Journal of Sustainability (2026) 2:1, 1-17
https://doi.org/10.55845/jos-2026-21103

RESEARCH ARTICLE

Advancing the Sustainable Urban Air Mobility Indicators (SUAMI) Framework: Integrating Non-Core Indicators and Proposing New Metrics for UAM

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Received: 16. December 2025 / Accepted: 13. April 2026 / Published: 26. April 2026

Abstract

The integration of Urban Air Mobility (UAM) into urban transportation systems represents a significant step towards sustainable and innovative mobility solutions. Building upon the Sustainable Urban Air Mobility Indicators (SUAMI) framework introduced previously, this study extends the framework by analysing and integrating non-core indicators from the Sustainable Urban Mobility Indicators (SUMI). Each indicator's relevance and applicability to UAM are systematically evaluated, and necessary adaptations are proposed. Furthermore, this paper identifies critical gaps in the existing framework and introduces new indicators tailored to address the unique characteristics and challenges of UAM. These include environmental, operational, societal, and infrastructure-specific metrics essential for the practical assessment and successful implementation of UAM in smart cities. By refining and expanding the SUAMI framework, this work provides municipalities and policymakers with a comprehensive tool to evaluate and guide UAM integration, supporting sustainability, safety, and efficiency objectives.

Keywords Urban Air Mobility (UAM) · Sustainable Urban Air Mobility Indicators (SUAMI) · Sustainable Urban Mobility Indicators (SUMI) · Smart Cities · Non-core Indicators · Urban Mobility Metrics · Air Mobility Integration · New UAM Indicators

1. Introduction

The future of urban transportation systems is shifting towards more sustainable, efficient, and multimodal solutions. Alongside traditional transportation modes such as cars, buses, trains, and aeroplanes, Urban Air Mobility (UAM) is emerging as a promising solution to urban mobility challenges. UAM, powered by innovative electric vertical take-off and landing (eVTOL) aircraft, introduces cleaner, quieter, and more efficient alternatives to existing mobility options. By utilising vertical space and integrating specialised stations like vertiports (Al-Rubaye et al., 2023), UAM has the potential to reduce congestion, enhance urban connectivity, and promote environmental sustainability (Al-Rubaye et al., 2023; Moradi et al., 2024; Kelly, 2024; Krull & Muhammad, 2022; Wijaya et al., 2021).

However, the successful integration of UAM into urban transportation ecosystems requires comprehensive regulatory frameworks to address critical challenges, including safety, affordability, energy consumption, noise pollution, and equitable access (Mou et al., 2021; European Commission, 2023a; European Union Aviation Safety Agency, 2022a). In Europe, the Sustainable Urban Mobility Plan (SUMP) framework (Rupprecht Consult, 2019) has served as a critical tool for promoting sustainable urban transportation systems. Central components of SUMPs are the Sustainable Urban Mobility Indicators (SUMI) (European Commission, 2020), which provide measurable benchmarks to evaluate key areas such as accessibility, safety, air quality, and energy efficiency.

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While the SUMI framework effectively assesses ground-based transportation, it lacks provisions for emerging aerial solutions like UAM and Unmanned Aerial Vehicles (UAVs). This gap highlights the urgent need for extending and adapting existing indicators to evaluate the environmental, operational, and societal impacts of UAM within urban settings (Tojal & Paletti, 2023; Wang et al., 2023). Moreover, despite the increasing policy and academic attention to UAM, there is currently no structured and empirically informed approach for extending established urban mobility indicator frameworks to UAM contexts in a transparent and comparable manner.

To address this gap, the Sustainable Urban Air Mobility Indicators (SUAMI) framework was developed as an extension of the Sustainable Urban Mobility Indicators (SUMI) framework to capture UAM-specific challenges (Palaiologk & Arvanitidis, 2025). The original SUAMI framework established a foundational set of core indicators for UAM through an in-depth qualitative study combining literature analysis and expert consultations from the fields of sustainable development, aviation and urban planning. Prior work by Tojal and Paletti (2023) examined the applicability of SUMI indicators to Urban Air Mobility by classifying the core SUMI indicators into three levels of applicability—high, medium and low—based on their relevance to UAM contexts, as summarised in Table 1. That study provided detailed justifications for the assigned applicability levels but focused exclusively on the core indicators of the SUMI framework, leaving the non-core indicators unexamined.

In our previous work (Palaiologk & Arvanitidis, 2025), a comparable applicability assessment was conducted for the core indicators within the SUAMI framework, validating and adapting their relevance for UAM contexts. Building on this body of work, the present study extends the SUAMI framework by applying the same systematic evaluation logic to the non-core SUMI indicators. In this context, the study is guided by the following research question: How can existing sustainable urban mobility indicator frameworks (SUMI) be systematically extended and adapted to effectively assess the environmental, operational, and societal impacts of UAM? To address this question, the study examines the relevance and applicability of non-core SUMI indicators to UAM, identifies the necessary adaptations to ensure their validity, and explores the need for additional indicators that capture UAM-specific characteristics not covered by existing frameworks. Specifically, the study systematically evaluates the relevance and applicability of the SUMI non-core indicators in emerging UAM contexts, proposes adaptations grounded in expert knowledge and literature evidence to better reflect the operational and sustainability characteristics of UAM systems, and introduces two novel indicators—Maturity and Availability of Service—that address critical gaps related to operational readiness and service reliability. Through this extension, the study completes the applicability assessment of the SUMI framework for UAM and further strengthens SUAMI as a comprehensive and coherent indicator framework for evaluating UAM integration into urban mobility systems.

This paper is structured as follows. Section 2 describes the research methodology, including the expert consultations, literature review and analytical approach used to evaluate and extend the SUAMI framework. Section 3 presents the results, explaining the assessment of SUMI non-core indicators, the proposed adaptations and the newly introduced UAM-specific indicators. Section 4 summarises the main conclusions and outlines directions for future research.

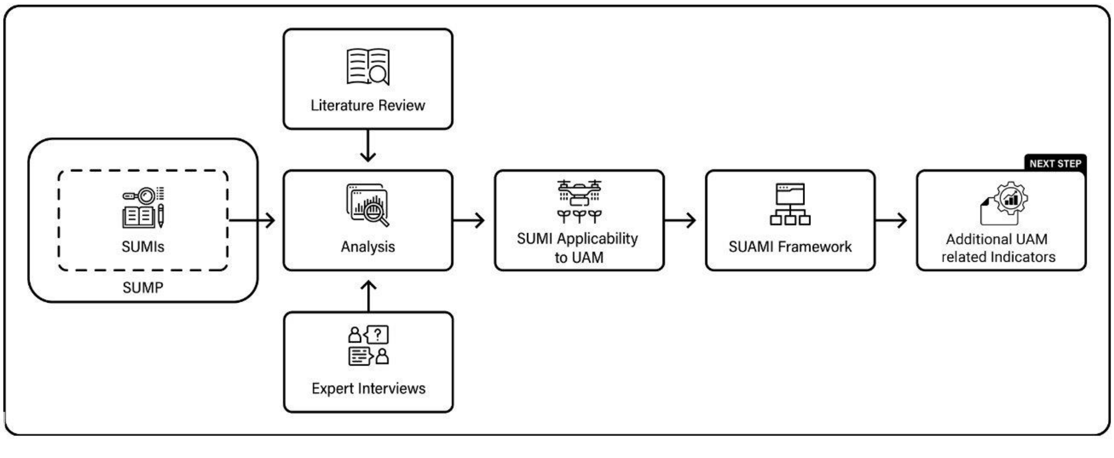

Figure 1. Methodological approach for extending the existing SUAMI framework through the evaluation of non-core SUMI indicators and the introduction of UAM-specific metrics.

Table 1. Overview of SUMI core and non-core indicators, showing their original applicability within the SUMI framework and the proposed applicability following adaptation within the extended SUAMI framework.

Indicator name	Definition of the indicator	Applicability within SUMI framework	Proposed applicability within SUAMI framework
Core Indicators			
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
Noise hindrance	Hindrance of the 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-wheel 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
Non-Core Indicators			
Quality of public spaces	The perceived satisfaction of public spaces.	–	High
Urban functional diversity	Functional diversity refers to a mix of spatial functions in an area, creating proximity of mutually interrelated activities.	–	Medium
Commuting travel time	Duration of commute to and from work or an educational establishment, using any types of modes.	–	Medium
Mobility space usage	Proportion of land use, taken by all city transport modes, including direct and indirect uses.	–	High
Security	The perceived risk of crime and passenger security in urban transport.	–	Medium
Not an indicator, but a parameter for several indicators			
Modal split	The percentage of travellers using a particular mode of transport compared to the ratio of all trips made.	–	High

2. Materials and Methods

Building on the SUAMI framework introduced in prior work (Palaiologk & Arvanitidis, 2025), this study focuses on extending the framework by examining the applicability of the non-core indicators of the SUMI framework to UAM contexts. The methodology followed in this study combined literature and desk research with qualitative expert consultations to assess indicator relevance, identify conceptual and operational gaps, and propose adaptations where necessary. In addition, insights from the literature and expert discussions were used as input to the definition of new indicators addressing UAM-specific challenges related to operational readiness and service availability. Together, these steps result in an extended SUAMI framework tailored to support sustainability assessment and planning for UAM systems. To ensure traceability and analytical consistency, a structured evaluation protocol was applied systematically across all indicators. The same analytical steps—literature review, expert consultation, indicator evaluation and adaptation—were applied across all indicators, following the structured workflow illustrated in Figure 1.

To ensure analytical consistency, each non-core SUMI indicator was evaluated using a structured three-step analytical protocol:

1. Conceptual relevance: assessment of whether the indicator captures environmental, operational, spatial or societal dimensions directly or indirectly affected by UAM.
2. Need for adaptation: identification of required modifications in definition, scope or calculation methodology to reflect UAM-specific characteristics.
3. Final applicability classification: assignment of a High, Medium or Low applicability level based on the combined assessment of relevance and operational feasibility.

This structured protocol was applied consistently to each indicator to ensure comparability and reproducibility of the analytical logic.

This approach allows the analytical logic behind the proposed adaptations and new indicators to be replicated or extended in future studies on emerging mobility systems.

2.1. Expert Consultations and Qualitative Data Collection

The study results are based on qualitative expert consultations as part of ongoing research and project activities related to UAM. In total, insights from 26 experts were collected through open, unstructured discussions focusing on sustainability challenges, operational considerations and indicator relevance for UAM systems. The expert consultations analysed in this study correspond to the same set of 26 expert discussions reported in the previous study (Palaiologk & Arvanitidis, 2025), which are here re-analysed with a specific focus on non-core indicators and framework extension. Experts were selected based on their professional involvement in UAM-related domains, including academia, industry, public authorities and research organisations. Insights from the expert discussions were analysed qualitatively and combined with findings from the literature and desk research to refine existing indicators and develop new UAM-specific metrics.

To ensure a structured and transparent analysis of the expert consultations, a qualitative content analysis approach was applied. Notes from the interviews were systematically reviewed and compared across experts to identify recurring patterns and insights. In particular, the analysis focused on how each indicator performs in a UAM context, whether it is directly applicable, requires adaptation, or reveals gaps that necessitate new UAM-specific metrics. The analysis was guided by a set of predefined dimensions aligned with the objectives of the study, including operational feasibility (e.g., integration with vertiports and airspace management), environmental impact (e.g., noise and energy use), and societal implications (e.g., accessibility and public acceptance). Although a formal coding scheme was not employed, the consistent use of these dimensions enabled a structured comparison of expert views and ensured a coherent interpretation of the collected insights across all consultations.

The expert consultations were conducted between 2023 and 2024 as part of ongoing research and project activities related to UAM. Individual discussions typically lasted between 45 and 60 minutes. Most consultations were conducted online via video conferencing platforms, while a limited number took place in person during project meetings and conferences. Notes were taken during all consultations. Given the exploratory and professional nature of the discussions, sessions were not audio-recorded. Responses were documented in aggregated and non-identifiable form. Experts were drawn from diverse organisational backgrounds, including academia, industry, research institutions and public authorities, representing 4 EU Member States (France, Portugal, Cyprus, Slovenia). None of the participants was in a hierarchical or supervisory relationship with the authors.

The consultations were designed as exploratory discussions rather than structured interviews, reflecting the early-stage and evolving nature of UAM implementation and assessment practices. While no formal interview guide was applied, discussions were typically initiated using a small set of indicative questions to ensure a shared thematic focus. These questions served to stimulate open discussion rather than to structure responses. No formal interview questionnaire was used. Examples of indicative questions included: – How do you assess the relevance of this indicator when applied to Urban Air Mobility contexts? – Which aspects of this indicator would require adaptation to reflect UAM-specific operational or sustainability challenges? – Are there important dimensions of UAM sustainability or readiness that you consider insufficiently captured by existing mobility indicators? Insights from the expert discussions were analysed qualitatively and combined with findings from the literature review and desk research to refine existing indicators and to develop new UAM-specific metrics. This approach allowed participants to freely raise issues considered most relevant from their professional perspective.

Notes from each expert consultation were summarised into key themes. Common viewpoints were identified and cross-checked with the literature review. Indicator adaptations and classifications were based on this combined evidence, rather than on individual opinions. This approach enhanced the robustness of the analysis.

2.2. Literature Review and Desk Research

In addition to the expert consultations, for this study, a targeted literature review and desk research were conducted focusing on sustainability assessment frameworks, urban mobility indicators and emerging UAM concepts. Given the early-stage development of UAM systems, the review combined peer-reviewed academic literature with policy documents, technical reports and official frameworks. Academic sources were identified through searches in scientific databases such as Scopus, Web of Science and Google Scholar, using keywords including Urban Air Mobility, sustainable mobility indicators, SUMI, sustainability assessment frameworks and related terms. Policy and technical sources were collected from recognised European and international organisations, including the European Commission, EASA, OECD and sector-specific initiatives.

No strict publication year boundary was applied. However, emphasis was placed on recent literature reflecting current regulatory, technological and policy developments in Urban Air Mobility. Earlier foundational works on sustainable mobility indicators were included where methodologically relevant. Sources were included if they addressed sustainability assessment, indicator development or evaluation frameworks relevant to urban or emerging mobility systems. Studies focusing exclusively on conventional aviation operations or unrelated transport modes were excluded unless they provided transferable methodological insights. The inclusion of policy frameworks and grey literature was considered appropriate due to the limited availability of peer-reviewed studies and the strong role of policy-driven frameworks in shaping UAM development.

Findings from the literature review and desk research were used to identify existing indicators and key gaps, and were combined with expert insights to adapt indicators and develop new UAM-specific metrics.

The applicability classification followed explicit criteria. An indicator was classified as:

- High applicability when it directly captures UAM-relevant impacts and can be operationalised with minimal adaptation;
- Medium applicability when indirectly relevant, context-dependent, or requiring moderate conceptual adaptation;
- Low applicability when conceptually misaligned with UAM characteristics or offering limited analytical value in early-stage deployment contexts.

These criteria were applied consistently across all indicators to support transparent and reproducible classification.

The classification was carried out by the authors based on a combined assessment of the literature and insights from expert consultations. In cases of uncertainty or differing interpretations, the authors reviewed the evidence jointly and reached a consensus through discussion. This iterative process ensured a consistent and transparent evaluation across all indicators.

3. Results

This section presents the results of the extension of the SUAMI framework, structured in three complementary parts. First, Section 3.1 focuses exclusively on the analysis of the SUMI non-core indicators, evaluating their relevance and applicability to UAM contexts. For each non-core indicator, the assessment examines its conceptual fit, data requirements and potential need for adaptation in order to capture UAM-specific environmental, operational, spatial and societal impacts. For completeness and comparability, Table 1 presents both the applicability of the core indicators as established in previous work (Palaiologk & Arvanitidis, 2025) and the results of the present study for the non-core indicators. The table therefore provides a consolidated overview of the full indicator set, showing the original applicability within the SUMI framework alongside the proposed applicability within the extended SUAMI framework, with the latter reflected in the final column. Second, Section 3.2 introduces two newly proposed indicators—Maturity and Availability of Service—which address critical gaps identified in existing urban mobility indicator frameworks, particularly with respect to operational readiness, infrastructure preparedness and service reliability of UAM systems. These indicators are defined, structured and justified based on literature evidence and expert insights. Third, Section 3.3 discusses Modal Split as a supporting parameter within the SUAMI framework. While not treated as a standalone indicator, Modal Split is analysed due to its cross-cutting role in informing multiple sustainability indicators, particularly in the context of mixed passenger and freight UAM operations.

3.1. SUAMI Non-Core Indicators

3.1.1. Quality of Public Spaces. This indicator evaluates the perceived satisfaction of public spaces. To calculate it, a city must conduct a survey with approximately 500 respondents using the following questions:

- Generally speaking, please tell me if you are [1] satisfied, [2] rather satisfied, [3] rather unsatisfied, [4] not at all satisfied, or [5] DK/NA (do not read out), with each of the following issues in your city or area:
- Public spaces such as markets, squares, and pedestrian areas.
- Green spaces such as parks and gardens.

The quality of public spaces may fluctuate based on the location and size of UAM infrastructure, such as vertiports, which could replace existing parks or public areas. Previously satisfied citizens might express dissatisfaction if UAM infrastructure disrupts valued public spaces (Biehle, 2022). Research (Biehle, 2022) indicates that UAM can influence the perceived quality of urban public spaces, particularly through the establishment of vertiports and the introduction of low-level air traffic. The presence of eVTOLs (electric vertical take-off and landing vehicles) may alter how citizens perceive safety, privacy, and overall enjoyment of these spaces. Factors such as noise pollution and visual aesthetics play significant roles in shaping public sentiment towards these areas. Moreover, the same study states that the successful integration of UAM into urban environments will depend on finding a balance between economic benefits derived from airspace usage and the quality of public spaces experienced by citizens. Urban planners must consider how to configure airspace usage in ways that minimise negative impacts while maximising accessibility and mobility benefits. Therefore, in the context of UAM, it is crucial to assess whether citizens feel safe and at ease with drones flying over public spaces. Questions about whether drone operations cause anxiety or stress should be included, as they directly impact individuals' overall well-being (Saini et al., 2021; Defense Technical Information Center, 2021). These questions could be integrated into the "Quality of Public Spaces" indicator or addressed through a new, dedicated metric. Further studies are needed to determine the necessity and definition of such a new indicator. 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. The indicator is straightforward to integrate and effectively captures public sentiment regarding UAM impacts on public spaces.

3.1.2. Urban Functional Diversity. Functional diversity refers to the mix of spatial functions in a given area, fostering proximity between interrelated activities. To calculate this parameter, the city's territory is divided into 1 km × 1 km grids, and the following functions are examined in each grid:

- Business (industry, offices, logistics)
- Hospital and medical services
- General services (post, administration)
- Schools
- Commercial (shops, supermarkets)
- Sports and recreation
- Residential (families)
- Residences for elderly people
- Parks and greens

The European Union's Urban Air Mobility and Sustainable Urban Mobility Planning report (European Commission, 2023b) emphasises the need for a holistic planning approach that integrates UAM into existing urban transportation systems. This integration is crucial for enhancing urban functional diversity, as it allows UAM to complement other modes of transport, thereby improving overall mobility and accessibility within functional urban areas. The study on socially sustainable urban air mobility in Europe (European Union Aviation Safety Agency, 2021) highlights that the assessment of UAM services should primarily focus on their ability to enhance accessibility to urban transportation systems rather than solely on urban functional diversity. The research suggests that the effectiveness of UAM will depend more on the spatial distribution and operational performance of vertiports, which can exist independently of urban functional diversity metrics. Therefore, in the context of UAM, this indicator does not appear to be essential for assessing UAM's impact on the city. It does not provide specific information or comparative insights regarding the effects of UAM activities or other transport modes. However, as a non-core indicator, it can serve as a complementary element within the framework. It provides valuable information about the types of activities occurring in specific parts of the city, which can guide the planning of mobility services and infrastructure placement. Minimal or no adjustments would be needed to integrate this indicator into the SUAMI framework.

Based on the preceding analysis and supported by expert input, the applicability of this indicator is classified as medium within the SUAMI framework. While not critical, it offers additional insights that may enhance urban planning for UAM-related infrastructure.

3.1.3. Commuting Travel Time. This indicator measures the duration of commutes to and from work or educational institutions using various modes of transport. To calculate it, a survey with 500 respondents is recommended, asking the following:

- What were your modes of transport for your commute? (Car, Motorcycle, Public Transport, Ferry, Bike, Walking, Car & PT, Bike & PT, Walk & PT).
- Could you provide details about your main commute:
- Average travel distance (one way) in km (per mode).
- Average travel time to work in minutes (per mode).
- Average travel time to return home in minutes (per mode).

Alternatively, data from mobility surveys that aggregate daily trips by mode and purpose can be used (Banister, 2005; Eurostat, 2020). This indicator could become particularly useful if air taxis or air buses are deployed on a large scale and become accessible to most citizens. Studies suggest that integrating novel transport modes such as UAM into urban systems has the potential to significantly reduce commute times and improve overall accessibility (Schweiger & Preis, 2022). However, since such scenarios remain speculative at this stage of UAM implementation, it is recommended that cities refrain from prioritising this indicator during the early deployment phase. In the future, it could serve as a valuable metric to quantify commuting travel time alongside conventional transport modes (Baena et al., 2024). The analysis and expert consultations indicate a medium level of applicability of this indicator within SUAMI. Its relevance remains limited due to the nascent stage of UAM deployment, but it holds significant potential as UAM services evolve.

4. Mobility Space Usage

This indicator aims to capture all transport-related space within an urban area. To achieve a comprehensive assessment, additional aspects such as tram tracks, bus lanes, and logistics centres should be included, particularly if they are not already accounted for in the road space surface data. Below, we outline the various components and considerations necessary for calculating this indicator:

- **Roads**: When precise data on street surfaces is unavailable, standard widths can be assumed to estimate their spatial footprint.
- **Parking Lots and Petrol Stations:**
  - To estimate parking space usage, multiply the number of parking spaces by their average surface area (~13 to 18 m^2 per car).
  - For petrol stations, the total space can be estimated by multiplying the average surface area of a petrol station (e.g., 800 m^2 per station in Brussels) by the number of registered petrol stations.
- **On-Street Parking**: This is typically considered direct use and is included in the road space surface, unless more precise street data is available to differentiate between parking usage and mobility usage.
- **Public and Private Parking:**
  - Public parking refers to all parking spaces accessible to the public, such as those in multi-story car parks. These are accounted for by their total parking space surface.
  - Private parking includes spaces not open to the public, such as residential or office parking garages, and is also measured by its surface area.
- **Stations**: "Stations" refer to transport stations not already included in direct-use calculations. The inclusion of these depends on the availability of data. For instance:
  - Road surface data might already account for mass rapid transit stations.
  - Tram systems and railways may include associated stations in their calculations.

This approach ensures a detailed evaluation of land dedicated to various transport-related uses, providing a comprehensive understanding of the urban transport spatial footprint. The indicator of mobility space usage can be expanded in order to include the land taken for the implementation of U-space and UAM activities, as well. Similarly, for UAM activities to take place in the air, the necessary ground infrastructure must be established. For example, vertihubs are envisioned as substantial structures located in high-traffic urban areas, typically requiring significant land space to accommodate multiple landing pads, parking areas, and maintenance facilities. More specifically, a vertihub might have around ten take-off and landing areas along with additional spaces for parking or maintenance operations (Stolz & Laudien, 2022). The amount of land that UAM infrastructure occupies, such as vertiports, stations, parking near the vertiports, take-off and landing areas, etc., will need to be taken into account. The impact of UAM infrastructure can be demonstrated through both the Mobility Space Usage and Quality of Public Spaces indicators. Another important consideration is the inclusion of vertical space in these indicators. Evaluating how much space in the air UAVs occupy and the amount of visual pollution caused by UAM activities is critical for comprehensive UAM impact assessment (Ceccato & Loukaitou-Sideris, 2022; Masoumi & Fastenmeier, 2016). Considering both the literature and expert insights, the indicator is assessed as highly applicable within the SUAMI framework. As mentioned earlier, this is because the indicator provides critical insights into the spatial impact of transportation infrastructure, which is directly relevant to urban planning and sustainability assessments. Its broad applicability across various transport modes, including emerging UAM infrastructures, makes it an essential metric for cities aiming to optimize land use while integrating new transport technologies. In the context of UAM, this indicator can be expanded to include land occupied by U-space infrastructure, such as vertihubs, vertiports, and take-off/landing areas. For example, a vertihub could require significant land for multiple take-off pads, parking zones, and maintenance facilities. Additionally, vertical space usage and visual pollution caused by UAV operations could be integrated into this indicator. This indicator demonstrates strong relevance for UAM contexts and is therefore classified as having high applicability within the SUAMI framework. Its relevance lies in providing critical insights into the spatial footprint of UAM infrastructure, aiding urban planners in optimizing land use.

4.1.1. Security. This indicator evaluates citizens' perceived security regarding crime and safety in urban transport systems. Key aspects of this indicator include:

- Perceived safety in public transport (day and night)
- Walking safety (day and night)
- Cycling safety (day and night)
- Car theft and risks of crime in car traffic

All these aspects of security are important issues for the well-being of citizens. Passenger security and the perceived risk of crime in urban transport systems have been extensively studied in the literature. Ceccato et al. (Ceccato & Loukaitou-Sideris, 2022) provide a systematic review of crime and safety in transit environments, highlighting the factors that contribute to perceived insecurity across various transport modes. This study explores how transit environments influence crime and perceived safety, linking urban landscapes to security concerns. A recent study (Adorean et al., 2021) presents a methodical approach to evaluating passenger perceptions of security in public mass transportation systems, emphasising the role of infrastructure and measures in shaping passenger confidence. In the context of UAM, it is important to take into account whether citizens will feel safe when drones are flying over their cities. Questions regarding whether drone presence will cause them anxiety or stress are necessary in order to assess individuals' overall health. On top of physical security, it is crucial to expand the current metric into the categories of cybersecurity and privacy, since with the implementation of UAVs, concerns arise regarding cyberattacks and data protection. In this way, the appropriate precautions can be taken from both the industry's side and public authorities in order to prevent these types of violations. Below, we refer separately to the key dimensions of security in the context of UAM, focusing on both cybersecurity and privacy, as these aspects are critical to ensuring safe and trustworthy UAM operations.

- **Cybersecurity**: UAV systems are vulnerable to cyberattacks such as jamming, spoofing, and denial-of-service (DoS) attacks (Cavallaro & Dianat, 2021). A new indicator addressing cybersecurity incidents or intrusion attempts is suggested.
- **Privacy**: The use of surveillance cameras for vertiports and UAV operations raises privacy concerns, particularly near private properties. A metric for privacy violations or reported concerns is necessary to assess the impact.

The combined evidence from the analysis and the expert consultations supports a medium applicability classification for this indicator within the SUAMI framework. While critical for urban safety, its application to UAM requires further refinement and exploration.

Table 2. Summary of adaptations and applicability of non-core SUMI indicators within the extended SUAMI framework

Indicator	Applicability in SUAMI	Main Adaptation for UAM	Key UAM-Specific Considerations
Quality of Public Spaces	High	Integration of drone presence, vertiport infrastructure and noise perception into public satisfaction assessment	Public acceptance, visual impact, perceived safety, noise effects
Urban Functional Diversity	Medium	Limited adaptation; contextual interpretation for UAM infrastructure placement	Spatial complementarity, vertiport location planning
Commuting Travel Time	Medium	Future-oriented inclusion of air taxi and aerial passenger services	Early-stage deployment limitations, scalability dependency
Mobility Space Usage	High	Inclusion of vertiports, vertihubs, U-space infrastructure and vertical airspace occupation	Land-use impact, spatial footprint, visual pollution
Security	Medium	Expansion to include cybersecurity and privacy dimensions	Cyberattacks, data protection, public trust, and passenger safety
Modal Split (parameter)	High	Consideration of UAV passenger and freight contributions in the modal distribution	Multimodal integration, freight-passenger balance

Table 2 provides a concise overview of the main adaptations and applicability classifications of the non-core SUMI indicators within the extended SUAMI framework.

4.2. SUAMI New Proposed Indicators

The rapid development of UAM requires new metrics to assess and support its integration into urban ecosystems effectively. While existing core and non-core indicators provide valuable insights, they must be complemented with additional indicators that address UAM's unique challenges. This section introduces two newly proposed indicators—Maturity and Availability of Service—designed to measure the operational readiness and reliability of UAM systems. These indicators enable cities to assess key factors such as infrastructure preparedness, regulatory frameworks, and service efficiency, ensuring successful UAM implementation.

4.2.1. Maturity. A new indicator is proposed, focusing on the readiness of emerging technologies, which is essential for determining or predicting when UAM services will become operational. The indicator evaluates the readiness level across three key dimensions, which will be discussed later on:

- Regulation (e.g., flight authorisations)
- Infrastructure (e.g., CNS equipment, vertiports), Technology (e.g., batteries, engines, software)
- Personnel (e.g., flight crew, Air Navigation Service Provider (ANSP), Common Information Service Provider (CISP), U-space Service Provider (USSP), supervisors)

The main goal of this indicator is to create a structured checklist of necessary elements within each category, enabling cities to easily assess their readiness for deploying UAVs in urban spaces.

a) Regulation.

A robust regulatory framework is a fundamental pillar for enabling Unmanned Aircraft Systems (UAS) operations in urban airspace. Both the Federal Aviation Administration (FAA) and the European Union Aviation Safety Agency (EASA) have been actively developing guidelines to ensure the safe integration of these operations. The FAA's Urban Air Mobility (UAM) Concept of Operations Version 2.0 emphasises the need for regulatory adaptations to support the increasing density and complexity of UAM operations in urban airspaces (Federal Aviation Administration, 2024). Similarly, EASA has introduced key building blocks for UAM regulation, including airworthiness, operational testing, airspace integration, and other research initiatives such as the SAFIR-Med project, which explores the practical implementation of U-Space/UTM services (SAFIR-Med Consortium, 2024). These efforts highlight the importance of comprehensive regulations to address challenges such as airspace management, operational safety, and societal acceptance. Without such frameworks, UAM activities cannot proceed effectively, and bureaucratic hurdles may hinder progress, particularly for stakeholders with limited experience in the field.

The checklist includes the following key components:

- Certifications for staff, UAVs, and equipment: all personnel involved in UAM operations, including remote pilots, flight planners, and maintenance staff, must meet specific certification requirements. UAVs and associated equipment must also adhere to airworthiness standards established by regulatory authorities such as EASA and FAA. For instance, EASA's guidelines for drone certification under the Specific and Certified categories outline requirements for UAV design, manufacturing, and operational reliability (European Union Aviation Safety Agency, 2023; European Union Aviation Safety Agency, 2022b). Similarly, the FAA mandates airworthiness certifications and operational approvals for UAS in the National Airspace System (NAS) (European Union Aviation Safety Agency, 2024a).
- Steps for obtaining flight permits: a structured process is crucial for safe and authorised UAM operations (authorisation requests, ATM coordination, meteorological clearances, geofencing compliance) (European Union Aviation Safety Agency, 2023; Zeng et al., 2016).

By incorporating these elements, the Maturity indicator provides city planners and regulators with a structured approach to evaluating the readiness of their regulatory frameworks for UAM deployment. The indicator's outcome will categorise the city's regulatory maturity into one of the following levels:

- Not ready for deployment: significant gaps exist in regulatory preparedness.
- Close to deployment: most regulatory elements are in place, but some critical aspects require further attention.
- Ready for deployment: the city meets all regulatory requirements for UAM operations.

b) Infrastructure and Technology.

A similar checklist is proposed for evaluating the availability of necessary infrastructure and technological components. The checklist includes:

- Infrastructure for take-off and landing (e.g., vertiports)
- 4G–5G network coverage
- GNSS (Global Navigation Satellite Systems)
- Navaids (navigation aids)
- Visual aids (e.g., lights, air-ground lights, QR codes, or image patterns)
- HD cameras for secure area monitoring and operations
- Warehousing for MRO (Maintenance, Repair, Overhaul) and hangars for large eVTOLs
- Power distribution systems for recharging and operations
- Local meteorological data (e.g., AWOS, wind sensors)
- Waste management systems for recycling batteries
- Proximity sensors (e.g., basic radar) for landing areas and surveillance, including non-collaborative UAS detection
- Communication systems for ATM (Air Traffic Management) coordination and data exchange

This checklist ensures that cities can systematically assess their infrastructure maturity and identify any gaps that need to be addressed for UAM readiness.

c) Personnel.

The readiness of trained and certified personnel is another critical factor for UAM maturity. This indicator evaluates the availability of essential human resources, including:

- Maintenance and repair staff
- Operators
- Ground operators
- Remote pilots
- Supervisors
- Flight planners and authorizers

Ensuring the presence of adequately trained personnel is necessary for the safe and efficient deployment of UAM services. The Maturity indicator is a newly proposed metric within the SUAMI framework, and its applicability is classified as high.

4.2.2. Availability of Service. Another crucial indicator for UAM deployment is the "Availability of Service". This metric includes various factors, including the downtime required for recharging UAVs, the time needed to reserve airspace, issue flight plans, and receive authorisations, as well as the availability of take-off and landing slots. It also includes ground handling operations, repairs, and the exchange of spare parts, all of which are critical to maintaining consistent and efficient UAM operations (Zeng et al., 2016; Claesson et al., 2016). Within UAM contexts, Availability of Service is particularly critical for time-sensitive applications, most notably medical and emergency operations, where reliability, response time and continuity of service are decisive factors. Medical emergencies represent a key application domain through which the relevance of the Availability of Service metric can be illustrated, as they place stringent requirements on system reliability, response time and operational continuity. UAVs have already demonstrated their potential to improve emergency response times by delivering life-saving supplies such as automated external defibrillators (AEDs), medicines, blood, and other critical items faster than conventional transportation methods (Claesson et al., 2016; Pulver et al., 2016; Schierbeck et al., 2022). Studies show that drones can dramatically reduce response times for out-of-hospital cardiac arrests, significantly improving survival rates (Claesson et al., 2016; Schierbeck et al., 2022). Additionally, UAVs could enable rapid transport of medical personnel, including doctors and nurses, to emergency sites, bypassing congested or inaccessible areas. While the use of UAVs for transporting medical supplies is well-documented, the deployment of drones to rapidly transport medical personnel, such as doctors and nurses, to emergency sites is an emerging concept with limited practical implementation. The future of UAV technology holds the potential to transport people, as explored in initiatives like the iMOVE Australia project (iMOVE Australia, 2024). Passenger drones, or eVTOL aircraft, are being developed to carry individuals, marking a significant shift from traditional unmanned UAVs. These advancements are driving research and regulatory updates to enable safe and efficient human transportation in urban airspaces.

For cities to assess and optimise UAM service availability, it is essential to understand the operational readiness of these systems. Key considerations include flight planning efficiency, airspace coordination, and infrastructure readiness, such as recharging stations and maintenance facilities. Furthermore, robust ground handling and maintenance frameworks are vital for ensuring minimal downtime and operational reliability (Claesson et al., 2016). By incorporating this indicator, cities can better evaluate how quickly and efficiently UAV services can be deployed, particularly in time-sensitive situations. This metric enhances preparedness for emergency scenarios and also provides a comprehensive understanding of the overall reliability and availability of UAM systems.

4.3. Modal Split

The modal split measures the share of different transport modes relative to total passenger or freight trips. The following definitions are applied:

- Passenger mobility:
- Modal split by passenger-kilometres travelled
- Modal split by number of trips made
- Freight transport:
- Modal split by goods vehicle-kilometres travelled
- Modal split by tonne-kilometres travelled

Given that UAVs can be utilised for both freight and passenger transport, this parameter is essential for evaluating UAM's integration into existing transport systems (Banister, 2005; Rodrigue et al., 2016). Studies highlight the adaptability of modal split metrics to represent new transport technologies, including UAVs, in both urban and interurban contexts (Goodwin, 2004; Federal Aviation Administration, 2024). Proper calculations ensure that UAM operations are adequately represented in terms of passenger and freight contributions (Schweiger & Preis, 2022). Based on the above, and further validated through expert insights, the applicability of the modal split indicator is classified as high within the SUAMI framework. Its adaptability to emerging transport modes makes it a critical metric for transportation behaviour analysis. In line with the SUMI framework, Modal Split is treated in SUAMI as a supporting parameter rather than a standalone indicator, as it informs and contextualises multiple sustainability indicators.

5. Policy Implications and SDG Alignment

The extension of the SUAMI framework has important implications for urban policy, planning, and governance, particularly in the context of integrating UAM into existing transport systems. By translating complex technological and operational aspects into measurable indicators, the framework provides a structured decision-support tool for municipalities and policymakers to assess, monitor, and guide the deployment of UAM services.

In particular, the framework supports evidence-based policymaking by enabling cities to evaluate the environmental, operational, and societal impacts of UAM in a systematic and comparable manner. It complements existing Sustainable Urban Mobility Plans (SUMPs) by extending their analytical scope to include aerial mobility solutions, thereby supporting a more integrated and multimodal approach to urban transport planning. Furthermore, the inclusion of non-core indicators—such as those related to public space quality, spatial usage, and security—allows policymakers to capture indirect and context-dependent impacts, including public acceptance, land-use implications, and perceived safety.

The extended SUAMI framework also aligns with key United Nations Sustainable Development Goals (SDGs), particularly those most directly related to urban mobility, sustainability, and innovation. Specifically, it contributes to SDG 11 (Sustainable Cities and Communities) through indicators addressing accessibility, public space, and multimodal integration; SDG 13 (Climate Action) through environmental performance and emissions-related considerations; SDG 9 (Industry, Innovation, and Infrastructure) through indicators related to technological readiness and infrastructure development; and SDG 3 (Good Health and Well-being) through aspects related to safety, noise, and overall urban quality of life. These SDGs are highlighted as they represent the most immediate and relevant dimensions of UAM deployment within urban environments.

While the present study does not aim to provide a comprehensive mapping between SUAMI and the full SDG framework, the identified alignments demonstrate the potential of the framework to support broader sustainability objectives. This positioning reinforces the role of SUAMI as a policy-relevant tool that connects technological innovation with societal and environmental priorities.

Finally, the findings highlight the need for adaptive and forward-looking regulatory frameworks to support UAM integration. Policymakers must address emerging challenges related to airspace management, safety, cybersecurity, and data protection, while ensuring public trust and societal acceptance. In this context, the proposed indicators provide a structured basis for assessing readiness, identifying gaps, and supporting informed decision-making for the sustainable deployment of UAM systems.

6. Limitations

This study follows an exploratory approach, combining literature review with expert input to extend the SUAMI framework. While this is appropriate given the early stage of UAM, some limitations should be acknowledged. First, the expert consultations were based on open discussions, which allowed for rich insights but did not follow a fully structured method. Future work could apply more formal approaches (e.g., the Delphi method) to further validate and prioritise the proposed indicators. Second, the classification of indicators (High, Medium, Low) is based on a consistent evaluation process using both literature and expert judgement. However, as with any qualitative assessment, alternative interpretations may be possible, especially as UAM technologies continue to evolve. Third, the proposed framework has not yet been tested in real urban environments. Therefore, the results should be seen as a strong methodological foundation rather than a fully validated tool. Future research will focus on applying the framework in real-world case studies to further refine and validate it. Overall, these limitations reflect the early-stage nature of UAM. The study provides a clear and structured approach that can be further strengthened through more formal expert methods and real-world testing.

7. Conclusion and Future Work

This study extends the previously proposed Sustainable Urban Air Mobility Indicators (SUAMI) framework (Palaiologk & Arvanitidis, 2025) by systematically incorporating non-core indicators and introducing new UAM-specific metrics to address gaps in existing urban mobility assessment tools. By expanding the analytical scope of SUAMI, the proposed framework enables a more comprehensive evaluation of the environmental, operational and societal impacts of Urban Air Mobility (UAM), supporting its informed integration into Sustainable Urban Mobility Plans (SUMPs).

The inclusion of non-core indicators—such as Quality of Public Spaces, Urban Functional Diversity and Security—allows for the assessment of indirect and context-dependent effects of UAM on urban environments, complementing the core sustainability dimensions. In addition, the introduction of the Maturity and

Availability of Service indicators provides new means to assess operational readiness, infrastructure preparedness and service reliability, which are critical for the practical deployment of UAM services. Together, these extensions enhance the analytical robustness and practical relevance of SUAMI as a decision-support tool for urban planners and policymakers.

Future research should focus on strengthening the empirical grounding and operationalisation of the extended SUAMI framework. Key directions include the development of implementation guidelines and manuals to support consistent application by municipalities, as well as the development of a digital, web-based platform that enables the systematic calculation, visualisation and comparison of SUAMI indicators by cities and planning authorities. Such a platform would support scenario analysis, benchmarking and evidence-based decision-making within SUMP processes. Pilot implementations in selected urban contexts will be essential to validate and refine the proposed indicators under real-world conditions. Further work is also needed to support integration with existing SUMP processes and to explore harmonisation across different urban and regulatory settings. Capacity-building activities, including training programmes for public authorities and practitioners, can facilitate uptake, while advances in data-driven technologies such as artificial intelligence and Internet of Things solutions may further enhance data availability and analytical capabilities. Overall, the findings underline the importance of adopting a holistic and adaptive approach to assessing UAM within urban mobility systems. As UAM technologies evolve, continued collaboration between researchers, policymakers and industry stakeholders will be essential to ensure that urban air mobility contributes effectively to a sustainable, efficient and inclusive urban transport future.

Acknowledgements The presented study would not have been possible without the valuable contributions of expert inputs and insights from professionals in their respective fields, and without the support of research assistants in our team at Future Needs. We are deeply thankful to the experts: Evelyn Otero Sola, Associate Professor in aeronautical engineering, Vice-Director of the Centre for Sustainable Aviation (CSA); Antonio Torija Martinez, Professor in Acoustic Engineering at the University of Salford, UK, and Human Response and Metrics expert in the NASA Urban Air Mobility Noise Working Group; Sofia Kalakou, Assistant Professor and Director of BSc in Industrial Management and Logistics from the Department of Marketing, Operations and General Management at ISCTE Business School, Portugal; Jose Ignacio Rodrigues Modrono, Managing Director at Bluenest (powered by Globalvia); Mirjam Snellen, Professor of Acoustics in the Faculty of Aerospace Engineering at Delft University of Technology; Dr. Milan Rollo, Senior researcher at the Artificial Intelligence Center, Faculty of Electrical Engineering, Czech Technical University in Prague and CTO at AgentFly Technologies; Vangelis Stykas, Security consultant and Co-founder and CTO at Atropos.ai; Marta Tojal Castro, project Manager at Instituto Tecnologico de Galicia, Spain; and Fereniki Vatavali, Architect and Applied Researcher at the Institute of Social Science of the National Center of Social Research, Greece. A big thank you goes out to the following team members from Future Needs: Anastasia Bafouni, Nikoleta Krousouloudi, Georgia Nikolakopoulou and Panagiotis Chatzimathios. Their support has been invaluable throughout the publication preparation process.

Authors' contributions AP led the study conceptualisation and overall direction. KD and EG developed the methodology, carried out the analysis, and drafted the manuscript. All authors contributed to revisions and approved the final version.

Funding Research work described in this publication has been conducted in the project "Impact and Capacity Assessment Framework for U-space Societal Acceptance" funded by the European Union's Horizon Europe research and innovation programme (Grant Agreement No 101114776). The project has been supported by the Single European Sky ATM Research Joint Undertaking (SESAR JU).

Data availability Not applicable. No proprietary or confidential data are included in this manuscript.

Declarations

Competing Interests The authors declare no competing interests.

Ethics approval/consent The study involved expert consultations conducted as professional stakeholder consultations. No personal data was collected, and responses were reported only in aggregated, non-identifiable form.

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