the affected zones, multiplied by the VP results. The annoyance sensitivity values (Table 4) are derived from previous research results [18].

Type of area	% Annoyed	% Highly Annoyed
Commercial	30	20
Industrial	60	40
Residential	80	60

Table 4: Annoyance sensitivity values

For example, the indicator PC-3 represents the total number of annoyed people due to visual exposure for a given time period (e.g., 1h), within a given zone. The results for this indicator's calculations are aligned with the VP indicators' results.

3- Parcel delivery: Recommendations

- Influence of the UAM traffic volume on indicator results

It is important to consider the impacts of a single drone flight and of multiple operations. The MUSE indicators are complementary and enable a complete overview of the situation (for example, even when studying a drone fleet, one can focus on one specific flight).

- Influence of the time of day

Taking into account population behaviour is key to addressing their quality of life. Population presence outside determines the indicator results. Since it is strongly correlated with the time of the day, this factor can be considered when analysing indicator results. In addition, the volume of operations also varies across the day.

- Influence of gender and age

Citizens affected are the ones present in the area of interest at the time of the flights. In the MUSE case studies, women and active population were the most affected types of citizens. This means that consultation on service design and impacts should primarily involve these categories of citizens to represent affected people most accurately. However, the relative proportion of these population segments' representation should be considered to avoid misinterpretation.

- Influence of the network structure

Noise indicators show higher drone traffic impact on citizens in the free-route network because the trajectories are generally flown at lower altitudes. Visual pollution indicators show the opposite, since higher drones are visible from further away. Other aspects also influence the final results (e.g., street pattern), which enhances the necessity to use decision support tools to analyse the trade-offs of a situation before proposing new policies.

Emergency delivery case study results

1- Emergency delivery: Impacts assessed

Only the access and equity focus area (specifically the indicator AE-2 measuring the reduced travel time for health care-related deliveries) is estimated for the emergency delivery scenario, since the indicator values for other focus areas, such as noise, visual pollution and privacy concerns, are negligible in the case of emergency delivery, due to a small number of flights.

2- Emergency delivery: Performance results

The results of estimated time savings are derived from a comparison between the delivery times of drones and those of traditional car transport. The greater improvements are observed during typical rush hours (morning peak and afternoon peak), while during nighttime, the advantages of the drones are less pronounced. With 87 DJI and 93 Eiger drone flights per day, the average daily time savings amount to roughly 10 to 14 h. These results substantially lead to higher overall operational efficiency and a significant reduction in driving time for hospitals (Table 5).

Metric	DJI Matrice 600	RigiTech Eiger
Minimum reduction (min)	1.6	2.4
Maximum reduction (min)	18.8	25.7
Average reduction per flight (min)	7	9.6
Daily number of flights	87	93
Average daily reduction (min)	612.1	890.3

Table 5: Summary of the emergency use case results

3- Emergency delivery: Recommendations

The literature on the social acceptance of urban air mobility shows that citizens select the use of drones for emergency deliveries as the best use case, with acceptance levels up to 80%. Compared to ambulances or motorcycles, drones generate significantly less disruptive noise and no greenhouse gas emissions, which is especially beneficial in dense urban environments. They are also expected to be more cost-effective than conventional ambulance transport, especially for time-sensitive but lightweight deliveries.

However, despite the number of demonstration flights being executed in cities across the world, many drones are still on the ground, waiting for permission to take off, and the ones that have obtained permission are not flying at scale. For now, emergency air deliveries are mainly found in rural areas or above water, where the ground risk is considered low, and the mitigation measures are easier to put in place. The current barriers to having scaled delivery services in our cities come from the current regulatory restrictions for BVLOS flights above high-density areas. Advances in regulation, such as the EASA guiding material for eVTOL certification or the recently published enhanced SORA 2.5 in Europe [19], shall help solve current safety issues. Projects, such as SAFIR-Ready, have set the basis for regular delivery between hospitals and remote users. The experience has shown the actual benefits and cost savings of this type of operation, but it has yet to be generalised within cities.

Wider effects on health, spatial planning, energy systems, wildlife and environment

The results presented above provide concrete and reliable information on specific impacts of UAM operations on citizens' quality of life. It is important to understand the wider effects of the defined impacts on society, to better use these results in local and regional policy and operational planning.

Noise and visual pollution related effects

Drones' distinct acoustic signatures (higher pitch for very small drones, tonal components and specific temporal exposure patterns) may generate significant annoyance among residents. The annoyance can be further investigated, considering annoyance curves, and correlating noise exposure levels with reported community annoyance rates. Prolonged exposure to such auditory stressors can contribute to **adverse mental and physiological outcomes**, including heightened stress responses, sleep disturbances, reduced cognitive performance, and long-term effects on cardiovascular health [20]. Visual pollution resulting from the recurrent sight of low-flying vehicles or the presence of illuminated vertiports can further exacerbate **psychological discomfort** and contribute to a sense of spatial intrusion or loss of visual tranquillity.

Access and equity challenges

Vertiport placement is especially tricky in urban areas: the best locations in terms of capturing demand would be in densely populated areas, but this will impact a larger number of people, with the added constraint of having available space to build these facilities.

Furthermore, although the most densely populated areas account for the bulk of demand and resources, they generally benefit from a wide range of other transport services,, whereas remote or isolated areas are the ones with the highest needs in terms of transportation options. If UAM services do not bring relevant solutions to citizens needing them, the negative externalities on their quality of life increase. This **spatial planning approach** also addresses the question of **UAM operations' business models** and is key to their deployment. In this respect, addressing access and equity aspects of UAM services is fundamental for their social acceptance and policy integration.

Privacy concerns framework

The MUSE privacy concern indicators mostly assess the number of people visible from the drone position during flight. However, privacy concerns are related to personal data. Key elements of privacy protection for UAM operations would focus on the **collection, storage, use, and transfer of any private data** in the framework of these services. Privacy concern is linked to whether or not one is visible by a drone, but most importantly, whether or not the drone is capturing visualised data. A drone without a camera would, for example, remain out of privacy concern issues. Therefore, more **information on the characteristics of the aircraft operating the UAM services** needs to be shared with the citizens affected, and when necessary, consent collection processes can be required. These types of requirements and operational processes should be part of data & privacy strategies at local and regional levels.

Emissions and energy impacts

Beyond emissions expected to be saved by the use of electric UAM services in replacement of heavier-emitting transportation modes, vertiports will require a **substantial energy network**. Indeed, it is estimated that at least 1MW of capacity is needed to recharge multiple eVTOLs simultaneously and supply power to their systems [21]. Therefore, a high-power electrical grid connection at the location will be essential. Integration with renewable sources and smart-grid management will be crucial to ensure sustainability and reduce indirect emissions associated with electricity use. Considering the changes in routing and vertiport location mentioned, the operations will be less efficient from an energy-saving perspective due to longer routes, forbidden areas that have to be avoided and sub-optimal vertiport locations that induce longer access and egress transport to and from the final destinations of the passengers and cargo. The specific effect will vary and should be analysed on a case-by-case basis. In the end, a trade-off between impacts has to be considered when defining a UAM network.

How to use the MUSE tools

Considering the impacts assessed in the project and their wider effects on society, it is fundamental that the right stakeholders take up the tools developed by the MUSE partners to exploit their potential in improving UAM operations.

- **Drone manufacturers, pilots, operators, and end-users**

Drone operators and pilots may use the MUSE tools to optimise their operations, balancing efficiency with environmental and social impact. Different similar flights may be analysed before departure (ex-ante) to select the least impactful one. On the other hand, historical flights may be assessed (ex-post) to learn from previous experiences. The project case studies show multiple impacts and results informing on altitude and trajectory constraints, among others.

Drone manufacturers will benefit from the tool by testing their new models in realistic scenarios in order to optimise their design (e.g., with regard to performance) and minimise social and environmental effects. The results obtained for specific drone models in the MUSE case studies can provide valuable insights in that sense.

Finally, for both operators and manufacturers, the MUSE outcomes raise awareness of citizens' perspectives and concerns related to their activities, and how to best address them. All these insights also play an important role for drone operation end users, namely logistics services, police and firefighters' departments, and health services, including pharmacies and hospitals.

- **U-space service providers (USSPs)**

The U-space Environmental and Social Impact Assessment Framework enables a future U-space service focused on ensuring that UAM operations are both socially acceptable and environmentally sustainable. To this end, the framework supports USSPs in quantifying and evaluating the social and environmental externalities of UAM operations. The MUSE project has developed and demonstrated the capacities of new indicators and methods, based on several research sectors, which enable the measurement of UAM operations' noise, visual pollution, and impacts on citizens' access to emergency services and privacy concerns. These indicators and methods will support USSPs in enriching their competences and refining their available services.

- **Insurance sector**

In terms of insurance, the MUSE measurement tools can be used for drone and UAM service assessment in view of funding and warranty, and bring additional information on other defined criteria. The results obtained in the case studies can also inform on the potential impacts of specific drone models and planned operations.

- **Aviation authorities**

The proposed indicators only define a measurement mechanism for the different impacts of drones on citizens. It is the duty of aviation authorities to define acceptable thresholds for those indicators. Providing a tool to simulate realistic scenarios helps them make informed decisions on noise, visual pollution, privacy, and access and equity thresholds.
The results also provide indications of airspace structures to favour in defining U-space airspaces, depending on local areas. They demonstrate some consequences of different flight phases as well, such as take-off and landing, and inform on the impacts of other flight characteristics such as altitude, time of the day, and nature of the overflown area. These inputs can be relevant when defining authorisation and prioritisation processes.

In addition, many of the indicators defined in MUSE may be translated to general and commercial aviation, contributing to the goal of making Europe the most efficient and environmentally friendly sky to fly in the world (European ATM Master Plan, 2025 Edition).

- **Municipalities, regional and national governments, European policymakers**

For policymakers, the results obtained in the MUSE project underline the importance of carefully balancing operational efficiency with public acceptance criteria. The framework's ability to incorporate demographic data (e.g., gender, age) offers a clear understanding of who is most affected, when and how, enabling targeted mitigation strategies. By adjusting parameters such as traffic volume or airspace design, decision-makers can directly test scenarios and evaluate the social and environmental consequences of their choices. In this way, the MUSE project provides an evidence-based approach that does not depend on speculation, providing a concrete basis for regulations that can enhance societal acceptance of future drone operations. In particular, the MUSE solutions will help policymakers understand which areas might be more affected, which segment of the population would be distressed, and which better solutions would be possible.

This is especially relevant for municipalities and regional governments, who have unique contexts to address and need tools and methods to adapt the proposed services. Among others, the population mapping tools and methods used and enhanced in the MUSE project are instrumental for them, as they evolve into complex data-driven ecosystems. These tools can help them understand how populations interact with space and time, which is a basis for designing equitable, sustainable, and resilient urban environments. The fusion of mobile network intelligence, pervasive sensors, and emerging communication technologies opens a pathway toward real-time, adaptive models of human presence. This vision calls for interdisciplinary collaboration, robust data governance, and a commitment to ethical innovation, where population mapping becomes not just a technical tool, but a catalyst for shaping cities that are more responsive to the needs, behaviours, and rhythms of their citizens.

- **Research and development institutes and funding institutions**

MUSE is a highly interdisciplinary project integrating knowledge from a variety of disciplines. Academia and research centres working on noise modelling, satellite imagery analysis, mobile network data analysis, trajectory generation, concept of operations and performance definition will benefit from the different results of the project, deliverables, research papers and published data.
Funding institutions like SESAR will benefit from the synergies of this project with other research projects and future calls, which will help in transferring the project results to the subsequent stages of the R&I cycle. In particular, the conclusions and recommendations gathered in the publications and the White Paper of the MUSE project should be instrumental for that purpose.

- **Health sector and citizen representatives**

It remains difficult to determine which thresholds citizens might accept, since the MUSE study did not aim to identify them. The health sector and citizen representatives can use the comparative conclusions drawn from the MUSE case studies to inform their requests and positions, and the indicators to support their contributions to the definition of thresholds.

Conclusions

Considering the diversity of fields addressed in the MUSE project, multiple conclusions are to be drawn. This section addresses conclusions for distinct aspects of the research and provides an overall vision of how the MUSE results could influence UAM and European cities and regions in the future.

Future research

Performance Framework: As the study of UAM's impact on quality of life is still in its early stages, further research is essential to strengthen the reliability of these assessments. In particular, there is a growing need for data collection through interviews and surveys to validate these indicators and enhance impact predictions. Gathering such data will enable more accurate assessments of UAM's effects across different geographical regions, taking into account diverse demographic and socio-economic profiles. This will be crucial for refining performance evaluation models and ensuring that future UAM implementations are both safe and socially acceptable.

Concept of operations: Municipalities and regional governments must get involved in the governance of their airspace and, together with the Airspace Safety Agencies, start planning the design of the desired urban air mobility and its integration in existing transport networks. This process involves making critical decisions on a wide range of factors (e.g., geographical limits, allowed time periods, ground infrastructure, airspace design).

Noise pollution calculations: Future research should focus on refining methodologies for accurate and meaningful noise impact assessment. This includes investigating criteria and methodologies for determining when simplified versus detailed noise source models are required. Additionally, the methods for acquiring, classifying, and integrating background noise data in diverse environments (urban, suburban, rural) may be improved to ensure realistic baseline conditions for indicator calculation. Developing models to estimate indoor perceived noise from drone and eVTOL operations, accounting for façade transmission loss, building typologies, and occupancy patterns would add an important dimension to residential impact assessment.

Research should also examine the influence of different averaging periods (e.g., 15 min, 1h, or adaptive intervals) on noise indicator accuracy, interpretability, and correlation with human perception of disturbance. Threshold values, needed for some indicators, are also subject to discussion. Finally, field experiments and community surveys should be conducted to empirically validate model outputs, annoyance predictions, and the relationship between calculated indicators and perceived noise impact.

Population mapping: The accuracy of population mapping will directly affect the outcomes of a large number of proposed indicators. Therefore, further work is needed to improve pedestrian detection methodologies by leveraging additional satellite images and increasing statistical reliability in estimating outdoor populations. The integration of GPS data for outdoor population estimates should be refined to address biases in the data and account for underground transportation networks, which may increase the population detected with MND and GPS but not with satellite images. The exploration of additional data sources to validate the presence of pedestrians outdoors should be pursued.

Future UAM ecosystem and network integration

UAM services are currently scarce but already ensuring transport services, in cities like Dublin and Helsinki, for example. They are also used in multiple places by specific local and regional public services in the traffic, building, police, firefighting, and agricultural sectors as well. Therefore, it is already important to assess their consequences on the population in urban, peri-urban, and rural areas.

Based on the European Union's predictions, the amount of existing operations will increase, and new use cases will emerge, leading to a more impactful ecosystem. In particular, urban use cases are multiplying, and local and regional governments are increasingly concerned about the place of UAM services in several aspects of their organisational structure. Impacts on the urban landscape, the transport network, the data exchange and exploitation strategies, the energy grid, and the local economy are crucial topics with a progressively higher place on their agenda. These impacts require cooperation between multiple departments at the government level, which is a real challenge for cities and regions, which are directly addressed by citizens and locally implanted stakeholders.

In that sense, reliable information on the impacts of new services such as drone flights is fundamental to defining the future of these innovations. Impact assessment is an instrument to inform policymakers, but also to answer citizen questions and support decisions, which influence funding opportunities and development capacities. The MUSE project's contribution to the development of UAM and the future of European urban ecosystems can therefore be very wide.

This requires, however, awareness and the capacity to exploit the outcomes. Capacity building is necessary in local and regional governments, but also at national and European levels in related sectors, to achieve a competitive drone sector in the EU, as targeted in the EU Drone Strategy. Collaboration between multiple stakeholders is key, and is, among others, enabled by reference data, obtained through well-developed assessment tools.

Appendix A - Acronyms and Definitions

Acronym	Expansion	Definition
AE	Access and Equity	Access and Equity focus area in MUSE Performance Framework
ATM	Air Traffic Management	The integrated process of managing the safe and efficient movement of aircraft in the air and on the ground
BVLOS	Beyond Visual Line of Sight	Drone operations where the remote pilot cannot see the aircraft with their own eyes
ConOps	Concept of operations	Document describing the characteristics of a proposed system from the viewpoint of an individual who will use that system
DC	Distribution Center	Logistics facility that receives goods from suppliers, stores them temporarily and forwards them to their final destination, whether retailers, wholesalers or consumers
EA	Economic Aspects	Economic Aspects focus area in MUSE Performance Framework
EASA	European Union Aviation Safety Agency	Regulatory authority for aviation safety in the EU
EM	Emissions	Emissions focus area in MUSE Performance Framework
EU	European Union	Economic and political union
eVTOL	Electric Vertical Take-Off and Landing	New category of aircraft that can take off and land vertically like a helicopter but is powered by electric motors instead of conventional combustion engines
MND	Mobile Network Data	Set of anonymized mobile phone records generated by the user
MUSE	Measuring U-space Social and Environmental Impact	Project’s full name
NO	Noise	Noise focus area in MUSE Performance Framework

Acronym	Expansion	Definition
PC	Privacy Concerns	Privacy Concerns focus area in MUSE Performance Framework
PI	Performance Indicator	A quantifiable measure to monitor and understand the performance of the system that may not have associated targets.
PS	Public safety	Public safety focus area in MUSE Performance Framework
SAFIR-Ready		EU-funded project aiming to develop new U-space advanced services together with a central command and control centre (C2C), as well as an automated ground integration (Drone Cargo Port - DCP) to facilitate automated time-critical drone-based services for medical and non-medical use cases.
SESAR	Single European Sky ATM Research	Is the technological pillar of the EU's Single European Sky (SES) initiative, a research and development program focused on modernizing and harmonizing Europe's air traffic management (ATM) system.
SORA	Specific Operations’ risk assessment	Methodology for the classification of the risk posed by a drone flight
UAM	Urban Air Mobility	The safe, secure and sustainable air transport of passengers and cargo in urban environments, enabled by new-generation technologies integrated into a multimodal transportation system
U-space	U-space	Set of new services relying on a high level of digitalisation and automation of functions and specific procedures designed to support safe, efficient and secure access to airspace for large numbers of drones
USSPs	U-space Service Providers	Certified entity that provides digital and automated services to manage unmanned aircraft operations within designated U-space airspaces
VP	Visual Pollution	Visual Pollution focus area in MUSE Performance Framework
WL	Wildlife	Wildlife focus area in MUSE Performance Framework

Table 6: Acronyms & Definitions

Appendix B - MUSE Performance Indicators

Performance Indicator	Unit	Description
NO-1: Area based people exposure to noise (L_Aeq)	person	The number of people exposed to an equivalent sound pressure level higher than a certain threshold in dBA, for a fixed period of time, within an area.
NO-2: Area based people exposure to Day-evening-night noise level (L_DEN)	person	The number of people exposed to a weighted equivalent sound pressure level higher than a certain threshold in dBA, over a whole day (24 hours), within an area.
NO-3: Trajectory based people exposure to noise (SEL_A)	person	The number of people exposed to a sound exposure level higher than a certain threshold in dBA, for a single drone operation, for a time period fixed by the drone trajectory, within an area.
NO-4: Area based Person-Event Index	N.person	The number of events N exceeding a certain noise level in dBA multiplied by the number of people exposed, over a fixed period of time, within an area.
NO-5: Area based people exposure duration to noise	D.person	A certain duration D of noise levels exceeding a certain threshold in dBA multiplied by the number of people exposed, over a fixed period of time, within an area.
NO-6: Area based people exposure to Event Emergence	dB.person	Difference between the noise generated by the overflying drones and the local background noise level multiplied by the number of people exposed, over a fixed period of time, within an area.
NO-7: Area based intermittent exposure to noise	%.person	The number of people multiplied by the ratio of intermittent and continuous sound (Intermittence Ratio), over a fixed period of time, within an area.
NO-8: Area based people exposure to maximum noise (L_Amax)	person	The number of people exposed to a maximum noise level higher than a certain threshold in dBA, for a fixed period of time, within an area.
USSPs	U-space Service Providers	Certified entity that provides digital and automated services to manage unmanned aircraft operations within designated U-space airspaces
VP	Visual Pollution	Visual Pollution focus area in MUSE Performance Framework
WL	Wildlife	Wildlife focus area in MUSE Performance Framework

Table 7: Noise Performance Indicators

Performance Indicator	Unit	Description
VP-1: Trajectory-based people exposed	person	The amount of people exposed to a single drone operation, i.e., sum of individual persons that are able to see the drone.
VP-2: Trajectory-based people exposed by concentration threshold	person	The amount of people exposed to a visual pollution concentration higher than a threshold, for a single drone operation.
VP-3: Trajectory-based people exposed by temporal and concentration threshold	person	The amount of people exposed to a visual pollution concentration higher than a threshold, for a period longer than T, for a single drone operation.
VP-4: Trajectory based visual exposure	person.vp.h	Total visual pollution exposure perceived by the people exposed to a single drone operation.
VP-5: Area based people exposed	person	The amount of people exposed to UAM traffic, within an area.
VP-6: Area based people exposed by concentration threshold	person	The amount of people exposed to a visual pollution concentration higher than a threshold at least once a day, within an area.
VP-7: Area based people exposed by temporal and concentration threshold	person	The amount of people exposed to a visual pollution concentration higher than a threshold, for a period longer than T, along the day, within an area.
VP-8: Area based visual exposure	person.vp.h	Total visual pollution concentration perceived by the people exposed to UAM traffic, within an area.
VP-9: Visual exposure per kilometre	person/km	Kilometres travelled above a zone multiplied by the population density in that zone.

Table 8: Visual Pollution Performance Indicators

Performance Indicator	Unit	Description
PC-1: Trajectory-based people visually annoyed	person	Total amount of people annoyed by (presence of) a single drone operation.
PC-2: Trajectory based people exposed to hovering drone	person	Total amount of people visually exposed to hovering drone at a distance less than a certain threshold for a single drone operation.
PC-3: Area based people visually annoyed	person	Total amount of people annoyed by presence of UAVs within an area, during observed time period.
PC-4: Area based people exposed to hovering drone	persons	Total amount of people visually exposed to hovering drone(s) at a distance less a certain threshold, within an area, during observed time period.
PC-5: Area based duration of different hovering drone visual exposure	person.vp (hovering drones).h	The accumulated visual exposure to hovering drones in a given area for a given time.

Table 9: Privacy Concern Performance Indicators

Performance Indicator	Unit	Description
AE-1: Deliveries of goods to areas with limited or no transport connections	number	The number of deliveries of goods and equipment to areas with limited or no transport connections.
AE-2: Reduced travel time for health care-related deliveries	seconds	The amount of time reduced for health care-related deliveries by UAVs compared to the delivery by road transport.
AE-3: Deviation of noise exposure from mean value	number	The amount that noise exposure within an area deviate from the mean value for all the areas.
AE-4: Deviation of visual pollution exposure from mean value	number	The amount that visual pollution exposure within an area deviate from the mean value for all the areas.

Table 10: Access & Equity Performance Indicators

Performance Indicator	Unit	Description
EA-1: Area of positive economic influence	km2	Area* expressed in km2 that would fall into the zone with new jobs as a consequence of drone operations.
EA-2: Area of negative economic influence	km2	Area* expressed in km2 that would fall into the zone where property values decrease as a consequence of exposure to regular/frequent drone operations.
* the number of dwellings or people within an area could also be calculated instead of area		

Table 11: Economic Aspects Performance Indicators

Performance Indicator	Unit	Description
EM-1: Actual average CO2 emission per flight	kg CO2 per flight	Amount of fuel burnt x (CO2 emission index/kg of the fuel used e.g.: conventional or sustainable fuel) divided by the number of flights
EM-2: Trajectory-based energy consumption	kwh	The amount of energy consumed by a single drone operation (based on the type of UAM and trajectory).
EM-3: Trajectory-based CO2-eq emission	kg CO2 -eq	The amount of CO2-eq emitted by a single drone operation. Based on the type of drone (battery energy), trajectory – duration of flight, and based on the existing energy mix of the country where UAM operates
EM-4: Area based CO2-eq emission	kg CO2-eq/h	The amount of CO2-eq emitted by UAVs, within an area during observed time period. Based on the type of UAM (battery energy), trajectory – duration of flight, and based on the existing energy mix of the country where UAM operates
EM-5: Area based CO2-eq emission decrease	kg CO2-eq/h	The amount of CO2-eq emitted less for the observed deliveries with UAVs introduction (compared to road traffic delivery), within an area, during observed time period. It represents the difference between total amount of CO2-eq emitted by cars (for the road trajectory depending on OD) which could be replaced with drones and total amount of CO2-eq drone emission for the given deliveries. The number of cars replaced by UAVs, for traffic scenario (day) could be calculated as number of drone operations during observed time period (day) divided by number of deliveries per car (assumed value).

Table 12: Emissions Performance Indicators

Performance Indicator	Unit	Description
WL-1: Exposure on wildlife for a given trajectory	wildlife	Total amount of wildlife exposed within noise and appearance contours.
WL-2: Exposure on wildlife for a traffic scenario	wildlife	Total amount of wildlife exposed within an area, during observed time period.
WL-3: Annoyance level for single trajectory	wildlife	Total amount of affected wildlife within noise and appearance contours.
WL-4: Annoyance level for a traffic scenario	wildlife	Total amount of affected wildlife within an area during observed time period.
WL-5: Disruption of wildlife for a traffic scenario—noise contour	wildlife	The difference between the total amount of wildlife within noise contours for the two consecutive measurements.
WL-6: Disruption of wildlife for a traffic scenario—wildlife appearance contour	wildlife	The difference between the total amount of wildlife within their appearance contours for the two consecutive measurements.

Table 13: Wildlife Performance Indicators

Performance Indicator	Unit	Description
PS-1: Area based exposure to hovering drone	drones	Total amount of drones hovering at height below a certain threshold, within an area, during observed time period.
PS-2: Area based duration of exposure to hovering drone	Minute	Total duration of drones hovering at height below a certain threshold, within an area, during observed time period.

Table 14: Public Safety Performance Indicators

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