Integrating Urban Air Mobility into Sustainable Urban Mobility Plans: A Framework and Occupational Profiles for Smart Cities

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***Abstract*—The present study focuses on two goals. Firstly, it introduces the Sustainable Urban Air Mobility Indicators (SUAMI), which is a term we introduce to the Urban Mobility discipline as a modification of the well-established term Sustainable Urban Mobility Indicators (SUMI) used in the Sustainable Urban Mobility Plans (SUMP), thus integrating UAM into current urban mobility strategies. Through a qualitative study, including a narrative literature review and in-depth interviews with 26 stakeholders (each of them being expert in sustainable development, aviation and urban planning), the most impactful indicators for UAM were identified. The proposed SUAMI framework provides cities, drone operators, policymakers and other relevant stakeholders with a tool to assess the environmental footprint, operational efficiency, and socio-economic impact of UAM, while supporting its effective implementation and regulation. Furthermore, in this work, we identify occupational profiles for which these indicators can be of value, as we expect these profiles to be tasked with overseeing and managing UAM operations in cities. Our approach aims at delivering a practical tool that will enable the incorporation, monitoring and evaluation of UAM deployment in urban environments, while avoiding adverse effects on urban transportation, climate, public health, and overall population welfare.**

Keywords: Urban Air Mobility (UAM), Sustainable Urban Mobility Indicators (SUMI), smart cities, occupational profiles, air mobility integration

I. Introduction

In the future, cities are expected to embrace a new mode of transportation alongside traditional options like cars, buses, trains, and airplanes: eVTOL (electric vertical take-off and landing) aircrafts. These innovative, electrically powered vehicles, capable of vertical take-off and landing, are anticipated to become a key component of Urban Air Mobility (UAM). By providing cleaner, quieter, and more efficient travel options, eVTOLs could play a significant role in reducing urban pollution and promoting sustainability [1–4]. EVTOL aircrafts are envisioned to connect through specialised stations known as vertiports [5], located on rooftops, transport hubs, and city outskirts. As research and testing advance, the adoption of eVTOLs in urban transportation systems is expected to grow steadily. However, widespread deployment must be supported by comprehensive regulation to ensure safety, reliability, affordability, and operational efficiency. Key challenges such as air traffic management, noise pollution, energy consumption, and equitable access must be addressed to ensure that eVTOLs contribute to a sustainable and inclusive urban mobility ecosystem [6–8].

UAM is considered a promising solution to address the mobility challenges faced by smart cities [9]. In the current post-COVID-19 era, European cities are focusing on both growth and environmental sustainability, making UAM especially pertinent. In 2013, the Directorate-General for Mobility and Transport (DG Move) released a particular process to foster European cities in creating their own Sustainable Urban Mobility Plans (SUMPs). SUMPs [10] are strategic frameworks designed to enhance urban transportation systems while prioritising sustainability, accessibility, and quality of life. Introduced by the European Commission in 2013 and updated in 2019, SUMPs aim to shift urban mobility towards more sustainable practices by integrating environmental, social, and economic objectives. A key component of these plans is the Sustainable Urban Mobility Indicators (SUMIs) [8], which provide measurable benchmarks to evaluate progress in areas such as air quality, accessibility, safety, and energy efficiency. However, while the SUMI framework presents a comprehensive set of practical indicators for evaluating urban mobility systems, it does not account for UAM in general or the use of Unmanned Air Vehicles (UAVs) as transportation modes. As the framework primarily focuses on traditional ground-based transport, there is an urgent need to update these indicators to incorporate emerging concepts and technologies, such as UAM, which integrates innovations like eVTOL aircraft and advanced air traffic management systems.

An analysis of SUMI's applicability to UAM by Tojal & Paletti [11] classified the indicators into three levels of applicability: high, medium, and low, as presented in Table 1. The study provided detailed justifications for the assigned applicability levels of the core indicators of the SUMI (note that the SUMI consist of non-core indicators as well, but were not analysed in [11]). One of the main objectives of this paper is to further validate the SUMI applicability results (high, medium, low) for the core indicators, extending the scope of the original study [9]. Additionally, some indicators will be expanded to address the unique requirements of UAM, and potential new metrics will be discussed to capture aspects specific to this emerging mode of transportation. These activities contribute to the development of a new framework, referred to as the Sustainable Urban Air Mobility Indicators (SUAMI) framework, which is tailored to the evolving needs of UAM and provides a comprehensive tool for assessing its impact within urban environments.

Another important aspect that will be discussed in this study is the occupational profiles related to UAM. The European Skills, Competences, Qualifications, and Occupations (ESCO) [12] is a multilingual classification system developed by the European Commission that aims to bridge the gap between education, training, and labor market needs across Europe. UAM introduces novel challenges and opportunities for urban transportation systems, necessitating the development and adaptation of occupational profiles to address its unique requirements. An additional objective of this work is to update current occupational profiles related to UAM integration to reflect the evolving needs of smart cities.

Summarising, the objective of this study is twofold: i) to develop the SUAMI framework and ii) to build on the ESCO framework and earmark current occupational profiles in need of an update so as to reflect the evolving needs of smart cities. Overall, this work aims to provide local authorities and other policy stakeholders with the tools necessary to seamlessly integrate UAM into sustainable urban mobility plans.

II. Materials and Methods

The methodology for developing the SUAMI framework involved a literature review, comprehensive desk research, and expert consultations, including in-depth interviews with 26 stakeholders, all of whom are experts in sustainable development, aviation, and urban planning, to further validate the results. An in-depth examination of the SUMI framework has been performed to identify gaps and opportunities for adapting the framework to the UAM-specific context. Implementation strategies are discussed for indicators that align well with UAM, and potential extensions are proposed. With these refinements we introduce the Sustainable Urban Air Mobility (SUAMI) framework, an extension of the existing SUMI framework, accounting however for the inclusion of UAM into city transport thus enabling the assessment of UAM impact on cities (see Figure 1 illustrating the methodology followed).

The methodology for updating the current ESCO occupational profiles to address UAM deployment in cities, relied on a comprehensive literature review through which we aimed to gather insights related to the tasks, duties, skills, and competencies required for UAM readiness and the implementation of SUAMI in smart cities. To validate and refine these findings, interviews with experts representing or closely related to the identified occupational profiles were conducted. These interviews provided valuable feedback, ensuring the relevance and practicality of the proposed updates. Based on these combined findings, suggestions were made to update occupational profiles to address operational, regulatory, and technological challenges while aligning with UAM objectives such as safety, efficiency, and sustainability (see Figure 2 illustrating the methodology followed).

The suggested approach ensures that current occupational profiles will be updated to match the requirements of UAM and align with the broader goals of sustainable urban development and technological innovation. The updated occupational profiles, such as those of drone pilots, airspace managers, and urban planners, will contribute to the smooth and more effective integration of UAM into smart city ecosystems.

III. Results

This section presents the results of our analysis of SUMI parameters and their adaptation to the newly introduced SUAMI framework, designed to address the needs of future urban mobility. Later in this section, we also present the analysis conducted for occupational profiles, emphasising the need of additional vocational training for people holding these critical roles for the successful implementation of UAM.

A. SUAMI

1) Affordability of public transport for the poorest group: Affordability of public transport for the poorest group is defined as the share of the poorest quartile of the population's household budget required to hold public transport (PT) passes (unlimited monthly travel or equivalent) in the urban area of residence. At this stage of UAM deployment, air taxis or similar services are not available for the public and thus the price of a monthly PT pass including the use of UAV as transport modes for the general public cannot be easily calculated.

A rough estimation of the cost to fly an air taxi ranges from 1,5€/km to 6,5€/km. This information comes from estimates of organisations such as NASA [13], Joby aviation [14], Lilium [15], Archer aviation [16] etc. For drone delivery services, the estimated cost per delivery is around 1€. The cost estimations are based on the assumption that the package weighs less than 2,2kg and the delivery distance is less than 16km (distance of warehouse to delivery site) [17]. Nevertheless, research shows that public perception of UAM varies significantly by income level. For instance, only 39% of respondents earning less than 57.000€ annually had positive reactions towards UAM, compared to over 50% among those earning above 142.000€. This disparity suggests that lower-income individuals may view UAM as an expensive option, further complicating its adoption among these groups [18]. It is generally understood that a specific pricing model for all possible cases cannot be developed before the large-scale deployment of these services.

While there is optimism about reducing costs through technological advancements and economies of scale in production, initial business models often target wealthier demographics. This focus could lead to a situation where affordability remains a barrier for the poorest segments of society unless strategic measures are implemented [19]. To ensure inclusivity in UAM services, it is essential to develop indicators that assess the affordability and accessibility of these transport modes for all societal segments, particularly marginalised groups. This includes evaluating how well UAM integrates with existing public transport systems and its impact on overall mobility equity [20, 21].

Concerning current public transportation systems, a report by the European Parliament [22] emphasises that transportation should be considered an essential service that everyone should have access to, highlighting the need for policies that enhance affordability for disadvantaged groups. So, granting access to UAM services as a public transportation system to all economic strata is essential for the deployment and development of UAM services in urban areas.

Based on the findings from the literature review and the conducted expert interviews, it becomes evident that the indicator of affordability can be used in the same way as in current modes of transport.

2) Accessibility of public transport for mobility-impaired groups indicator: Accessibility of public transport for mobility-impaired groups determines the accessibility of public transport services to persons with reduced mobility. Such vulnerability groups include those with visual and audial impairments and those with physical restrictions, such as pregnant women, users of wheelchairs and mobility devices, the elderly, parents and caregivers using buggies, and people with temporary injuries.

This indicator evaluates real-life accessibility for individuals with reduced mobility by combining the accessibility levels of vehicles, stops and stations, and ticketing systems, including machines and offices. For UAM, accessibility of stops, stations, ticket machines and offices can be treated, more or less, in the same way as other modes of transport. The use of web portals and mobile applications allowing users to purchase e-tickets online and present them upon request while using the service is not a new concept. Moreover, buying a ride through a physical ticket machine or ticket office is something that the public is already familiar with. Accessibility of these aspects is not expected to change with the deployment of UAM. The same applies for stops and stations for eVTOLs, meaning the vertiports and vertipad locations.

Throughout our research, we found several reports and articles presenting guidelines for vertiports referring to the importance of accessibility to all groups in UAM deployment. Specifically, the Federal Aviation Administration (FAA) has released design guidelines for vertiports, which include recommendations for designing facilities that accommodate all passengers, including those with mobility impairments. The guidelines serve as a foundational step for developers to create inclusive environments [23]. At the same time, the European Union Aviation Safety Agency (EASA) has published

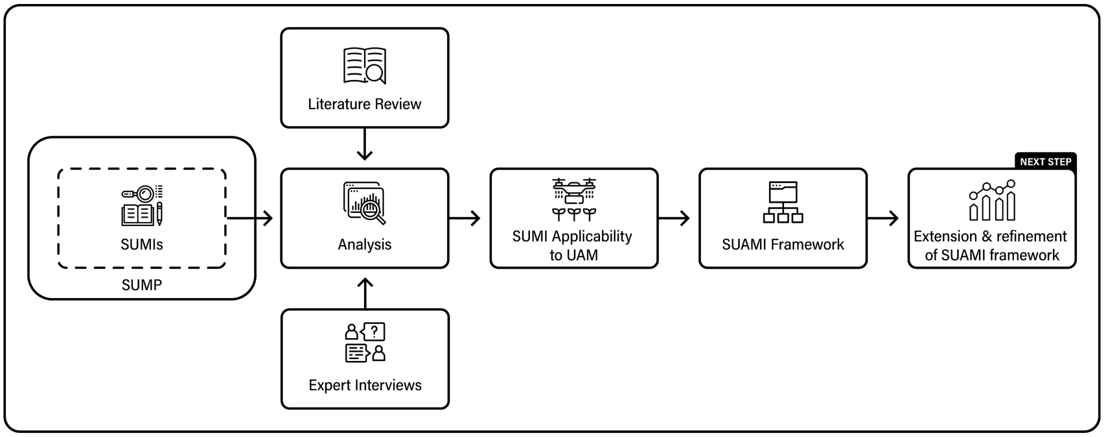

Fig. 1. Methodology followed for the current study for the SUAMI framework.

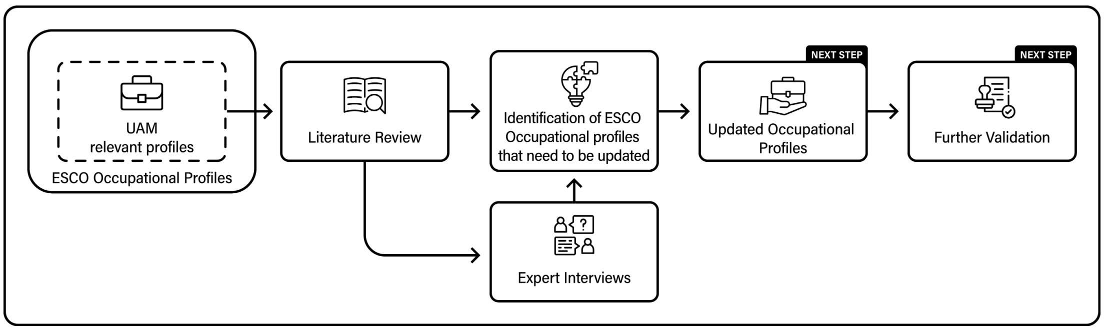

Fig. 2. Methodology followed for the current study for the occupational profiles updates.

guidance specifically addressing vertiport design, which includes considerations for accessibility. This guidance aims to set a "gold standard" for safe vertiport operations and emphasises the need for infrastructure that accommodates diverse passenger needs, including those requiring wheelchair access [24].

Accessibility must be a primary consideration from the concept phase of design [25]. Vertiports should be inclusive and accessible to all and utilise all accessibility features of modern stations of other transport modes such as train stations and bus stations. Specifically, designs of vertiports consider access for wheelchairs to all parts of the facilities and especially to boarding areas in case stairs are present. Most elevated vertiports will have either ramps or an elevator to comfortably reach the take-off platform.

The accessibility of moving assets (vehicles) can be a more complex concept in the use of UAVs than other mainstream mobility systems. The limited space in an air taxi, for example, can be shown to be less accommodating for some parts of the population with reduced mobility [26, 27]. However, accessibility to vehicles is being considered in some eVTOL designs where the wheelchair or person with limited mobility can be moved near the open door of the flying vehicle and then with the help of some crew, be lifted up manually when there are no ramps [28, 29]. Larger vehicles for over 4 passengers will likely consider using a ramp for easier boarding. For ill patients, it will not be easy to board standard eVTOLs, so adapted vehicles or medical ones will have to be used instead [30, 31].

Based on the findings from the literature review and the conducted expert interviews, it becomes evident that the indicator of accessibility of public transport for mobility-impaired groups can be used in the same way as in the current modes of transport and therefore has high applicability.

3) Air pollutant emissions: Air quality is an important topic for urban environments since air pollution can lead to major health problems and can even be one of the leading causes of premature deaths [32]. While air quality can be estimated using indexes like the European Air Quality Index [33], these metrics lack information regarding the source (urban mobility, industrial activities, domestic fuel burning etc.) and the degree that each source contributes to air pollution. Around 25% of total air pollution is sourced in urban mobility (traffic, public transport, urban logistics, etc.) [34]. For ground modes of transport, different methods of quantifying the impact of air pollution have been developed such as the Air Pollutant Emissions Indicator from the SUMI framework which calculates the Emission Harm equivalent Index (EHI) for fine particulate matter (PM2.5) in the urban area. While this method can be used for the impact assessment of conventional modes of transport in air quality, the adaptation of the specific metric in order to include UAM activities has not been realised. At the same time, it is well-established that aviation's air quality impacts differ from those of other sectors due to the unique altitude at which emissions are deposited, influencing processes such as ozone formation, which is not fully captured in this indicator.

Another limitation of the SUMI's Air Pollutant Emissions indicator is its focus on assessing only one type of pollutant, $PM_{2.5}$. $PM_{2.5}$ refers to particulate matter with a diameter of 2.5 microns or less, which is harmful to human health. While $PM_{2.5}$ particles are inhalable and can penetrate deep into the respiratory system, they are not the only pollutants that pose significant health risks. Other harmful air pollutants include PM_{10}, which consists of coarser particles with

SUMI Indicator	**Definition**	**Applicability**[8]	**Proposed Applicability in SUAMI**
Affordability of public transport for the poorest group	Share of the poorest quartile of the population's household budget required to hold public transport (PT) passes (unlimited monthly travel or equivalent) in the urban area of residence.	High	High
Accessibility of public transport for mobility-impaired groups indicator	This indicator determines the accessibility of public transport services to persons with reduced mobility.	High	High
Air pollutant emission indicator	Air pollutant emissions of all passenger and freight transport modes (exhaust and non-exhaust for PM2.5) in the urban area.	High	High
Community noise impact	Hindrance of population by noise generated through urban transport.	High	High
Road deaths	Road deaths by all transport accidents in the urban area on a yearly basis.	Medium	Medium
Access to mobility services	Share of population with appropriate access to mobility services in their area (public transport).	High	High
GHG Emissions	Well-to-wheels GHG emissions by all urban area passenger and freight transport modes.	High	High
Congestion and delays	Delays in road traffic and in public transport.	Medium	Medium
Energy efficiency	Total energy use by urban transport per passenger km and tonne km (annual average over all modes).	Medium	High
Opportunity for Active Mobility	Infrastructure for active mobility, namely walking and cycling.	Low	Low
Multimodal integration	The more modes available at an interchange, the higher the level of multimodal integration.	High	High
Satisfaction with public transport	The perceived satisfaction of using public transport.	Medium	High
Traffic safety active modes indicator	Fatalities of active modes users in traffic accidents in the city in relation to their exposure to traffic.	High	Low

TABLE I
SUMMARY OF SUMI INDICATORS [8] AND PROPOSED APPLICABILITY IN SUAMI

diameters between 2.5 and 10 microns; Ultrafine Particles (UFPs), with diameters smaller than 0.1 microns; ground-level ozone (O_3); and nitrogen dioxide (NO_2). Each of these pollutants can negatively affect human health, highlighting the need for a more comprehensive approach to air pollutant impact assessment within the SUMI framework.

Different fuels and propulsion technologies used in UAM will influence the associated air quality impacts, both during direct operation and from a life cycle perspective. These factors must be carefully analysed and addressed. Additionally, the infrastructure required for UAM, such as the development of vertiports and related facilities, will also have implications for air quality, which need to be considered comprehensively. Furthermore, UAM could replace certain existing mobility modes that currently contribute to air quality issues. Regarding UAVs, their impact on urban air quality is generally expected to be positive. Since most drones are designed to be electrically powered—using lithium polymer (LiPo), lithium-ion (Li-ion) batteries, or hydrogen fuel cells—air pollution associated with UAM operations in urban areas is likely to be minimal. While hydrogen fuel cells emit only water vapor during operation, it is important to note that the production of hydrogen is often reliant on fossil fuels, which can offset some of its environmental benefits. However, this positive impact would not apply if UAVs powered by combustion engines were to be used extensively. For gas-powered vehicles, emissions of pollutants affecting air quality should be calculated in a manner consistent with current methodologies for ground transport modes. Özbek et al. [35] highlighted the environmental benefits of adopting all-electric UAVs in UAM and their potential to mitigate air pollution in urban areas. Noteworthy is also the fact that while no emissions occur from the use of the electrical vehicles themselves, the so called "lifecycle emissions" are to be considered for the production, operation and disposal of the vehicle itself and its batteries production and charging [36, 37]. Here are the key points specifically related to air pollution:

- Limited Operational Emissions: Electric UAVs powered by lithium-ion batteries or hydrogen fuel cells produce no harmful air pollutants during operation. While hydrogen fuel cells emit only water vapor, this is expected to have minimal impact on urban air quality and human health, though it may contribute to climate-related effects. This characteristic positions them as a sustainable alternative to traditional internal combustion engine vehicles, significantly reducing air pollution in urban environments.
- Impact on Urban Air Quality: The adoption of electrically

powered UAVs is expected to improve air quality in cities by eliminating emissions from aerial transport systems. This advantage is particularly important in densely populated urban areas with strict air quality regulations.

- Lifecycle Emissions: While the operational emissions are limited, the chapter acknowledges the importance of considering lifecycle emissions. These include emissions from the production and disposal of batteries and the generation of electricity required for charging UAVs. The environmental impact of electricity sources (e.g., renewable vs. fossil fuels) plays a critical role in determining the overall sustainability of electric UAVs and varies significantly by country, depending on the energy mix used for electricity generation. As highlighted in Otero et al. [38], this variability is evident in transportation mode comparisons, such as train versus airplane, where the CO_2 emissions per kilowatt-hour of electricity production differ across countries based on their reliance on fossil fuels or renewable energy [39].
- Hydrogen Fuel Cells: UAVs powered by hydrogen fuel cells also produce minimal emissions, with water as their primary byproduct. While this technology offers a cleaner alternative to fossil fuels during operation, the production of hydrogen—particularly through Steam Methane Reforming (SMR), which relies on fossil fuels—can significantly impact its overall environmental footprint. This underscores the importance of considering the hydrogen production method when evaluating its potential to reduce urban air pollution.

Based on the findings from the literature review and the conducted expert interviews, the impact of UAM on air quality has been identified as a critical factor. Consequently, incorporating an Air Pollutant Emission indicator is essential. Within the SUAMI framework, this indicator has been assigned a high level of applicability due to its importance in assessing and managing the environmental impact of UAM operations.

4) Community noise impact: The community noise impact indicator measures the hindrance of the population by noise generated through urban transport. The calculated parameter is the percentage of the population hindered by urban transport noise, based on hindrance factors for noise exposure data of the population by noise bands. Previous research [40] reveals how the current regulation, noise metrics and evidence of health effects of aircraft noise might not a great fit for application to UAS and/or UAM noise. Several reasons are discussed, including that the noise produced by UAM aircraft is substantially different to conventional aircraft and rotorcraft, and that UAS/UAM aircraft will operate closer to communities traditionally not exposed to aircraft noise. The noise produced by UAS/UAM configurations, based on multiple propellers or ducted fans, is expected to have a significant content in tonal and high-frequency noise, both factors with a strong correlation with noise annoyance [41, 42]. The current metrics for aircraft noise certification (i.e., Effective Perceived Noise Level - EPNL, and Sound Exposure Level - SEL), and aircraft noise exposure (i.e., A- weighted Energy Equivalent Sound Pressure Level integrated over time $t - L_{Aeq,t}$) might be unable to account for these unconventional noise profiles of UAM aircraft [43]. There is a significant uncertainty of whether existing WHO recommendations for aircraft noise, based on $L_{Aeq,t}$, will be appropriate for UAM noise, as there is no evidence supporting that communities will respond to UAM noise in a similar way to conventional aircraft noise.

Existing methods for aircraft noise certification [44], based on very well-defined and standard aircraft operations during take-off and landing stages, or flyover operations for rotorcraft, will unlikely be of application for UAM air vehicles. UAVs will fly at relatively close distances from communities, and therefore, not only take-off and landing stages should be accounted for, but also flyovers. Moreover, transient operations in UAM aircrafts (e.g., transition from hover to forward flight) are likely to produce significant sound levels (see discussion in Green et al. [45] for UAS), and will require novel procedures for the measurement of UAM noise.

From non-acoustics factors point of view, in cases where vehicles are considered beneficial for the communities they operate in (e.g., delivery of emergency equipment, medical supplies or transportation of patients), the actual noise hindrance to the public would be lower than expected since priority will be given to more urgent matters. Another point to take into consideration when expanding the metric for UAM operations is the timing of operations. The noise originating in UAM activities might be perceived differently in the morning and afternoon when a lot of urban noise is present in the city in comparison to the nighttime when everything tends to be quieter and calmer. Torija et al. [46] discusses the effect of existing ambient noise on noise annoyance due to UAS operations in urban and peri-urban environments.

Another relevant publication [47] highlighted the key challenges and research gaps in understanding human responses to UAV noise. It examines the unique noise characteristics of such types of emerging aerial vehicles and emphasises the necessity for further research in several areas: assessing the impact of UAV noise on public health and well-being, developing metrics to evaluate community noise exposure, establishing acceptable noise levels for UAV operations, informing best practices for drone operation with noise profiles in mind, and predicting the long-term noise effects of large-scale UAV deployment. Addressing these gaps is essential to effectively manage UAV-related noise issues and safeguard the health and quality of life of affected communities. A recent review paper [48] highlights the lack of studies focused on further understanding the effect of the existing ambient noise and the number of events on UAS noise annoyance.

Furthermore, the NASA report on UAM Noise [49] emphasises that although UAM offers transformative opportunities for urban transportation, addressing its environmental and noise impacts is crucial to ensure its sustainable integration into urban settings. Traditional aircraft noise certification methods are inadequate for UAM vehicles. Addressing these gaps demands new noise measurement standards, predictive tools, and low-noise design technologies. Community acceptance will depend on early engagement, transparent communication, and consideration of psychoacoustic factors, such as the context and timing of operations. Regulatory frameworks must establish clear guidelines for noise certification, operational procedures, and vertiport placement to mitigate environmental impacts and promote public trust. By proactively addressing these challenges, UAM can contribute to smarter, cleaner, and quieter urban environments.

To achieve these goals, a multidisciplinary and ambitious approach is required. The field of human response to noise exposure, traditionally rooted in public health and social sciences, must be integrated with engineering research and expertise in public acceptance and community engagement. This collaboration will be critical in building the necessary knowledge base to address UAV noise challenges comprehensively.

Based on the findings from the above literature overview and from our expert interviews, the applicability of the noise hindrance indicator and its potential extensions within the SUAMI framework is highly relevant, therefore it is set as "high" in terms of applicability (see Table I).

5) Road deaths: This indicator refers to road deaths by all transport accidents in the urban area on a yearly basis. The parameter value is the number of deaths within 30 days after the traffic accident as a corollary of the event per annum caused by urban transport per 100,000 inhabitants of the urban area. According to an EASA study on the social acceptance of UAM in Europe [50], safety was identified to be one of the main challenges for the successful deployment of UAM and also a factor that plays an important role in public acceptance. While UAM refers to activities taking place in the air, UAM operations can affect ground activities as well (e.g., a drone malfunction or crash into an obstacle due to weather conditions and fall to the ground). In the case of a drone activity being responsible for a death, the metric can be used in the same way as conventional modes of transport. At the same time, it is important to note that UAM can also impact the indicator indirectly by reducing road traffic through the use of UAVs for tasks traditionally performed by ground vehicles, such as those used for medical purposes (e.g., if replacing the use of ground vehicles for medical purposes). However, this shift may not necessarily lead to a direct reduction in overall traffic volume. In this case UAVs replace a vehicle driving in the streets of the city, possibly causing accidents. On top of that, studies have shown that drones can help to deliver life-saving defibrillators to people with suspected cardiac arrest at accident sites faster than ambulances [51]. In this way a road death caused by conventional modes of transport can be prevented. The same applies, of course, for non-emergency traffic, such as replacing delivery vans or scooters in the busy streets of a city. To better capture the risks associated with UAM, it is important to measure the accidents directly caused by UAM activities when considering their cumulative effect. Conversely, a comprehensive analysis should also account for the potential reduction in road accidents due to UAM introduction, reflecting its positive contribution to road safety. For this reason, we distinguish two categories of impacts related to UAM operations. The first focuses on accidents caused by UAM, containing both direct and indirect effects on urban areas. The second highlights accidents avoided because of UAM, reflecting its potential to reduce road traffic and related fatalities. The relevant indicators are:

- Accidents related to UAM: Similarly with the indicator for road deaths, a new indicator for accidents related to UAM operations in the area needs to be defined. Following the same principles as "road deaths", but replacing the number of deaths with the number of accidents can be a useful and practical way to establish this new metric.
- Accidents avoided because of UAM: By providing an alternative to traditional ground transportation, UAM can decrease the number of vehicles on the road. This reduction in ground traffic is expected to lower the incidence of road accidents, as fewer vehicles lead to fewer collisions and related fatalities [52]. Moreover, UAM systems, particularly those utilising electric vertical take-off and landing (eVTOL) technologies, have been shown to have a lower accident rate compared to conventional road transport. The inherent safety features of these aerial vehicles, such as advanced collision avoidance systems, contribute to a reduced risk of fatal accidents [53]. All-in-all, UAM can have a positive impact by reducing road deaths (less ground traffic, faster supply of medical equipment at the accident site, etc).

Another important factor to consider with respect to potential accidents caused, is the integration of UAM into cityscapes. It necessitates careful consideration of its impacts on urban safety, particularly concerning road traffic [54]. The placement and operation of vertiports—the designated take-off and landing sites for UAM vehicles—are critical factors. Strategically situating vertiports is essential to minimise potential conflicts with existing road infrastructure and to ensure the safety of both air and ground transportation systems. It is evident that the interaction between UAM operations and ground traffic requires thorough analysis [55].

Therefore, while "Road deaths" is traditionally a metric for ground transportation, it becomes relevant for UAM when considering the holistic safety of urban mobility systems. Adapting this indicator to encompass the safety implications of UAM operations can provide valuable insights into the overall impact of UAM on urban transportation safety. Based on the findings from the literature review and further validated through expert interviews, the applicability of the "Road Deaths" indicator within the SUAMI framework is classified as high. However, additional efforts are needed to develop methodologies for accurate quantification and adaptation to the unique dynamics of UAM operations.

6) Access to mobility services: This indicator refers to the share of the population with appropriate access to mobility services (public transport). The parameter calculated is the percentage of population with appropriate access to public transport (bus, tram, metro, train). Research indicates that UAM has the potential to complement existing public transport systems [56]. A study focused on the Munich Metropolitan region developed models to analyse how UAM could integrate with public transport, highlighting its role in improving overall mobility access for residents [57]. This integration is crucial to ensure that UAM services can effectively expand access to mobility for various demographic groups, including those in underserved areas. The indicator of access to mobility services could be used mainly for UAM in the case of air taxis. However, it is evident that vertiports or similar infrastructure for citizen mobility in U-space cannot serve people with the same proximity as bus and tram stops [58]. For this reason, the distance base value in order to assess how accessible is a service (e.g., 5 min walking for the case of bus and tram stops and 10 min walking for metro and train stops) should be adjusted appropriately for UAM services in order to represent as accurately as possible the level of accessibility offered in terms of distance and examined in combination with availability of bus/tram/metro stops nearby the vertiport. In this way, the current metric can be adapted and expanded in order to include people's physical mobility in the context of UAM.

Based on the discussion above, and further validated through insights from the interviewees, the applicability of this indicator is classified as high within the SUAMI framework.

7) Greenhouse gas emissions: This indicator measures well-to-wheels greenhouse gas (GHG) emissions from all passenger and freight transport modes within urban areas. It is highly relevant for assessing the impact of UAM on GHG emissions, but adapting it to include UAM presents several challenges.

Carbon dioxide emissions can be calculated for UAM in a similar way with conventional means of ground transport. However, the CO_2 emissions from drones depend on their energy source, manufacturing processes, and operational context. More specifically, a recent study [59] examined the environmental impact of UAM operations, specifically focusing on carbon dioxide emissions. It utilised a computational model to analyse different scenarios involving UAM and ground transportation, indicating that emissions can be assessed in a manner similar to traditional transport methods. Adapting this indicator in a way that includes UAM can be slightly more complex than conventional means of transport, since GHG emissions also depend on the altitude of UAV' operations [60]. When UAVs fly relatively close to the ground, it is indeed a good estimation to use similar metrics as those used for ground modes of transport, since CO_2 is the main source of climate impact. However, for flights in substantially higher altitudes (e.g. aviation) CO_2 accounts for only a third of the total impact. In higher altitudes NO_x also plays a significant impact on climate [61].

For the battery-powered UAVs the flight altitude does not play any role since no direct pollution is produced during the operation. In this case the overall UAVs carbon footprint can be calculated by taking into account the following:

- Emissions generated in the Vertiport process due to electricity consumption, "amortisation" of the construction, battery recharge etc.
- Emissions generated by the UAV: construction, operation and recycling.
- Emissions generated in the intermodal platform: construction and operation.

To mitigate emissions, it is anticipated that vertiports and droneports will be designed as sustainable, energy-efficient facilities. These sites should aim for self-sufficiency, relying on renewable energy sources to power UAM operations. However, some UAM platforms, such as eVTOLs, require significant energy (in kW) for flight, making the source of electricity crucial. If battery recharging relies on non-renewable energy, UAM could create a negative environmental footprint [38]. A thorough comparison of UAM and conventional urban logistics will be essential to maximise sustainability and guide decisions on adopting UAM as part of an integrated urban mobility strategy.

The greenhouse emissions indicator is undeniably of critical importance in the context of UAM and therefore we define its applicability to be high. Integrating this indicator into the SUAMI framework will allow cities to assess the environmental footprint of UAM operations with greater precision, supporting informed decision-making and fostering sustainable urban development.

8) Congestion and delays: Congestion in cities is on the rise and this is a major problem that requires the restructuring of mobility. A direct result of congestion is the high rate of pollution, which is taken into consideration in both current public transport and in UAM, under the GHG Emissions indicator. New resilient infrastructures are needed to provide new safe, sustainable and connected mobility and to help cities reduce the level of pollution and congestion in urban centres in last-mile transport. By making good use of the vertical dimension and utilising direct air routes, the necessary travel time and distance for mobility of people and goods in an urban context can be reduced significantly. In the case of UAM traffic congestion needs to be considered in two levels: ground traffic and air traffic.

In conventional land transport, delays are significant, as predicted by queuing theory, often resulting in inefficiencies [62]. The ability to offer premium urgent transport services, where reducing transport times provides a distinct competitive advantage, positions UAM as a valuable solution in time-sensitive scenarios. For such calculations, journey times based on standard traffic conditions in urban centers serve as the baseline reference. UAM is anticipated to positively impact congestion by leveraging its ability to bypass traditional ground traffic bottlenecks [63].

However, in the context of delays, several operational factors must be considered. Many UAV platforms are electrically powered, and battery recharging can impose limitations on the pace of operations. The capacity of batteries, in terms of energy storage, and the availability of fast-charging capabilities directly affect the likelihood of delays [64]. Implementing battery-swapping mechanisms where feasible can help mitigate these delays and enhance operational efficiency. Additionally, stable weather conditions are essential for ensuring smooth and uninterrupted UAM operations, highlighting the need for robust contingency planning to address weather-induced disruptions. Furthermore, vertiport capacity, specifically the number of take-offs and landings it can accommodate per hour, might serve as a critical limiting factor in achieving seamless UAM operations.

In the future when the density of air traffic is increased, the indicator can be used to describe congestion in the same way as ground modes of transport. This study, for example, highlights that while UAM has the potential to alleviate ground traffic congestion, it may also lead to increased air traffic density [65] and consequently lead to "visual pollution", a factor that SUMIs do not address as it is not of relevance for ground transportation modes [66, 67]. The findings indicate that medium and high-density UAM operations could place significant demands on airspace management systems. However, these operations are expected to be managed by U-space services rather than traditional air traffic controllers, mitigating the risk of unmanageable workloads while addressing potential airspace congestion through automated and digital solutions. Currently, it is crucial to quantify delays caused by factors specific to UAM operations. Although these delays originate from different sources than those in conventional transport, they affect travel times in a similar manner to delays in ground-based modes of transport.

Based on the findings from the literature review and the conducted expert interviews, it becomes evident that the indicator of congestion and delays needs to be used for UAM and therefore it has high applicability.

9) Energy efficiency: This indicator measures total energy consumption in urban transport per passenger-kilometre (pkm) and tonne-kilometre (tkm) annually across all modes. A pkm represents transporting one passenger over one kilometre [68], while a tkm refers to moving one tonne of goods (including packaging) over one kilometre by any transport mode [69].

As aforementioned, air vehicles designed for UAM operations are primarily powered by three types of energy sources: batteries, hydrogen fuel cells, and combustion engines. Through the indicator of energy efficiency, the amount of electricity or fuel used will be calculated per pkm and tkm in order to explore how efficient UAM operations are. A comparison with other modes of transport would be essential in order for cities to assess the impact of each mode. In this way, smart cities will be able to make better decisions regarding the more sustainable use of different transport modes in their areas. The indicator "Energy efficiency" is suitable for this assessment with minor adjustments so that all UAM air vehicles and power options are included in the calculation. All in all, as Tojal & Paletti [11] mention UAM should aim to be as energy efficient as possible: From the design of vehicles and hubs to the selection of routes, it is important to make UAM as sustainable as possible. Still, the energy consumption of airborne transport solution will be higher than the comparable ground-based solutions [70].

Building on the discussion above and further validated through insights gained from interviewees, the applicability of this indicator has been reclassified as high within the SUAMI framework, revising its initial designation as medium in the original study.

10) Opportunity for Active Mobility: This indicator refers to the infrastructure for active mobility, namely walking and cycling. The parameter calculation takes into account the length of roads and streets with pavements, bike lanes, 30 km/h (20 mp/h) zones and pedestrian zones related to the total length of the city road network (excluding motorways).

This indicator does not seem to be affected by future UAM activities. Thus, no extensions or adaptations are recommended for SUAMI at this stage. This metric will not be helpful for smart cities who wish to assess the impact of UAM in their areas. However, similarly with other city infrastructure, it is important to consider the opportunities for active mobility when building vertiports and other UAM related infrastructure. This will be considered in the indicator named "Access to mobility services", taking into consideration how UAM users can reach the vertiport or vertipad.

Based on the findings from the literature review and the conducted expert interviews but also empirically, it becomes evident that the indicator of opportunity to active mobility can not be used in the same way as in current modes of transport and therefore has a low applicability.

11) Multimodal integration: Multimodal integration refers to the seamless coordination and interconnection of various transportation modes within urban environments. Its goal is to enhance the efficiency, accessibility, and sustainability of urban mobility systems. This integration focuses on enabling users to easily transition between different transport options, such as buses, trams, trains, and active modes like cycling and walking. It assesses factors such as the availability of connections between modes, ease of transfers, and the overall user experience when using different transport options.

To include UAM in the assessment of multimodal integration within a city, it is essential to expand the list of possible transport modes. As this indicator focuses on people's mobility, the inclusion of air taxis as a transport mode is necessary to account for this emerging mode in future evaluations. Airbus discusses how UAM can positively contribute to a multimodal mobility system, enhancing connectivity within urban areas, introducing a holistic approach that integrates UAM with other transport modes to improve overall urban mobility and accessibility [71]. Moreover, integrating with public transport systems is crucial to maximising societal benefits and enhancing urban mobility [72].

Within the UAM context, it is expected that alongside vertiports and droneports, transport hubs will evolve to include additional facilities such as parking lots, charging stations, bus terminals, e-bike and scooter pick-up stations, and even metro and train connections. To assess the extent of multimodal integration at these hubs, the proposed indicator can be applied similarly to the SUMI framework, with minor adjustments to accommodate UAM-specific characteristics. Based on the discussion above, and further validated through insights from the interviewees, the applicability of this indicator is classified as high within the SUAMI framework.

12) Satisfaction with public transport: The indicator of satisfaction measures users' perceived satisfaction with their experience using public transportation services in urban areas. This indicator evaluates several key factors, including reliability, comfort, convenience , safety, affordability, and accessibility. This is typically assessed through surveys that gather feedback from a representative sample of the population. For example, the NZ Transport Agency [73] provides guidelines for standardised public transport satisfaction surveys, focusing on timelines, service frequency, value for money, and overall satisfaction to ensure reliable data collection. Additionally, survey templates offer structured questions to effectively quantify user experiences, such as rating overall satisfaction on a scale from satisfied to unsatisfied. By assessing these aspects, this indicator provides insights into the performance and user experience of public transport, helping identify areas for improvement and contributing to the development of more efficient, accessible, and user-friendly urban mobility solutions.

Satisfaction with public transport is a suitable indicator for assessing UAM activities as part of the broader public transport network. To evaluate additional aspects of UAM operations not covered by this indicator—such as the transportation of goods—rephrasing existing survey questions or adding new ones would help achieve more accurate and comprehensive results. Overall, adapting this indicator to include UAM appears to be a straightforward process with minimal complexity. Based on the discussion above, and further supported by insights from the interviewees, the applicability of this indicator is classified as high within the SUAMI framework, revising its initial designation as medium in the original study [74].

13) Traffic safety active modes indicator: This indicator refers to fatalities of active mode users (e.g., cyclists and pedestrians) in traffic accidents within the city, measured relative to their exposure to traffic. In the SUMI framework, there are two indicators related to fatalities: this one and the "Road Deaths" indicator. These two indicators follow distinct rationales:

- Road Deaths: According to SUMI, this indicator aims to provide urban areas with insights into the overall extent of road safety issues, independent of the urban area's population size. It allows authorities to determine whether road safety has reached a critical level requiring local measures. Moreover, it helps urban areas understand whether they can address the problem independently or need to engage other regions or administrative levels for support.
- Traffic Safety Active Modes: This indicator focuses on providing insights into the extent of road safety problems specific to active modes of transport (cycling, walking), independent of the number of active mode trips. The relative estimation per number of trips addresses the correlation between active mode unsafety and low active mode usage. For instance, unsafe cycling infrastructure discourages cycling, leading to fewer biking trips—a bias mitigated by this indicator.

To better capture the risks associated with UAM within the assessment framework, the introduction of a new indicator is essential, e.g. "Accidents Related to UAM". This new metric could measure all types of accidents caused by UAM activities. Then, it would be unnecessary to use a specialised indicator like "Traffic Safety Active Modes" for UAM-related assessments. Based on this and further validated through insights from the interviewees, the applicability of the "Traffic Safety Active Modes" indicator within the SUAMI framework is classified as low, revising its initial designation as high in the original study.

B. Updated Occupational Profiles

The ESCO framework [12] provides detailed descriptions of various profiles, some of them very relevant to the aviation and UAM/Innovative Air Mobility (IAM) sector. These profiles highlight both technical skills, such as aircraft flight control systems and air traffic control operations, and soft skills, such as communication and teamwork, which are essential for the successful execution of aviation roles. However, adapting these profiles to meet the specific demands of UAM is essential for enhancing workforce readiness, facilitating urban integration, and promoting sustainable smart city ecosystems.

For instance, the role of a drone pilot, already included in ESCO, can be expanded to include responsibilities for UAV operations in passenger transport, delivery, and surveillance within dense urban areas. Similarly, urban planners, transport planners, and land planners will need to incorporate UAM-specific considerations, such as the placement of vertiports, multimodal transport integration, and the optimisation of air corridors in city landscapes. Mobility services managers will also play a critical role, evolving to manage air mobility services, ensure their smooth integration with ground transportation networks and enable efficient, end-to-end mobility solutions. Airspace managers, on the other hand, will focus on low-altitude air traffic coordination to address the unique safety challenges of UAM and ensure the reliability of airspace allocation in congested areas. Airside safety managers will focus on compliance with operational standards and maintain safety and security at vertiports and during flight operations. The responsibilities of aviation communications and frequency coordination managers will expand to include managing UAV communication channels and preventing interference in crowded urban airspaces. Similarly, aviation surveillance and code coordination managers will oversee UAV tracking, manage identification codes, and prevent collisions.

The adaptation of these profiles necessitates the integration of additional tasks and responsibilities to enhance their relevance and effectiveness within the context of UAM. These additions were identified during the analysis stage through the literature review and subsequently validated and grouped during focus groups and workshops and are presented in the next paragraphs.

Key complementary responsibilities include UAM Performance Analysis and Quality Assurance, ensuring operational efficiency and reliability; UAM Project Execution and Resource Management, focusing on the allocation and optimisation of resources; UAM Safety Governance and Compliance Control, addressing adherence to regulatory frameworks and safety protocols; and UAM Infrastructure Development and Maintenance, supporting the establishment and upkeep of critical physical and digital infrastructure. Furthermore, these roles need to involve responsibilities regarding UAM Operational Documentation and Financial Stewardship, ensuring meticulous documentation and fiscal oversight; Team Leadership and UAM Capability Development, fostering workforce competency and cohesion; UAM Public Engagement and Awareness Campaigns, promoting societal acceptance and awareness; and UAM Inspection Management and Damage Control, aimed at mitigating risks and ensuring operational integrity.

In conclusion, by extending and adapting these roles, the ESCO framework can address the challenges introduced by UAM, ensuring the workforce is equipped to support its safe, secure, efficient, and sustainable integration into urban environments.

IV. Conclusion and Future Work

This study introduces the SUAMI framework, an extension of the existing SUMI framework, to account for the inclusion of UAM into city transport and enable the assessment of its impacts. By analysing and adapting key indicators, SUAMI provides municipalities, urban planners, drone operators, policy makers and other relevant stakeholders with a comprehensive tool to assess and manage the environmental, operational, and societal impacts of UAM. The framework ensures that UAM can be seamlessly integrated into SUMPs, supporting the EU's goals for transportation, climate action, public health, and social equity.

Additionally, this work introduced updated occupational profiles tailored to UAM. By building on the ESCO framework, new competencies, tasks, and responsibilities were identified for roles such as drone pilots, airspace managers, urban planners, and UAM-specific infrastructure developers. These profiles aim to equip the workforce with the necessary skills to ensure safe, efficient, and sustainable UAM operations.

Future work will focus on refining and extending the SUAMI framework to account for non-core indicators of the SUMI framework and to introduce new metrics tailored to UAM-specific needs, not encountered in other modes of transport. We further plan to test the SUAMI framework in real-world settings to test its practicality and adaptability. Furthermore, the updated ESCO occupational profiles will undergo further validation through workshops with experts from different countries, ensuring global applicability and relevance. These efforts will contribute to the ongoing development of UAM, enhancing its role in creating sustainable, efficient, and inclusive urban mobility systems.

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