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Smart Cities and U-space. Preparing for UAV operations in urban airspace

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Abstract. This article presents the 4D Urban Area Model for Unmanned Aerial Vehicle (UAV) Risk Assessment – a framework designed to support the safe integration of drones in low-altitude urban airspace. The model builds on interoperable 3D city models, is in line with the Specific Operations Risk Assessment (SORA) methodology and U-space regulations, and introduces a fourth dimension: time. Through a nationwide survey of Polish municipalities and consultations with Polish Air Navigation Services Agency (PANSA) experts, the author identified population density and mobility data as essential for assessing drone-related risks. As a result, a 12-interval daily temporal layer was proposed to support dynamic risk zoning – initially with historical data on traffic density and ultimately, in the future, with real-time updates of this data and other obstacles via digital twins. The model divides urban airspace into two zones: I – Safe UAV Flights, and II – Acceptable Risk UAV Flights. In Poland, 72% of cities supported creating UAV safety zones and 68% expressed interest in standardised 3D services. In Helsinki, where urban airspace remains under national control, municipal officials confirmed their readiness to support operations through Geographic Information Systems (GIS) tools and a future digital twin. The 4D model contributes to UAV policy and geoinformatics by enabling real-time risk simulations and strengthening the capacity of local authorities to co-govern urban airspace.

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Contents:

1. Introduction

The theory of city complexity, which underpins the activities of various actors and development planning processes, has been discussed by numerous authors, including Parysek and Mierzejewska (2025), Batty (2006), Batty and Marshall (2012), Portugali (2012b) and Portugali and Stolk (2016). The development of highly complex urban systems requires a systematic planning approach, and smart cities – characterised by high levels of innovation, digital infrastructure and systemic learning (Komninos, 2002a; 2002b; Szymańska, 2023: 91; Szymańska et al., 2024) – offer a favourable environment for testing and implementing new solutions, including those involving Unmanned Aerial Vehicle (UAV) integration. These cities are increasingly expected to harmonise spatial, mobility and digital policies in response to technological advances and the growing demand for new forms of public service delivery. UAVs already support a wide range of municipal functions such as environmental monitoring, infrastructure inspection and emergency response and are poised to become a key element in the development of urban logistics.

Managing urban airspace poses a particular challenge. Operating below the range of traditional Air Traffic Management (ATM) systems, the lower layer of urban airspace is especially complex due to its proximity to people, buildings and critical infrastructure. This complexity, coupled with the anticipated increase in UAV operations, necessitates new governance mechanisms supported by digital tools. Within the EU regulatory framework, this layer – extending from ground level to 120 metres above ground level (a.g.l.) – has been defined as the operational ceiling for standard UAV flights (Commission Implementing Regulation EU 2019/947) (*Note* 1). The European Union Aviation Safety Agency (EASA) (*Note* 2) identifies this zone as one requiring dedicated traffic management solutions and introduced the U-space concept: an ecosystem of automated services enabling the safe and efficient integration of drones into urban airspace through features such as real-time geofencing, dynamic airspace restrictions and flight path coordination.

Despite these developments, many European cities remain unprepared to manage low-level urban airspace. Critical deficits include the absence of interoperable 3D city models, urban digital twins and integrated Geographic Information (GIS) platforms capable of supporting real-time UAV risk assessments and Unmanned Traffic Management (UTM). These shortcomings highlight the need for interdisciplinary coordination between urban planning, spatial policy and technological systems.

Since 2019, the Polish Air Navigation Services Agency (PANSA) (*Note* 3) has been implementing U-space within the broader ATM Master Plan coordinated by EUROCONTROL and SESAR JU (*Note* 4). Its operational system, PANSA UTM, launched in 2020, integrates radar-based drone positioning and real-time coordination of manned and unmanned aviation. This system has gained international recognition, winning two categories at the ATM Awards 2020 and earning Poland fourth place in the global Unmanned Airspace ranking in 2022. However, subsequent regulatory changes under Commission Regulation (EU) 2019/947 introduced new procedures that have, to some extent, hindered the UAV sector's growth in Poland.

In this broader strategic context, the city emerges as both a host and beneficiary of UAV services. On the one hand, it must provide spatial and digital conditions for safe UAV operations and, on the other, use UAV services to improve the management and efficiency of the city. Eleven key urban policy areas related to UAV operations have been identified, including spatial planning (e.g., vertiport locations), risk and airspace management, crisis response, sustainable mobility and innovation policy.

Recognising the growing importance of integrating drones into low-altitude urban airspace, this study formulates the hypothesis that interoperable 3D city models – when enriched with spatial data on population density, mobility flows and aerial obstacles – can support Specific Operations Risk Assessment (SORA)-compliant UAV risk assessment and contribute to public safety. Building on this assumption, the author proposes a 4D Urban Area Model that incorporates a temporal dimension structured into 12 daily intervals, enabling dynamic recalibration of risk zones. The model introduces a two-tiered zoning system for urban airspace: Zone I for Safe UAV Flights and Zone II for Acceptable Risk UAV Flights, based on spatial and temporal exposure levels. The proposed framework not only strengthens municipal capacity for scenario-based planning but also supports future integration into digital twin environments. Findings from Polish municipalities and expert consultations highlight the need to develop tools based on real-time data. Moreover, the experience of Helsinki, which is preparing its GIS infrastructure to align with the ED-318 airworthiness certification for unmanned aircraft systems and identify spatial data gaps, confirms that access to harmonised, up-to-date spatial data is a precondition for reliable UAV risk management in both national and local contexts.

This hypothesis was originally inspired by a 2018 conversation with Prof. J. Kozuba (Silesian University of Technology) (*Note* 5), who proposed that 3D city models and emerging geoinformation technologies could support UAV risk analysis. Since then, the author has conducted longitudinal research in Poland and Finland (2018–2025), with a focus on municipal preparedness for UAV integration, the social acceptance of drone operations and the potential role of GIS and digital twin technologies in supporting safe and coordinated UAV services.

This study presents both empirical findings and a conceptual framework for a universal 4D Urban Airspace Model that may be embedded within the future U-space system. It also includes a case study of Helsinki, with recommendations from the City Office regarding strategy design for urban drone operations, based on municipal experience and lessons learned.

The research addresses three central questions:

1. How can technologies such as 3D city models and urban digital twins support the risk assessment of operations in low-altitude urban airspace?
2. To what extent are European cities prepared to integrate UAV flights into their development and transport policies?
3. What UAV services are socially accepted in urban environments?

2. Research background

2.1. Urban complexity, Smart Cities and system approaches to airspace management

The complexity of contemporary cities calls for integrative, systems-based approaches to governance. In Polish scholarship, Parysek (1985, 1997) and Parysek and Mierzejewska (2025) developed systemic models emphasising functional subsystems and temporal rhythms. Their framework included air as part of the biophysical subsystem, but without recognising vertical spatial layers or treating airspace as a governed urban domain (*Note* 6). Building on this, the present study extends their model by conceptualising urban airspace (0–120 m a.g.l.) as a managed public resource, structured into operational zones and supported by digital twins. There is no single definition of a smart city. Van der Meer and Van Winden (2003) describe it as adaptive governance, while Szymańska (2023) highlights its potential to address social and environmental challenges. Caragliu, Del Bo and Nijkamp (2011) define smart cities as those investing in human and social capital and ICT infrastructure to achieve sustainable growth and quality of life (*Note* 7). Cohen's (2011) six-dimensional model – including smart people, economy, governance and mobility – frames UAV integration as part of a broader shift toward intelligent transport (*Note* 8).

Digital tools such as the Internet of Things (IoT), Artificial Intelligence (AI) and digital twins enable real-time urban management (*Note* 9). Digital twins simulate urban processes and support evidence-based policymaking (Szymańska et al., 2019). Cities like Amsterdam, Helsinki and Singapore use such platforms to integrate spatial, environmental and mobility data, allowing scenario modelling and data-driven decisions (*Note* 10). Urban airspace has emerged as a new frontier in smart city governance. The growth of Urban Air Mobility (UAM) and UAV operations necessitates integrating vertical mobility into city infrastructure (Kosieliński & Mrozek, 2024). At the EU level, the U-space framework – led by EASA – offers digital services (geo-awareness, flight authorisation) aligned with the risk-based SORA methodology (Tsiamis et al., 2019). UAV integration requires more than physical infrastructure like vertiports; it depends on interoperable digital systems and institutional readiness (JARUS, 2023; Traficom, 2024). Urban airspace must be managed as a distinct digital layer alongside traffic, environment and planning systems. Cities such as Amsterdam demonstrate how open data and digital twins can support UAV mobility and resource management (*Note* 11). The safe deployment of UAVs, particularly in Beyond Visual Line Of Site (BVLOS) operations, brings new challenges in risk, social acceptance and system coordination (EASA, 2021; Kosieliński, 2023). Thus, smart cities and digital twins are no longer abstract concepts – they constitute essential foundations for citizen-oriented urban governance. These models support both the planning of airspace and the regulation of UAV operations. The next section explores how these systemic foundations can inform 4D risk assessment models for UAVs in urban environments.

2.2. The potential of 3D city models and digital twins

3D city models – developed using Open Geospatial Consortium (OGC) standards such as CityGML or CityJSON – are gaining strategic importance in urban management. These models form the foundation for urban digital twins (DTs), which increasingly underpin smart city planning, real-time analytics and cross-sector coordination) *Note* 12). However, as noted by Stoter (2020), their effectiveness depends on addressing semantic complexity and model interoperability.

Digital twins evolve in three stages: (1) static ***digital models***, (2) ***digital shadows*** enriched by sensor data and (3) fully bidirectional ***digital twins***, enabling real-time interaction between the physical and digital realms (Fuller et al., 2020; Grieves, 2023).

While many cities have developed 3D models, few have progressed beyond the first phase. Static models cannot reflect dynamic conditions such as wind, heat zones or temporary aerial obstacles – factors critical for UAV integration.

With growing interest in Urban Air Mobility (UAM), DTs offer promising applications in risk assessment, airspace segmentation and SORA implementation. Yet, many cities still rely on fragmented solutions, developed with diverse tools and lacking alignment with international standards (Virtanen, 2024). Stelmach-Fita (2021) emphasised that the success of DTs in spatial governance depends on harmonising datasets – especially land-use and planning documents (*Note* 13).

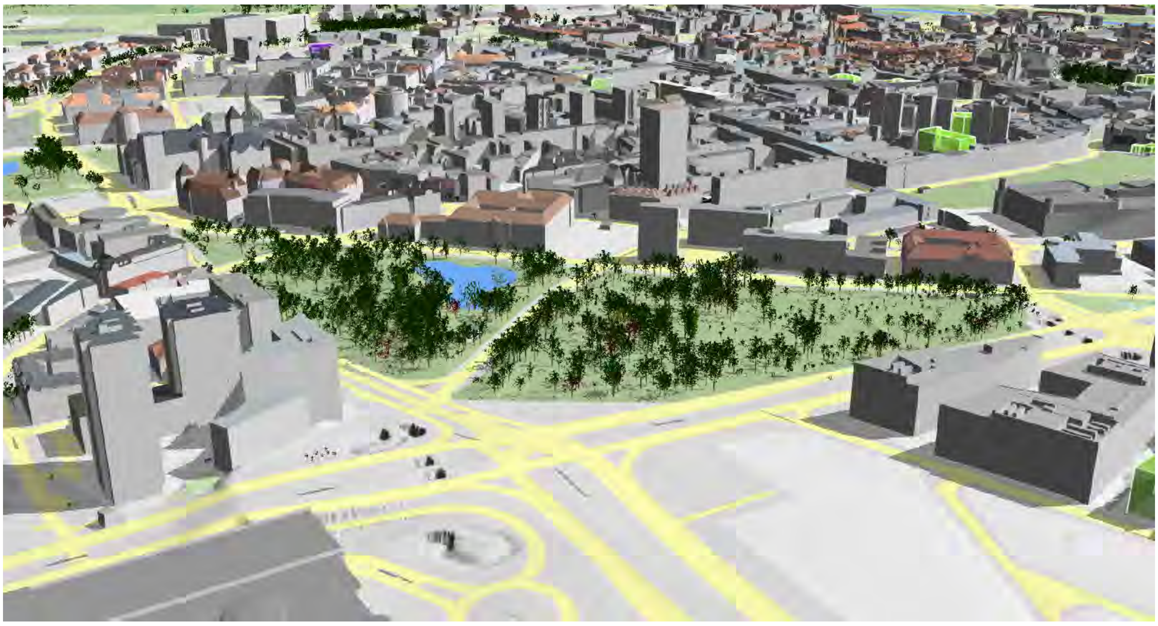

Fig. 1. The 3D city model of Poznań, developed using photogrammetric data, LiDAR scanning and orthophotos, illustrates a static urban representation used for visualisation and planning. Although not yet integrated with dynamic data, it serves as a potential foundation for digital twin development and UAV path simulation
Source: Own elaboration based on data from GEOPOZ – Geodesy and City Cadastre Board, Poznań City Hall (https://map.poznan.pl)

A major obstacle is ***semantic heterogeneity***: inconsistencies in structure, metadata and terminology that hinder reuse and integration. Lei, Stouffs and Biljecki (2023) observe that even high-quality models often lack the semantic alignment necessary for advanced applications such as UAV flight simulation or environmental impact modelling.

Standardised, interoperable modelling frameworks are essential – particularly in the context of U-space services and UAV corridor planning. Without harmonised digital base layers, cities cannot support real-time coordination or cross-regional interoperability.

A case in point is Poznań's 3D city model, which is publicly available through its geoportal. Built using aerial imagery, Light Detection And Ranging (LiDAR) data and orthophotos, it represents a static model useful for visualisation and planning (*Note* 14). Although it currently lacks dynamic data feeds or sensor integration, it forms a strong basis for future extensions toward UAV path simulation or no-fly-zone analysis, similar to initiatives in Helsinki or Rotterdam (*Note* 15).

The next phase of digital twin development must address not only technological but also institutional and semantic gaps. Harmonised frameworks will be key to enabling dynamic airspace management and building resilient, interoperable urban systems.

2.3. EU legal framework of the U-space concept and standards

The following section presents the legal framework as of 30 April 2025, based on current EU regulations and national guidelines concerning UAV operations, including *Implementing Regulations 2019/947 and 2021/664* (U-space) (*Note* 16). The core of the EU UAV legislation is *Commission*

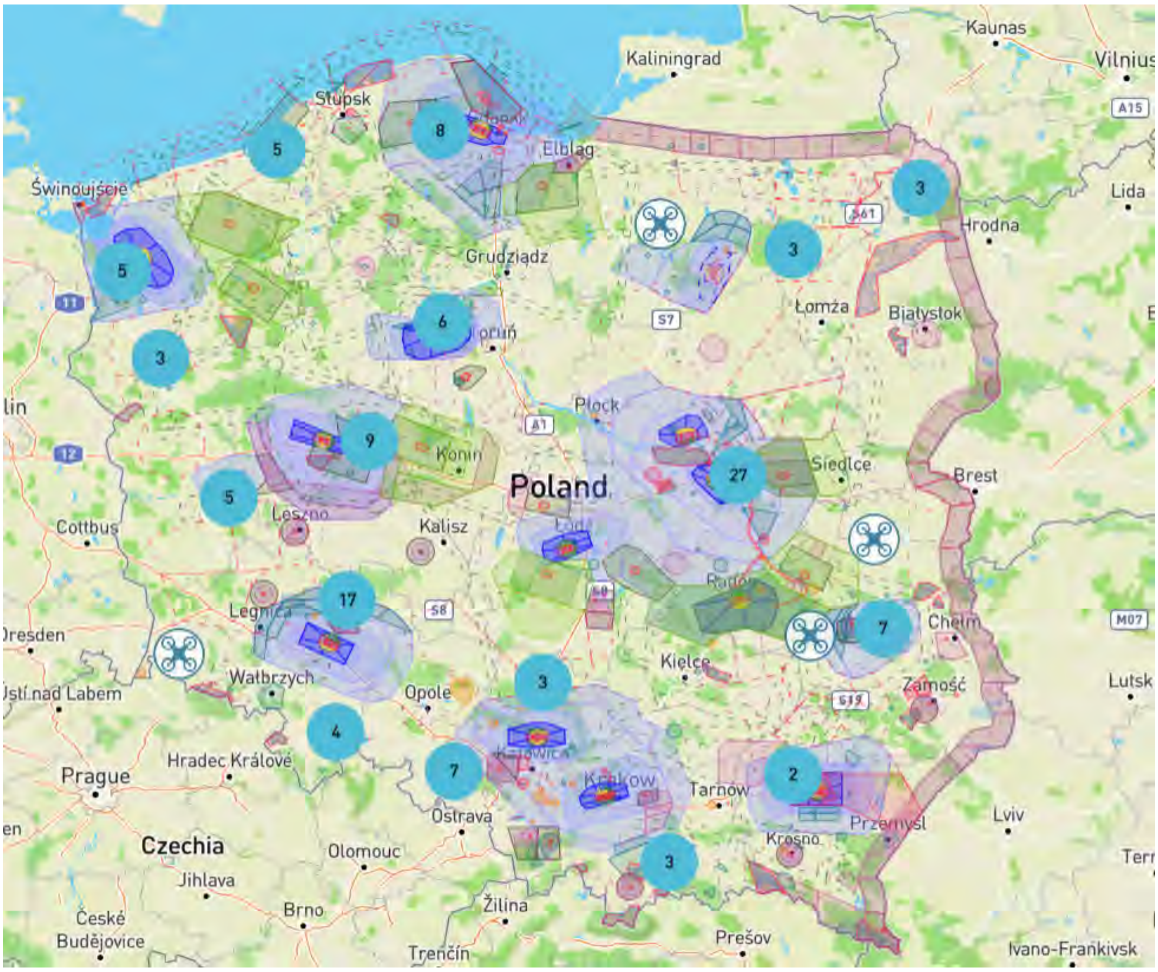

Fig. 2. Geographical zones for UAV operations in Poland, established under Article 15 of Commission Implementing Regulation (EU) 2019/947
Source: Own elaboration based on data from DroneMap PANSA service (https://dronemap.pansa.pl/)

Implementing Regulation (EU) 2019/947, which introduced a risk-based categorisation into open, specific and certified operation classes. It remains the cornerstone of drone regulation in all Member States (Kosieliński & Mrozek, 2024). A significant amendment–*Implementing Regulation (EU) 2022/425*–postponed mandatory technical requirements for the open category, offering more time for market adaptation (*Note* 17). Another key regulation is *(EU) 2018/1139*, which sets the broader legal basis for UAV integration into civil aviation and includes an exemption mechanism for public-interest operations (e.g., emergency services), applicable in Poland upon request to the President of the Civil Aviation Authority. For specific and certified categories, the SORA methodology – developed by the Joint Authorities for Rulemaking on Unmanned Systems (JARUS) – offers a harmonised risk assessment framework. As White et al. (2023) emphasise, SORA evaluates factors such as UAV characteristics, environmental conditions and airspace complexity. They further highlight the value of 3D city models and GIS tools in accelerating assessments and improving urban safety (*Note* 18). A key innovation of *Commission Implementing Regulation (EU) 2019/947* is Article 15, which allows Member States to designate geographical zones regulating UAV operations based on safety, environmental-protection or societal considerations. Poland's national guidance is provided in *Guidelines No. 6/2024*, and zone data is made publicly available via the PANSA DroneMap and DroneTower platforms. The map presents selected areas published on the PANSA DroneMap platform and serves as a reference for safe, regulated drone flights.

To manage high-density UAV operations in urban airspace, the U-space legal package comprising *Regulations 2021/664, 665*, and *666* entered into force in 2023. It defines U-space zones, i.e. airspace segments (typically ≤150 m a.g.l.) where operations are digitally coordinated by certified U-Space Service Providers (USSPs) via a Common Information Service (CIS). Each U-space zone must provide four digital services: Network Identification, Geoawareness, Flight Authorisation and Traffic Information (EASA, 2023).

Although the open category is generally limited to 120 m a.g.l., U-space zones allow operations up to 150 m under stricter technical controls. EUROCAE's *ED-318* (2024) standard defines interoperability rules for U-space implementation and harmonised airspace data exchange (*Note* 19). Importantly, U-space is not a separate operational category. *Regulation 2021/664* (Art. 6.3) confirms that UAVs operating in U-space must still comply with the requirements of *Regulation 2019/947* and obtain appropriate permits (*Note* 20). Thus, low-altitude UAV operations in urban environments may occur under open, specific or certified categories, depending on risk and flight profile. If a U-space geographical zone is established, operators must additionally meet digital coordination and system integration requirements.

In the context of the issues discussed in this article, cities are responsible for developing UAV infrastructure within geographical zones, in consultation with relevant stakeholders and local residents. The authorisation for operations, however, is granted by national entities responsible for UAV traffic management. This crucial aspect was also emphasised in interview by Christina Suomi, Project Director of Helsinki U-space 2024–2026.

2.4. Research and pilot projects supporting Urban Air Mobility in Europe and Poland

The development of Urban Air Mobility (UAM) in Europe is strongly supported by EU and national research initiatives. Flagship projects such as ASSURED-UAM, CITYAM and the EASA Societal Acceptance Study have addressed regulatory, technical and social challenges related to the safe integration of UAV systems. The ASSURED-UAM project (Dziugiel et al., 2023; Mazur et al., 2022; Duca et. Al, 2022) offers a decision-support framework for cities, emphasising not only technological maturity but also public trust and environmental sustainability. Its Acceptance, Safety and Sustainability Recommendations inform the design of U-space regulation and guide pilot implementations in European cities (*Note* 21). Simultaneously, the CITYAM project – funded by Interreg Baltic Sea Region – demonstrated drone applications in real conditions (e.g., port surveillance in Hamburg, infrastructure inspections in Stockholm). It produced a GIS-based tool to help municipalities identify safe UAV-operation zones based on population density, airspace restrictions and urban obstacles. The *EASA Societal Acceptance Study* (2021) surveyed public perceptions across Europe, identifying noise, privacy and safety as key concerns. It concluded that social legitimacy is a prerequisite for UAM deployment and must be supported by robust oversight and sustainable mobility planning. In Poland, these insights are reflected in the national PANSA UTM system

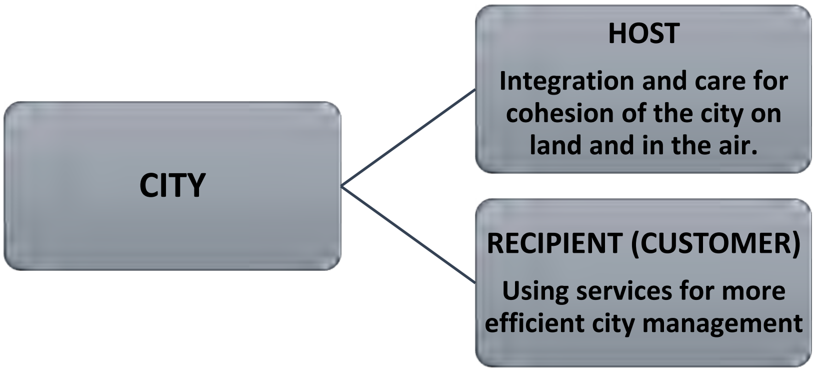

Fig. 3. The role of the city in the context of the UAV market
Source: Own elaboration based on presentation by M. Dziekański (2023)

developed under the Digital Poland Operational Programme. This platform enables real-time coordination of manned and unmanned flights and serves as a practical step toward U-space implementation (*Note* 22).

Pilot programmes led by PANSA and the Civil Aviation Authority illustrate Poland's role as an active testing ground. Notably, in 2020, PANSA and Farada conducted medical drone delivery trials linking hospitals in Warsaw, Pułtusk, Sochaczew and Otwock using Vertical Take-Off and Landing (VTOL) aircraft. Flights covered up to 60 km in under 45 minutes at altitudes of 100–120 m a.g.l., reducing medical transport time by nearly 50%.

Additional projects such as U-Space Kato and Drones Over the City underline the emerging role of cities in airspace governance. The Silesian Metropolis (GZM) identified 11 strategic areas – ranging from spatial planning to crisis response – where UAV services are expected to be integrated. These initiatives emphasised the dual role of cities as both operators and users of UAVs, supporting the creation of the *Drone-Friendly Cities* guidebook (*Note* 23). Figure 3 presents key areas of local government involvement in airspace governance, drone operations and integration into urban service systems.

Furthermore, the national Three Areas project (*Note* 24) implemented with the Ministry of Infrastructure aims to establish a nationwide digital infrastructure for advanced UAV services. Although still under development, this initiative reflects Poland's strategic intent to scale complex UAV operations through interoperable Information and Communication Technology (ICT) systems

European projects, including those involving Poland (e.g., CITYAM), provide recommendations and benchmarks for GIS tools that are intended for use in designing ground infrastructure for UAVs. They also provide GIS tools to support risk assessment for UAV operations. However, further research is needed, particularly in the areas of interoperability and the harmonisation of spatial datasets used to create geographic zones (geozones). This topic will be developed further later in this article.

3. Research materials and methods

The primary objective of this study was to assess the readiness of local authorities to adopt 3D and 4D geospatial tools for open urban airspace to support UAV risk assessment and to identify their expectations regarding spatial data UAV – based services. A key research question concerned whether cities would benefit more from generating mission-specific 3D models for each SORA-based UAV operation or from using pre-established flight corridors embedded in interoperable urban digital twins equipped with continuously updated data. The core empirical focus of the study was placed on urban municipalities in Poland (302 in total), while Finland (Helsinki) served as a complementary international case study. An original survey form was developed and distributed to all urban municipalities in Poland in 2020. To the author's knowledge, this was the first and only study of its kind to have been conducted nationwide. Table 1 summarises the thematic grouping of questions used in the online survey addressed to urban municipalities.

Field visits and expert consultations conducted in Helsinki enriched the analysis through

Table 1. Thematic grouping of questions in the online survey addressed to urban municipalities in Poland

No.	Thematic area	Questions in brief
-	Respondent identification	1) City/unit/name of specialist or manager
1.	Users of 3D city models	2–3) Need and interest in developing a 3D model of UAV accessibility zones
2.	Awareness and interest in UAV - specific planning zones	4) Opinion on the need to include UAV flight corridors in municipal planning documents (both textually and cartographically); 5) Preferred criteria and spatial features for designating safe UAV roues in cities or agglomerations
3.	Risk types and need for additional safety measures	6) Specific risks associated with low-altitude UAV operations and the need for additional protective measures (e.g., over critical infrastructure, buildings); 7) Suggestions for identifying specific threats relevant to advanced UAV operations
4.	Type of technological solution supporting risk assessment	8) Preferred typology of urban zones in the 3D model (e.g., safe, acceptable-risk); 9) Proposed complementary risk-based solutions for route planning; 10) Types of data that should be continuously updated in the model (14 data types listed); 12) Opinion on whether 3D models for UAV routes should be generated case by case or commissioned as public services
5.	Regulatory and technical parameters relevant to UAV safety	11) Assessment of which UAV parameters are critical to operational safety and compliance in automated flights under EU regulatory frameworks
6.	Potential applications of UAV services and comments	13) Anticipated use cases for UAVs in municipal tasks (14 predefined options); 14) Additional comments or suggestions from respondents

Source: Own author's draft

knowledge transfer and the examination of advanced urban airspace strategies (*Note* 25).

The research was grounded in an original hypothesis formulated in response to the emerging European regulatory framework for UAV integration – particularly the U-space directive and the SORA risk assessment methodology (*Note* 26). To examine this hypothesis, the study applied a triangulated methodological approach, combining both quantitative and qualitative methods.

The applied methods included: literature analysis; structured interviews with UAV operators; experts in 3D modelling and geospatial data, participant observation during international workshops and industry events; and two online surveys – one addressed to UAV experts and another to all 302 urban municipalities in Poland (2020). This triangulated design allowed for a comprehensive, interdisciplinary investigation of UAV integration into urban airspace governance. The triangulation approach was selected to enhance the robustness and contextual depth of the findings. The comparison between Poland and Finland is particularly meaningful due to their contrasting levels of digital maturity and institutional preparedness in urban airspace governance. While the Polish nationwide survey captured the broader state of readiness among urban municipalities, the Helsinki case offered an advanced reference point grounded in empirical interviews and field research. This allowed the study to test whether the needs and expectations identified in Poland align with the operational strategies already being implemented in a leading European city.

Two key international research visits to Finland complemented the domestic component of the study. The first, conducted in October–

November 2023, involved participation in the professional workshop "Smart City Digital Twins" (Business Turku, University of Turku) (*Note* 27), which provided practical insights into the phased development of digital twin infrastructure and its prospective applications in supporting UAV risk assessment and spatial decision-making.

The second visit, in September 2024, included structured expert interviews at Aalto University (*Note* 28) and Forum Virium Helsinki (*Note* 29), focusing on the role of geoinformation tools, 3D city models and the city's institutional approach to managing low-altitude urban airspace. The interviews addressed issues such as the interoperability of urban data platforms, stakeholder responsibilities in U-space governance, and technical challenges in real-time spatial zoning. A comprehensive written response was subsequently received in April 2025 from the Urban Environment Division of the City of Helsinki, further validating the conceptual framework and confirming key research assumptions related to the 4D Urban Area Model.

In Poland, the research was reinforced by additional interviews, professional workshops and two structured focus group studies conducted in 2023–2024 with UAV operators, urban planners and representatives of PANSA (*Note* 30) and the Civil Aviation Authority. These focus groups were held alongside the European Network of U-Space Stakeholders meeting (2023) and the national UAV conference in Warsaw (2024) and served to verify the findings of the 2020 online survey (*Note* 31). They enabled direct expert reflection on regulatory constraints, the feasibility of urban UAV risk assessment tools and institutional readiness at the municipal level.

In parallel, two international research visits to Finland complemented the domestic component of the study.

Although the research employed a triangulated methodology combining survey data, expert interviews and case study analysis, certain limitations must be acknowledged. First, as with any survey-based study, there is a risk of response bias, particularly due to the self-selection of municipal officials who may already be engaged in spatial data initiatives. Second, although the in-depth case study of Helsinki provides valuable insights into institutional readiness and geospatial innovations, the findings cannot be uncritically generalised to all European cities, given local legal, administrative and technical differences. These limitations highlight the need for further comparative research across diverse urban contexts.

4. Research results

4.1. Online survey addressed to urban municipalities

Aviation safety is a ***systemic and interdisciplinary domain*** that requires coordination between regulation, technology and spatial planning. As defined in operational frameworks, aviation safety is a condition in which the probability of an undesirable event is reduced and maintained at an acceptable risk level or managed through a continuous process of hazard identification and mitigation in all phases of mission preparation and execution.

Recognising this complexity, PANSA initiated the concept of U-space in 2019, aiming to integrate manned and unmanned aviation within a coordinated digital environment. Experts, however, stress that, on its own, U-space will not resolve the broader set of challenges facing the industry. There is a need to establish dedicated spatial and technical systems that support drone flights in urban space – hence, the development of tools such as PANSA's DTM – Autonomy service currently being implemented in the Three Areas project.

The objective of this research was to assess the demand for an innovative geospatial solution – based on 3D city models – that supports UAV risk assessment and enables new public-interest services. The underlying research hypothesis is grounded in spatial and technological realism: 3D city models transformed into urban digital twins could form the basis of "urban services" for drone operators and municipal offices, facilitating automated, real-time data analysis for UAV risk assessment (*Note* 32).

After expert consultations, the author developed a structured 14-question survey, sent in July 2020 to 302 urban municipalities in Poland. Responses were received from 130 cities, including nine voivodeship capitals (e.g., Kraków, Gdynia, Poznań) and 121 smaller municipalities, including coastal towns such as Krynica Morska, Łeba and Świnoujście. Below are the results grouped into six thematic areas, corresponding to the research design.

Users of 3D city models

Seventy-two percent of respondents recognised the need to develop a 3D-based solution with clearly defined UAV safety zones (Fig. 4). Additionally, 68% declared potential interest in a "3D model of accessibility zones for UAV flights". These responses confirm the feasibility of developing a shared city service based on digital twins to support risk assessment in accordance with the SORA methodology. Such a service could integrate data on building heights, population density and mobile obstacles. Direct users would include UAV operators applying for permits, as well as indirect users (municipal offices engaging in UAV-supported tasks).

Awareness of and interest in UAV-specific planning zones

Fifty-three percent of respondents support including UAV flight routes in municipal planning documents. However, 31% were undecided and 16% opposed. Among the 110 responses to Q5, common themes included: limiting UAV use to public interest tasks, integrating routes with existing infrastructure (e.g., along roads), environmental and privacy concerns, and the need to define planning zones using expanded 3D models. The study proposed a division of risk areas into: risk areas into:

- Zone I – safe (subject to PANSA oversight),
- Zone II – acceptable risk (technically permissible but requiring dynamic obstacle mapping), which was subsequently confirmed by survey results and is aligned with the modular concept of digital twins. Current regulations prevent municipalities from requesting the creation of geographical zones, suggesting the need for future regulatory discussion.

Risk types and need for additional safety measures

Seventy-seven percent of respondents confirmed the need for additional safety measures for advanced UAV operations in cities. Among the 98 responses to Q7, key threats included: collisions with infrastructure or trees, bird strikes (e.g., migration routes in Łeba), hijacking, misuse for surveillance or smuggling, and proximity to emergency helicopter routes. These answers confirm that a high-quality, localised risk assessment is essential for specific operations in urban space and that such assessments require detailed, up-to-date spatial data.

Type of technological solution supporting risk assessment

Fifty-seven percent of respondents indicated that UAV routes should be pre-defined in at least several configurations. Forty-three percent supported the division of urban space into zones of different risk thresholds. Respondents identified critical data layers to be continuously updated in the digital

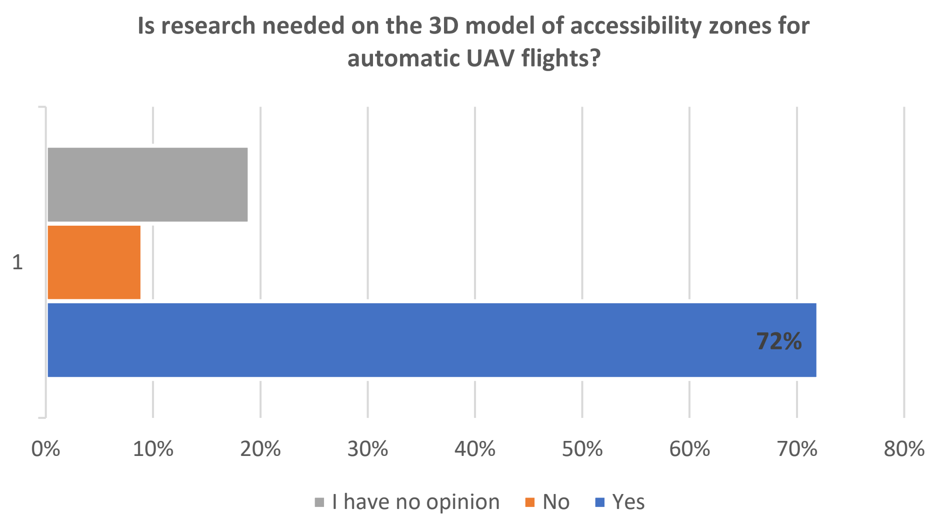

Fig. 4. Results of Question 2 – Need for research on 3D accessibility zone models for automatic UAV flights
Source: Own elaboration

Table 2. Results of Question 10: Which data in the 3D model require updating?

Question Letter	Types of answers	Number of YES responses
A	Designation of at least several routes for automatic flights	109
B	New tower cranes: stationary/on a building/mobile	101
C	New electric poles	101
D	Geographical zones for air flights	98
E	Extremely critical infrastructure/key services	82
F	Areas whose managers do not want drones flying over them	81
G	Weather conditions	79
H	Current wind directions and strength	77
I	Population density/restrictions on crowded areas	77
J	Notification of major construction (District Construction Supervision)	74
K	Distance restrictions from the building	58
L	Traffic intensity if there is a road in the zone	47
Ł	Areas with distance restrictions/new fences	38
M	In addition, others not listed above	34
N	I have no opinion	9

Source: own elaboration

Table 3. Results of Question 13 – Expected Areas of Drone Use According to Respondents (Q13)

Question Letter	Types of answers	Number of YES responses
A	Crisis management (actions in difficult terrain, etc.)	121
B	Specialised measurements (noise, temperature, smoke composition)	121
C	Monitoring public space	118
D	Activities of uniformed services (fire brigade, city guard)	112
E	Environmental protection (e.g., monitoring of waste landfills)	109
F	Inventory of urban spaces (e.g., orthophoto maps, 3D mesh grids)	101
G	Infrastructure inspection (e.g., inspection of overhead networks)	98
H	Monitoring infrastructure and urban phenomena (e.g., traffic intensity)	96
I	Promotion activities during mass events (e.g., filming)	83
J	Control of critical infrastructure and flight obstacles	74
K	Emission functions (e.g., ozonation, spraying, fertilisation, etc.)	58
L	Information functions (e.g., voice, visual)	70
Ł	In addition, still others not mentioned above	36

Source: own elaboration

environment (see Table 2), including: new tower cranes, electric poles, construction activity, wind conditions and population density. Question 12 demonstrated inefficiencies in current practices, where each UAV operation requires a separate risk assessment. The concept of automating this process using AI, GIS and data from urban digital twins was supported. However, it requires cooperation with mobile operators, spatial planners and digital twin managers (*Note* 33).

Regulatory and technical parameters relevant to UAV safety

Question 11 asked which UAV parameters are essential for safety and compliance. Responses aligned closely with the SORA methodology. Many of these parameters – height, weight, propulsion type – can already be linked to spatial constraints stored in municipal registers and digital twins, reinforcing the feasibility of developing integrated risk assessment systems.

Potential applications of UAV services

Responses to Q13 (Table 3) show high expectations regarding the use of drones in:

- crisis management (121 responses),
- specialised measurements (121),
- public-space monitoring (118),
- environmental protection (109),
- infrastructure inspections (98),
- and urban inventory tasks (101).

These results indicate social readiness for broader UAV adoption, provided that safety and data management frameworks are in place.

Additional comments

Question 14 generated 37 open responses. Selected insights include:

- The importance of multi-sectoral consultations and sharing good practices;
- The need for controlled corridors supervised by trained operators;
- Concerns about privacy and environmental impact (e.g., bird disturbance);
- Suggestions for UAV-based services such as real-time traffic mapping or marine ecosystem monitoring along coastal zones;
- The view that automated 3D risk models are essential for emergency UAV services (e.g., blood transport) and should not be generated manually for each flight.

Summary

The research results confirm the initial hypothesis that 3D city models – when properly developed into dynamic and interoperable urban digital twins – can effectively support the risk assessment of UAV operations in urban airspace and serve as a foundation for delivering automated public services involving unmanned aerial vehicles. This refers in particular to operations conducted in the public interest as part of statutory tasks of local governments, such as medical transport, crisis management, environmental monitoring or infrastructure inspection. The research results confirm the initial hypothesis that 3D city models – if appropriately extended into dynamic, interoperable urban digital twins – can support the risk assessment of UAV operations in urban airspace and enable the development of a new category of spatial public services. The responses provided by 130 municipalities, including both major urban centres and smaller towns, indicate a notable level of awareness and readiness to implement such tools – especially when UAV missions are conducted in the public interest.

First, the vast majority of respondents recognised the value of introducing 3D models for delineating UAV accessibility zones and supported the idea of a municipal or shared “city service” for risk modelling. Second, over half of the cities emphasised the need to incorporate UAV corridors into spatial planning documents, although the results also revealed legal and procedural gaps, particularly regarding local government competencies in establishing geographical zones. Third, respondents identified a wide range of specific threats linked to low-altitude UAV operations in urban environments – confirming that high-quality, localised risk assessment is necessary and that it should be based on real-time, spatially precise data. The cities identified a clear need for solutions that enable automated updates of safety-relevant spatial data (e.g., new tower cranes, high-risk infrastructure, weather and wind conditions) and a reduction in the time required to prepare regulatory-compliant risk assessments.

Fourth, there is growing interest in the development of standardised digital layers for urban UAV risk assessment – especially if integrated into a broader digital twin framework aligned with OGC standards (e.g., CityGML). However, respondents also expressed caution, underlining the need for multilateral consultation, legal clarity and phased implementation based on operational experience and citizen engagement. The study not only demonstrates social and institutional acceptance for further UAV integration in cities but also identifies areas for future research and technical development. In particular, the creation of automated, real-time tools for SORA-based assessments, supported by municipal digital twins, should be prioritised. The findings support the call for continued interdisciplinary Research and Development projects, involving geoinformatics experts, UAV operators, mobile network providers and public administration stakeholders. In the next phase of this research, follow-up interviews and prototype testing with selected cities – especially those with existing digital twin infrastructures – will enable a more detailed evaluation of feasibility, implementation models and governance implications. These steps will provide the basis for validating the proposed "4D Urban Area Model" for UAV risk management in real operating environments.

4.2. The verification of research results in Poland and in Finland (2023–2024)

4.2.1. Focus groups and expert consultations

The verification of the research hypothesis was conducted between 2023 and 2024 through expert consultations, participant observation and two structured focus group studies carried out in Poland and Finland. These activities provided critical feedback on the operational feasibility and institutional relevance of the proposed 4D Urban Area Model for UAV risk assessment. In Poland, key insights were gathered during the European Network of U-Space Stakeholders meeting organised by the GZM metropolis (2023) (*Note* 34) and the UAV conference held at the Military University of Technology in Warsaw (2024) (*Note* 35). These events served as the basis for one of the focus groups, which involved selected stakeholders from public administration, aviation safety institutions and regional planning offices. Experts from PANSA, including Krzysztof Kisiel, emphasised the need to extend 3D city models into the fourth dimension – time – to reflect dynamic risk factors such as population density. Maciej Włodarczyk (*Note* 36) highlighted the importance of continuous spatial data updates to maintain the validity of risk assessments. These views were echoed by Marcin Dziekański (GZM), who pointed to the increasing demand for municipal tools supporting UAV operations in urban settings.

A second focus group was conducted during the Smart City Digital Twins workshops in Turku (2023) (*Note* 37), complemented by a research internship at Forum Virium Helsinki. During these sessions, M. Lincolm presented recent EU-level findings, including EASA's recommendation to use digital twins to support UAV risk assessments, which reinforced the conceptual foundation of this study. In expert consultations, Juho-Pekka Virtanen emphasised that not all 3D city models can evolve into fully functional digital twins – those that can are those built with semantic consistency and based on interoperable formats such as CityGML. This supports the hypothesis that effective UAV risk assessment tools must rely on standardised, high-quality urban spatial datasets (*Note* 38).

Collectively, the two focus groups and accompanying expert consultations confirmed the relevance, originality and institutional feasibility of the proposed 4D Urban Area Model. They also highlighted the need for coordinated development through international and intersectoral partnerships.

4.2.2. Case study: City of Helsinki – approaches in urban UAV risk management

Structured interviews confirmed the validity of the author's hypothesis regarding the need to formally involve cities in regulatory and management processes concerning low-altitude urban airspace used for UAV operations (U-space) and to recognise their technical capacity to implement 3D-based tools for urban airspace management.

Despite its participation in numerous European innovation networks, the City of Helsinki maintains a pragmatic and cautious approach toward urban air mobility and the integration of UAV operations into municipal governance. Based on original qualitative research and structured interviews with representatives of the City Office and Forum Virium Helsinki, this case study analyses the institutional frameworks and geospatial strategies for managing low-altitude urban airspace under the U-space framework.

At present, Helsinki does not consider UAV risk assessment a municipal responsibility, emphasising that airspace management, including SORA or BVLOS risk analysis, remains under the exclusive competence of the national Civil Aviation Authority. The city has not submitted any SORA or BVLOS applications and lacks direct experience with specialised UAV categories. Nevertheless, it acknowledges a potential future role in supporting risk assessment processes, particularly by developing and maintaining high-quality GIS databases required under U-space and Air Risk Assessment (ARA) standards.

Currently, Helsinki employs GIS primarily for basic 2D spatial analyses, without operational use of 3D city models or urban digital twins for UAV-related purposes. However, city officials acknowledged that the technical capacity for transitioning to 3D-based planning exists and would be activated if necessary. Digital twins are envisioned as potential tools for simulating UAV scenarios, assessing risk and conducting citizen consultations through AI-assisted platforms. Rather than pursuing rapid U-space implementation, Helsinki is focusing on institutional readiness. It has initiated regional cooperation to harmonise UAV geozone processes and is preparing its GIS infrastructure for testing within the ARA framework. The city also plans to align with the *ED-318* standard and participate in future European U-space systems. Officials underscore that these early efforts are essential for identifying spatial data gaps and ensuring the reliability of future UAV risk assessments.

An important insight from Helsinki is the proposition that low-altitude airspace should be managed similarly to other layers of urban planning, such as underground infrastructure. This integrated view highlights the necessity for interdisciplinary teams – including urban planners, GIS experts and aviation specialists – to co-design spatial frameworks for airspace governance. Although the city does not currently manage its low-level airspace, it is building internal capacity and recommends engaging aviation experts in the first phase of design.

A major constraint on drone operations in Helsinki is the extensive controlled airspace (CTR EFHK), which covers over 80% of the city. Additionally, the ongoing national Airspace Reform (2024–27) does not include municipalities in formal decision-making, limiting their influence over U-space zone design. Despite these barriers, Helsinki is proactively preparing for future integration with UTM systems and the possible introduction of dedicated geographical drone zones via standardised APIs.

Recommendations based on Helsinki's experience stress the importance of clarifying responsibilities between municipal and national authorities and beginning with basic GIS validation to test the spatial data readiness for UAV operations. Cities should proceed gradually, adopting advanced planning methodologies only when justified by local conditions. Selective application of findings from EU-funded projects such as AiRMOUR and CITYAM is advised, based on available resources and institutional readiness.

Taken together, Helsinki offers a strategically cautious model for urban UAV preparedness rooted in long-term capacity building, clear governance and data infrastructure development. While it does not yet perform UAV risk assessments or manage urban airspace, the city is laying a strong foundation for future participation. Its approach illustrates that municipal roles in airspace governance must be strengthened and formalised, particularly in the context of high CTR coverage and limited legal agency. Helsinki's case emphasises the need for multilevel cooperation, integration of UAV considerations into spatial planning processes, and the recognition of urban airspace as a new but essential dimension of smart city development.

4.2.3. Answers to the research questions

In response to the first research question, the verification results clearly indicate that technologies such as 3D city models – if based on interoperable standards (e.g., CityGML) and enriched with semantic attributes – can serve as a robust foundation for identifying UAV safety zones. When extended into a fourth dimension (time), these models enable dynamic risk recalibration based on variable data, including population density, mobility flows and aerial obstacles. In both Poland and Finland, experts agreed that tools based on such models can become essential components of future urban digital twins supporting real-time UAV risk assessment and scenario planning. In Helsinki, digital twins will initially be used to test scenarios for advanced UAV operations, including route planning and real-time risk analysis, before being fully integrated into the city's airspace management system.

With regard to the second research question, the consultations and case study analysis demonstrate that European cities vary considerably in their readiness to integrate UAV operations into development and transport policies. Polish cities show growing interest in using UAVs for public-interest missions but face institutional and technical limitations. Helsinki presents a contrasting approach: while not yet responsible for UAV risk assessment, the city is actively preparing its GIS infrastructure for compliance with *ED-318* and ARA frameworks and is engaged in regional coordination to harmonise geozone procedures. This confirms that the decisive factor is not the level of regulatory decentralisation but, rather, the degree of institutional and infrastructural preparedness.

In addressing the third research question, the findings confirm that the highest levels of social acceptance in urban environments are associated with UAV operations serving public-interest purposes – particularly medical transport, emergency response, environmental monitoring and infrastructure inspections. Both survey responses in Poland and expert insights emphasise that citizens expect transparent risk management mechanisms and clearly defined operational zones based on reliable spatial data. Commercial and recreational uses of UAVs require additional public engagement and the implementation of mitigation strategies addressing concerns related to noise, safety and privacy.

In summary, the combined evidence confirms the validity of the initial hypothesis and supports the implementation of the proposed 4D model as a conceptual and operational framework for managing urban airspace through geospatial technologies and digital twin solutions.

5. Discussion

The integration of low-altitude urban airspace into smart city governance marks a pivotal transformation in the theory and practice of spatial planning. A central hypothesis was formulated: that new technologies – such as interoperable 3D city models and smart city digital twins – can be used to designate and simulate special low-altitude geographical zones in urban airspace, supporting UAV operations in compliance with the EU's U-space framework. This reflects two competing approaches in regulatory discourse: mission-specific 3D models for individual flights, versus persistent, standardised UAV corridors embedded in urban digital twins. The diversity of proposed airspace concepts has been reviewed by Bauranov and Rakas (2021), who emphasised the need for flexible governance structures for UAM corridors. This study supports the latter, proposing Safe Zones and Acceptable Risk Zones to streamline SORA-based assessments. The research responds directly to the needs of state and municipal administrations seeking scalable UAV risk evaluation tools in built-up areas. The hypothesis was tested through surveys addressed to all urban municipalities in Poland, expert interviews, focus research during national conferences (2023–2024) and international research visits in Finland.

The findings align with the conceptual evolution of smart cities as complex, adaptive systems (Komninos, 2002b; Szymańska, 2023; Szymańska et al., 2024), leveraging digital technologies, social capital, and real-time data for sustainability and quality of life (Gehl, 2010; Caragliu et al., 2011). In this framework, urban airspace emerges as a new frontier of public management – reflected in case studies like Helsinki and Amsterdam – where digital platforms simulate and regulate UAV operations (Komninos, 2002b; Batty, 2018; AiRMOUR, 2023; Szymańska, 2023; Szymańska et al., 2024). As defined by Caragliu, Del Bo and Nijkamp (2011), smart cities leverage digital technologies, social capital, and real-time data to increase sustainability and quality of life. In this context, urban airspace becomes a new frontier for public management. Examples from Helsinki and Amsterdam show how digital platforms are already used to simulate and regulate UAV operations (Batty, 2018; AiRMOUR, 2023). Recent analyses confirm this trend, with Cottam (2023) highlighting the rapid rise of digital twins as a cornerstone of smart city strategies.The triangulated research design over six years (2019–2025) enhances the robustness of findings, incorporating literature analysis, interviews, participant observation and nationwide surveys. Fieldwork and expert consultations in Finland offered a comparative basis. The research instruments were informed by the SORA methodology (Tsiamis et al., 2019) and the safety paradigm of Załęski, Kozuba and Rajchel (2018), thereby ensuring both conceptual and empirical consistency. SORA and the U-space regulations (*EU 2019/947* and *2021/664*) underline the need for dynamic risk modelling and real-time spatial data. Interoperable 3D city models, developed into bidirectional digital twins (Fuller et al., 2020; Grieves, 2023), a trend also noted by Cottam (2023), enhance UAV risk assessment. Yet, semantic inconsistency in 3D models (Stoter, 2020; Lei et al., 2023a; Lei et al., 2023b) remains a barrier, especially in Poland. Initiatives like Poznań's model or PANSA's DroneMap are promising but lack full real-time integration (Skóra, 2022). Additional implementation barriers at the municipal level

Table 4. The three levels of urban digital representation

No.	Stage	Definition
1.	Digital Model	A static digital representation of a physical object – e.g., a 3D city model with no data flow or interactivity. Common formats include **CityGML**, **CityJSON** or **OBJ**.
2.	Digital Shadow	A model that passively receives one-way data from the real world (e.g., via sensors, GPS, or traffic feeds) but does not send feedback or control signals
3.	Digital Twin	A two-way, real-time synchronised model that not only reflects urban dynamics but can also influence or respond to real-world conditions (e.g., real-time UAV rerouting or adaptive traffic light control)

Source: own elaboration

were also identified by Dziugiel (2022), particularly in relation to fragmented governance and spatial data coordination (Greenwood et al., 2019).

To clarify the conceptual difference between types of digital models referred to in this study, Table 4 provides a summary of the three levels of urban digital representation commonly discussed in the literature. The table highlights differences in data flow and integration, with increasing levels of real-time interactivity and control.

European projects such as ASSURED-UAM, CITYAM and the EASA Societal Acceptance Study confirm that technological capacity must be accompanied by social trust and institutional coordination (EASA, 2021; Mazur et al., 2022; Dziugiel et al., 2023). This aligns with findings on citizen perspectives from Melo et al. (2023), who emphasise the importance of social licence and transparency in urban drone deployments. National examples like GZM's U-space Kato and the PANSA–Farada trials highlight the municipal role in UAV governance. Confirmation by Christina Suomi (Helsinki, 2025) of the author's zoning model further bridges academic, strategic and regulatory spheres. This also resonates with broader mobility planning frameworks developed by GZM (Domański et al., 2021), which emphasise the need to overcome institutional and infrastructural barriers to sustainable urban transport.The results of the author's empirical study confirm that dynamic 3D models, supplemented by real-time spatial data, can support UAV risk assessment and facilitate corridor planning. Of the surveyed Polish urban municipalities, 72% acknowledged the need for safety zone tools, and 68% expressed interest in standardised UAV data services (*The Storm*, 2024). Respondents criticised inefficiencies in current risk assessment procedures and supported zoning into Safe and Acceptable-Risk categories.

Building on these findings, and in response to both national and international consultations, the author developed a practical framework to advance real-time UAV risk assessment and urban airspace governance. As a direct result of these findings and expert consultations with the Polish Air Navigation Services Agency (PANSA), the author developed a 4D extension of the interoperable 3D city model. This innovation introduces the fourth dimension – time – into UAV risk assessment, structured into twelve temporal intervals across a 24-hour cycle. The model incorporates dynamic spatial data on population density, mobility flows (pedestrian, vehicular, public transport) and aerial obstacles (e.g., registered construction cranes), allowing automated risk recalibration based on location and time. It is designed to build upon standards such as CityGML- and INSPIRE-compliant datasets, (OGC, 2016) supporting integration into digital twin environments while remaining consistent with the assumptions of the SORA methodology and U-space regulations.

A key insight emerging from both the Polish case study and the Helsinki experience is the need to systematise access to spatial data relevant to UAV risk assessment, especially in the context of more-advanced and more-automated operations. While most Polish cities still lack structured access to such datasets, Helsinki has initiated regional cooperation and is preparing its GIS infrastructure to align with the *ED-318* standard within the ARA framework. City officials emphasised that early actions – such as identifying aerial obstacles and harmonising UAV geozone procedures – are essential to ensure the future reliability of risk assessment models. This confirms the broader relevance of the proposed 4D approach, which offers a scalable and real-time framework for UAV corridor planning and risk-based airspace zoning in dynamic urban environments. The 4D model also introduces a two-zone classification of urban airspace: Zone I for safe UAV operations and Zone II for operations under acceptable levels of risk. This spatial-temporal zoning reflects both static and dynamic risk factors, offering a practical structure for municipal UAV corridor planning and automated permit decisions.

The CITYAM project illustrates the need for interdisciplinary cooperation and community involvement. The CGIS tool developed as part of this project (Honkavaara et al., 2025) exemplifies a weighted multi-criterion analysis approach to UAV site planning and zoning; however, a more detailed description of this tool is provided in the supplementary notes. This aligns with the proposed 4D model, integrating spatial zoning and temporal scheduling. Figures 5 and 6 illustrate this conceptual model and its data-driven implementation.

Figure 5 shows that the model distinguishes urban airspace into two operational categories: ***Safe Zones (Zone I)*** and ***Acceptable-Risk Zones (Zone II)***, defined not only by permanent spatial obstacles but also by ***temporal variables***, such as fluctuations in pedestrian and vehicle density or scheduled construction activities. Integrated within a smart city digital twin, the model provides a ***dynamic, data-driven framework*** to support automated UAV risk assessment and time-sensitive operational planning.

To complement the general structure shown in Fig. 5, Fig. 6 illustrates how dynamic data integration varies between Safe and Acceptable-Risk Zones in practical UAV operations. It highlights the role of temporal intervals (T1, T2, T3), which represent population density data not only in static or historical form, but also as real-time, dynamic inputs essential for risk recalibration.

Digital twins should be understood as analytical models decoupled from real-time systems and designed to explore dynamic feedback and future planning scenarios rather than simply to mirror physical processes (Batty, 2018; Kitchin, 2018, 2022). Their integration into planning must be rooted in communicative, participatory and context-sensitive governance models (Staffans et al., 2020a; Staffans et al., 2020b; Eilola et al., 2023).

Helsinki's pragmatic and staged approach, along with its emphasis on data quality and institutional competence, confirms the strategic importance of local digital infrastructure and interdisciplinary teams in preparing for UAV integration.

This extension of the traditional horizontal subsystems outlined by Parysek (1985, 1997) into a vertical 4D operational framework illustrates how contemporary urban governance must evolve to manage airspace as a functional layer of the city system (Portugali, 2012a; Portugali, 2023).

The survey and the case study converge on a key insight: sustainable low-altitude airspace governance requires real-time data, legal clarity and institutional cooperation. Interoperable digital twins can turn airspace into a managed public

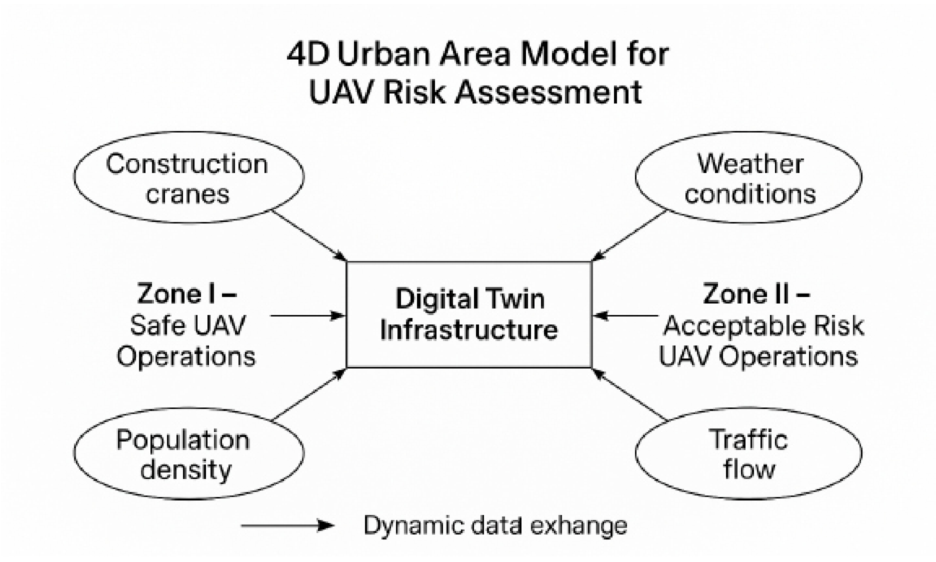

Fig. 5. Author's 4D Urban Areas Model for UAV Risk Assessment (Safe and Acceptable-Risk Zones)
Source: Own elaboration

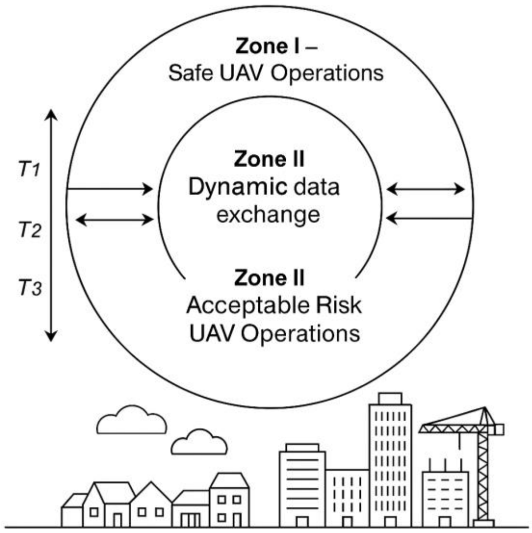

Fig. 6. Differentiated dynamic data integration in Safe (Zone I) and Acceptable-Risk (Zone II) UAV operational areas within the proposed 4D Urban Area Model. Temporal intervals (T1, T2, T3) represent population density data streams provided not only as static or historical information but also as real-time, dynamic inputs supporting risk recalibration. Legend: T1 – 00:00–02:00, T2 – 02:00–04:00, T3 – 04:00–06:00, T4 – 06:00–08:00, T5 – 08:00–10:00, T6 – 10:00–12:00, T7 – 12:00–14:00, T8 – 14:00–16:00, T9 – 16:00–18:00, T10 – 18:00–20:00, T11 – 20:00–22:00, T12 – 22:00–24:00
Source: Own elaboration

domain. Semantic harmonisation of land-use data is essential (Stoter, 2020; Stelmach-Fita, 2021) for deploying 4D models.

The 4D model has three implementation paths: (1) as an operational layer in Smart City Digital Twins; (2) as a real-time decision-support tool for UAVs, especially BVLOS flights; and (3) as a regulatory design foundation for U-space zones under Article 15 of *Regulation 2019/947* (Konert, 2020; Konert, 2021). Early user engagement is critical (Nummi et al., 2022).

This study offers a final synthesis of the research by introducing the 4D Urban Airspace Model – a dynamic, real-time framework for UAV risk assessment that integrates spatial and temporal variables. This model reinforces the importance of harmonised data infrastructures and participatory planning tools (Batty, 2018; Staffans et al., 2020), while also contributing to geoinformatics and urban governance scholarship. Its operational relevance and conceptual clarity offer cities a scalable tool to co-manage urban airspace under evolving European regulations.

The proposed model bridges static planning instruments and real-time decision-making, offering an adaptive governance tool compatible with smart cities and U-space. 3D visualisations support stakeholder engagement and participatory planning (Eilola et al., 2023). The model contributes to urban studies, UAV policy and geoinformatics and advocates for a multi-level governance approach rooted in spatial justice and local conditions.

6. Conclusions

This article has presented an original, interdisciplinary contribution to urban airspace governance by introducing the 4D Urban Area Model for UAV Risk Assessment. Validated through empirical surveys, expert consultations and a case study in Helsinki, the model offers a scalable and operational framework for integrating UAV operations into urban planning systems.

In contrast to many existing European initiatives that remain at the policy level, the proposed model provides a functional solution aligned with the SORA methodology, integrating real-time spatial data into UAV risk assessment processes. It facilitates the identification of safety-based geographical zones, supports automated permit procedures and enhances municipal capacity to co-manage low-altitude urban airspace.

This approach contributes to the evolving body of international research advocating for the integration of digital twins and participatory planning practices in smart city development (Batty, 2018; Staffans et al., 2020; Eilola et al., 2023). By operationalising the principles of spatial justice, co-responsibility and multi-level governance, the model helps bridge the gap between regulation, technology and local implementation.

The Helsinki case study confirms that successful implementation also depends on preparing GIS infrastructure in accordance with standards such as *ED-318* and the ARA framework and on identifying spatial data gaps early in the planning process. Municipal readiness can be strengthened through interdisciplinary teams and by involving aviation experts within urban planning departments.

The findings suggest that the successful deployment of such systems depends on formalised cooperation between municipalities, PANSA and civil aviation authorities – supported by legislative reform, harmonised geospatial infrastructure and pilot implementations. Moreover, the study opens new research avenues at the intersection of spatial planning, digital geotechnologies and real-time UAV risk assessment, offering cities a robust tool for navigating the complex realities of low-altitude drone integration.

As digital twins evolve into real-time urban management platforms, future research should focus on the role of AI in enhancing their responsiveness. Machine learning algorithms could enhance the interpretation of spatiotemporal datasets – such as population density, mobility flows or obstacle dynamics – by enabling predictive analytics and automated decision-making. AI-driven tools may significantly improve the responsiveness of digital twins to dynamic changes in urban environments, thereby supporting adaptive UAV corridor planning in compliance with U-space requirements. In this context, interoperable 3D city models should be tested as simulation environments for UAV operations in built-up areas. These models can serve as the foundation for future digital twins that support real-time risk recalibration and automated decision-making in complex urban airspace.

Key recommendations:

- Formulate national, regional and municipal strategies for low-altitude UAV operations, following a pragmatic, staged approach as exemplified by Helsinki, to provide clear responsibilities, harmonised geozone design processes, ground infrastructure and a roadmap for advanced operations (BVLOS, automated flights) under U-space.
- Pilot-test 4D-based UAV operational scenarios in cities such as Poznań and the GZM metropolis, using available spatial data and institutional partnerships.
- Enable municipalities to co-create and manage U-space zones.
- Promote interoperability of 3D/4D city models based on CityGML and OGC standards.
- Establish multi-level legal frameworks involving PANSA, the Civil Aviation Authority and local governments to enable collaborative spatial governance of urban airspace.
- Ensure the semantic and technical interoperability of 3D city models as a foundation for UAV risk assessment and digital twin development.
- Explore the application of AI and machine learning to support real-time risk calibration, data visualisation and adaptive management of UAV zones in cities.

Notes

1. In 2020, the PANSA UTM system won two categories at the ATM Awards and was cited as a key reason for Poland's fourth place in the global Unmanned Airspace ranking in 2022.
2. European Union Aviation Safety Agency (EASA). (2021). *U-space Concept and Services*. Available at: https://www.easa.europa.eu/en/domains/unmanned-aircraft-systems/u-space.
3. Polish Air Navigation Services Agency (PANSA). (2020). *PANSA UTM – Unmanned Traffic Management System*. Available at: https://www.pansa.pl/pansautm/.
4. SESAR Joint Undertaking. (2020). European ATM Master Plan: Roadmap for the Safe Integration of Drones into All Classes of Airspace. Brussels: SESAR JU.
5. The 2nd International Scientific and Technical Conference *Safety Management in Transport Techniques, Technologies and Policy* was held on 28–30 November 2018 at the Katowice-Pyrzowice Airport and in Ustroń. It was organised by the Silesian University of Technology (Faculty of Transport, Department of Aviation Technologies) in cooperation with the Civil Aviation Authority, Polish Air Navigation Services Agency (PANSA), the Department

of National Security and Logistics (Air Force Academy in Dęblin), the Air Force Institute of Technology, and the Aviation Personnel Training Centre. The conference, chaired by Prof. Jerzy Kozuba, provided a platform to discuss emerging UAV technologies, including the early development of the DroneRadar application – later integrated into checkin.pansa.pl and, from 2024, DroneTower (https://drony.gov; (accessed on 20.05.2023).

6. In Parysek's original model (1985, 1997) and in the latest publication (J. Parysek, L. Mierzejewska, 2025), air was classified under the biophysical subsystem, which was treated mainly as a natural condition. The model does not differentiate between horizontal and vertical dimensions of urban space, nor does it conceptualise airspace as a domain of urban governance.
7. Caragliu, A., Del Bo, C. & Nijkamp, P. (2011). Smart Cities in Europe. Journal of Urban Technology, 18(2), 65–82. The authors define a smart city as one that "invests in human and social capital along with traditional and modern communication infrastructure (ICT) to fuel sustainable economic development and a high quality of life".
8. Cohen's model of smart cities includes six dimensions: (1) smart people, (2) smart economy, (3) smart governance, (4) smart living, (5) smart environment and (6) smart mobility. Each of these plays a role in urban innovation and service efficiency.
9. Tools such as the Internet of Things (IoT), artificial intelligence (AI) and digital twins are increasingly being adopted to enable real-time monitoring, predictive modelling and automated urban system management.
10. Examples include Helsinki's digital twin project for mobility modelling, Amsterdam's open urban platform used in the AiRMOUR project (2023) and Singapore's Virtual Singapore initiative. These systems integrate geospatial, environmental and mobility datasets to support scenario-based planning and simulations.
11. Amsterdam's approach combines open data infrastructure with operational testing of UAV systems under U-space coordination protocols. The AiRMOUR project and City of Amsterdam (2022) publications document use cases and stakeholder coordination models.
12. 3D city models based on international standards (e.g., CityGML, CityJSON) serve as the structural foundation of urban digital twins, supporting spatial analyses, infrastructure planning and data integration.
13. Stelmach-Fita, B. (2021) emphasised that harmonisation of spatial data – especially land use and regulatory datasets – is a prerequisite for operational urban digital twins in Central and Eastern European cities.
14. Poznań's 3D city model, available via geoportal.poznan.pl, was developed using aerial imagery, LiDAR scans and orthophotos. It currently functions as a static digital model without dynamic data streams.
15. Pilot projects in Helsinki and Rotterdam have demonstrated application of urban digital twins in supporting U-space coordination, airspace management, and planning of UAV corridors.
16. This section reflects the legal state as of 30 April 2025, based on *Commission Implementing Regulations 2019/947* and *2021/664* and national documents including *CAA Guidelines No. 6/2024*.
17. *Regulation 2022/425* amended transitional provisions of *2019/947*, notably deferring technical compliance obligations for drones in the open category, including standard scenarios for VLOS and BVLOS flights.
18. White, B. et al. (2023) highlight the role of spatial datasets – particularly 3D city models and GIS – in enhancing risk assessments and reducing approval timelines under SORA procedures.
19. EUROCAE ED-318 (2024) establishes the standard for the semantic structure, exchange and interoperability of U-space data across national and EU UTM systems.
20. *Regulation (EU) 2021/664*, Article 6(3): "Before commencing operations in U-space, operators must comply with the requirements of *Regulation (EU) 2019/947…*"
21. The ASSURED-UAM project developed a framework for local authorities addressing technological and social dimensions of UAM. Its recommendations contributed to the development of traffic management protocols for U-space pilot cities.
22. PANSAUTM is a national UTM platform that coordinates real-time UAV operations and was developed under the Digital Poland Operational Programme. It reflects the principles of coordinated U-space implementation.
23. The U-Space Kato and GZM initiatives emphasised the city's role in UAV adoption and inspired the Drone-Friendly Cities guidebook, supporting procedural readiness and strategic planning at the municipal level.

24. The "Three Areas" project aims to implement a national system for UAV service integration, combining urban airspace governance, automated service delivery and technical standardisation. More information about the project and the new application can be found at https://www.drony.gov.pl/three-areas.
25. The Helsinki case study was chosen to explore international best practices in urban UAV integration, particularly regarding public sector innovation and U-space coordination.
26. The original research hypothesis was first formulated by the author in 2018 following a conversation with Prof. J. Kozuba (Silesian University of Technology), who emphasised the potential of combining 3D city models and geoinformation technologies for supporting UAV risk assessment in urban environments.
27. Participation in the "Smart City Digital Twins" workshop (University of Turku, Nov 2023 and online, May 2024) provided first-hand insights into the layered development of dynamic spatial data infrastructures for urban planning.
28. Aalto University experts, including Prof. Aija Staffans contributed perspectives on the integration of 3D modelling and real-time data for airspace governance and platform interoperability.
29. Representatives of two entities shared operational experience from digital twin testing and U-space planning support tools: 1) Forum Virium Helsinki, represented by: Mr Juho-Pekka Virtanen, Product owner (digital twin) and Ms Martijnse-Hartikka Renske, Smart Mobility Team, Senior Project Manager; 2) City of Helsinki, represented by: Ms Christina Suomi, director of the Helsinki U-space 2024–26 project, Department of Urban Environment, Strategic Spatial Planning.
30. In 2020, the PANSA UTM system won two ATM Awards and contributed to Poland's fourth place in the global Unmanned Airspace ranking in 2022.
31. The survey introduced basic regulatory context (U-space, SORA, open/specific categories) to improve the accuracy of stakeholder responses.
32. The research hypothesis assumes that urban digital twins, enriched with regulatory and geospatial data, can serve as "urban services" for both operators and municipal authorities conducting UAV-related tasks.
33. Automated risk assessment tools require cooperation among GIS specialists, urban planners, UAV operators, mobile network providers, and city departments responsible for planning and digital infrastructure.
34. European Network of U-Space Stakeholders meeting (2023), organised by GZM Metropolis.
35. National UAV conference (2024), hosted by the Military University of Technology (WAT), Warsaw.
36. The cited statements by Krzysztof Kisiel and Maciej Włodarczyk were provided during the national UAV conference in Warsaw (2024) and were subsequently reviewed and authorised by the experts prior to publication.
37. Smart City Digital Twins workshop (Oct–Nov 2023), University of Turku and Business Turku.
38. Juho-Pekka Virtanen forwarded his article to the author, confirming that most urban digital twins are based on 3D models of cities: Virtanen, J.-P. et al. (2024), *Contemporary development directions for urban digital twins*, ISPRS Archives, DOI: 10.5194/isprs-archives-XLVIII-4-W10-2024-177-2024.

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