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RISK IDENTIFICATION AND MITIGATIONS IN ADVANCED AIR MOBILITY OPERATIONS

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Abstract:

The following paper presents research aimed at identifying the most critical risks and their mitigations in Urban Air Mobility (UAM) operations. This topic is one of aviation's most significant challenges in the coming decades. Having many flying vehicles in a single airspace requires an innovative approach, rule redefinition, and traffic management. Some solutions are scalable and can be adapted from general aviation. Therefore, stakeholders must address new risks and implement dedicated methods while maintaining the highest level of operational safety. Simulation research is needed to validate solutions before systems operate in real environments. The response to those challenges is the development of a simulation tool that can serve as a test benchmark. The study is divided into two sections: identifying potential risks associated with the rapidly growing UAV market and its applications in urban environments and developing a simulation tool that addresses various Urban Air Mobility challenges. A set of test cases is presented to demonstrate the tool's functionality and capabilities for further analysis. The paper reviews the United States and European Union approaches to UAM integration, including NASA, FAA, SESAR, and EASA initiatives, and highlights differences in operational concepts and regulatory frameworks. The research identifies major categories of risks related to UAV operations, including technical failures, environmental hazards, human factors, and cybersecurity threats. Long-term challenges associated with increasing traffic density, autonomous operations, and airspace organization are also discussed. The research evaluates scalable safety solutions derived from commercial aviation and analyzes urban airspace concepts such as layers, zones, sky-lanes, and sky-corridors. The developed simulation environment, implemented for the Warsaw metropolitan area, enables modeling of large-scale UAV and VTOL operations, no-fly zones, vertiport hubs, and traffic distribution. The results demonstrate the importance of dedicated traffic structures, altitude separation, and decentralized traffic management systems in ensuring safe and efficient Urban Air Mobility operations.

Keywords: *urban air mobility, risk assessment, risk mitigation, vertiports, airspace safety, air traffic management.*

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1. Introduction

The growing complexity of advanced aviation systems brings new threats to safety and security and poses several regulatory and technical challenges. As Advanced Air Mobility (AAM), including Urban Air Mobility (UAM) and Unmanned Aircraft Systems (UAS), air traffic increases, it is essential to ensure safe integration into an air traffic management system initially designed to support manned aircraft (Bauranov, 2019; Graydon et al., 2020). The main challenge of integrating UAS into urban settings is that these environments are already densely used by ground traffic, people, and manned aircraft (Agouridas et al., 2021; Straubinger et al., 2020). The growing use of UAS in urban environments will increase the risk of collisions, incidents, and accidents that can result in severe losses or injuries (Bauranov, 2021; Perz, 2024). As the uses and applications of UAS are growing and diversifying, it is necessary to develop effective risk management practices, methodologies, and processes to ensure operational safety (Ellis et al., 2020). Identifying and understanding risk factors is key to developing risk mitigation and response measures for UAS operating in urban environments. This paper examines the most critical issues and challenges associated with the rapid growth of UAS operations in urban environments. The research seeks to identify potential hazards and determine which safety regulations and procedures applied in manned aviation are scalable and can be implemented in the UAS domain. The paper includes an analysis of existing risk prediction and mitigation technologies currently used in traditional aviation operations, to be applied to develop a time-based, system-wide safety assurance for autonomous systems.

This paper focuses on UAS integration in urban environments where safety regulations significantly restrict operations (Joyce et al., 2017). UAS are increasingly applied in other areas, such as international border patrol, forest surveillance, or precision farming. These missions are performed in non-urbanized regions and are less affected by the most challenging urban-related risks. In such applications, operations are safe, and UAS can be used freely, providing enhanced efficiency, significant cost savings, and increased profitability. Even though, in most cases, UAS implementation and technological development relate to UAS operations and do not directly translate into UAM development, the paper discusses applicable lessons learned, risk identification, and mitigation capabilities (Perz, 2024).

Similar research referring to Urban Air Mobility is being developed across the United States by NASA (ARMD – UAM projects), the U.S. Federal Aviation Administration (FAA), and in the European Union under the EASA and ESA under the various projects and programs: SESAR, EUROCARE, EUROCONTROL (CORUS, 2019; European Defense Agency, 2021; National Aeronautics and Space Administration, 2025). The paper compares the U.S. and EU approaches, noting both similarities and differences between the studies. The comparison aims to identify the most critical risks from the reports and analysis and generate the core challenges ahead for Urban Air Mobility. The risk identification identified a strong series of events that may be addressed by adopting solutions from commercial aviation. Since commercial aviation has achieved a high level of safety, a similar approach may succeed in UAM. However, a group of risks is unscalable and entirely new for the existing environment. The extremely rapid evolution of the UAV market and its applications forces regulations and laws to adapt faster, but they cannot keep pace. This significant inertia in safety regulations impedes the development of the UAS market (i.e., services or UAS package deliveries).

The infrastructure (airports, zones, corridors, etc.) is not ready to gather a high volume of UAS (commercial, private-use, service, etc.). Some of the adapted/proposed solutions from commercial aviation in the abovementioned reports are inadequate, and it is highly possible that they do not ensure sufficient safety.

The objective of the presented research is to provide an in-depth report on the risks, potential threats, and challenges posed by UAS in the urban environment, and to identify solutions and methods to mitigate these risks. The second objective is to present the Simulation Traffic Analysis Tool, which was developed to make those risk analyses more understandable to a broader audience. The simulation tool allows for performing various sets of simulation tests that show different impacts on citizens and traffic capacity or traffic smoothness. The tool's architecture is open and parameterized, making it relatively easy to implement new Air Traffic Management Systems

2. Research the development of the UAS in the U.S. and Europe

Both the European Union and the United States of America make significant efforts to address the challenges of integrating UAVs into non-segregated airspace. The Next Generation Air Transportation System (NextGen) in the U.S. and the Single European Sky ATM Research Program (SESAR) in Europe are currently the most significant initiatives developed to support the growing demand for aviation services. Both programs have similar objectives: to enhance air traffic safety, improve ATM system performance, and align with the requirements of all airspace users. Both concepts are envisioned to be gradually implemented into the existing airspace infrastructure. However, some differences between the approaches are identifiable. The U.S. approach is more visionary and focuses on the operational concept, including supporting multiple drone operation types (e.g., VLOS, BVLOS), the needs and responsibilities of airspace users, and airspace management aspects such as safety, security, and equity. The European program provides more detail, develops legal and regulatory requirements, and thoroughly describes drone operational procedures. These differences in strategies are related to the specific needs of each region, related experience, and development pace. SESAR primarily focuses on developing a common framework for the entire European Union to address fragmentation in European aviation (European Commission, 2019; European Commission, 2020; European Commission, 2021). The U.S. has a unique air navigation service provider. Instead of creating a unified regulatory framework, the development program assumes the implementation of Community-Based Rules (CBR). It focuses on applying innovative technologies to improve performance and increase the capacity of the airspace system (Federal Aviation Administration, 2019; Zieja et al., 2015).

2.1. The United States' approach

Within NASA, the Aeronautics Research Mission Directorate has launched several projects (see Figure 1) to support the Advanced Air Mobility Mission, identify roadblocks to safe operations, and search for creative solutions for the aviation industry.

The UAS Traffic Management project, which concluded in 2020, was run in partnership with the FAA and focused on developing the concept of operations for safely operating small, unmanned aircraft systems (UAS) in low-altitude, beyond-visual-line-of-sight airspace. The Unmanned Aircraft Systems Integration in the National Airspace System project, which started in 2011 and concluded in September 2020, conducted in collaboration with industry, academia, and government partners, has identified, developed, and tested technologies and methodologies to address technical challenges associated with integrating UAV operations into airspace occupied by manned aircraft.

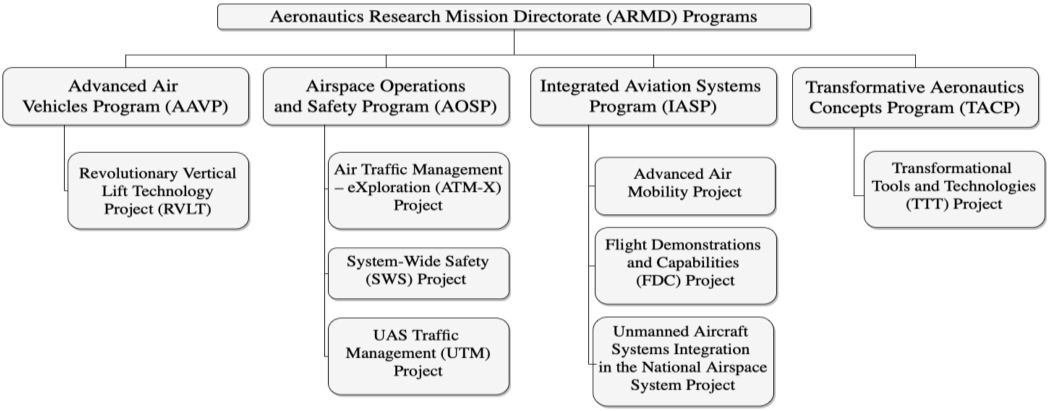

Fig. 1. NASA ARMD organization with UAM-related projects

Regarding the projects currently underway, the goal of RVLT is to safely develop and certify, in cooperation with government, industry, and academia, critical technologies that will enable revolutionary new possibilities in air travel, e.g., large cargo-carrying vehicles or passenger-carrying air taxis. The RVLT project focuses its research in the following areas: clean and efficient propulsion, efficient and quiet vehicles, safety, comfort and accessibility, modeling/simulation, and test capability. The Air Traffic Management – eXploration project researches the necessary transformations in air traffic management to safely accommodate the increasing demand for new air vehicles entering the airspace and performing various operations.

The System-Wide Safety project performs risk research to evaluate how technical advancements in aviation affect safety, identify potential hazards, and develop innovative solutions, ensuring the safety of UAM missions. The Transformational Tools and Technologies Project are developing scientific knowledge and technologies to predict flight performance for a wide variety of air vehicles expected to enter the airspace. Another area of research within this project's scope focuses on developing new, strong, lightweight materials. The Advanced Air Mobility project aims to develop and validate system-level concepts and solutions to safely integrate emerging technologies into the airspace, focusing on automation, contingency management, airspace management procedures, and infrastructure. The Flight Demonstrations and Capabilities project provides results from complex, integrated flight research demonstrations that support other ARMD programs in developing and validating solutions. The results of the FAA and NASA collaborative efforts have been documented in several publications, providing insights into their vision of UAS traffic management. However, these documents do not prescribe solutions or specific regulations. They present conceptual ideas, analyses, and operational examples, and state that UAS missions should be conducted in accordance with the Community-Based Rules (CBRs), which the FAA must approve.

2.2. European Union’s approach

The development of UAS integration solutions in Europe follows a slightly different approach. Similar to the U.S., there are several UAV-related research projects. In Europe, most projects are conducted as part of the SESAR (Single European Sky ATM Research) program. The SESAR research projects are categorized into three strands: Exploratory research, Industrial research, validation, and large-scale demonstrations. EASA has already published regulations that set out the framework for the safe operation of civil drones (EU Regulations 2019/947 and 2019/945).

Depending on the UAV's category, its operations must follow different rules. Regulation (EU) 2019/947, applicable since 31 December 2020, defines three categories of civil drone operations based on the risk involved in their missions: open, specific, and certified. The open category covers low–risk drone operations that do not require a pilot license or operational authorization before starting a flight. However, they are subject to strict operational limitations. Specific category concerns operations that pose a higher risk and do not meet the requirements of the open category. For this type of operation, UAS operators must be registered with the Civil Aviation Authority, and a thorough risk assessment must be conducted before the flight to determine which requirements are necessary to ensure the operation's safety. The Certified category covers the operations that pose the highest risk. Drone operators, their drones' certifications, and remote pilots' licenses are required to ensure safety. This category includes operations conducted over assemblies of people, involving the transportation of passengers or dangerous goods, that may pose a substantial risk to third parties in the event of an accident. In March 2020, the Polish Air Navigation Services Agency launched the first operational drone flight coordination system in Europe – PansaUTM - enabling the safe integration of unmanned aviation into subsequent controlled zones of airports and FIS sectors (Polish Air Navigation Services Agency, 2025). It aims to replace manual coordination of UAV flights with digital solutions. Through the PansaUTM deployment, 9 out of 16 U-space services (as shown in Figure 3) that European countries are supposed to implement by 2025 have been successfully implemented in Polish airspace (ATM Master Plan, 2020). PansaUTM functionalities include e-registration, e-identification, flight planning, acceptance and modification of a flight, real-time flight tracking, two-way non-verbal communication between air traffic services and the UAV operator, and collision detection and avoidance protocols. PANSA UTM supports the planning of VLOS and BVLOS operations in compliance with applicable European rules and is designed to follow the successive implementation of European regulations and requirements.

The Pansa UTM System is integrated with the DroneRadar mobile application. It supports UAV operations within three flight categories defined in European regulations: Open (A1, A2, A3 subcategories), Special, and Certified. Weight categories are adjusted to the regulations based on MTOW (0,25<5<25 kg). Based on aeronautical data, user-provided mission information, and local rules in the selected flight zone (DRA-R, DRA-I, DRA-T, DRA-U), the application indicates whether the planned operation can proceed: green indicates no restrictions, orange indicates restrictions, and red indicates the flight is prohibited. The latest Eurocontrol report (EUROCONTROL 2020) shows that Poland is a leader in implementing U-Space services among European countries. PansaUTM is a pioneering, operationally deployed system in Europe that enables the digital coordination of UAV flights and the management of requests and permissions for these flights (ATM Master Plan, 2020; EUROCONTROL, 2019). The pioneering work of the Polish Air Navigation Services Agency in developing a nationwide integrated ATM/UTM system is internationally recognized (Polish Air Navigation Services Agency 2025).

3. Risk in Unmanned Aircraft Systems

Several studies and documents were reviewed to create a list of potential threats and events related to drone operations. The goal was to gather the challenges identified in the U.S. government's approach and in European regulations and concepts.

3.1. Risk categories

As described by Sunil et al. (2015), two main threats can be identified. The first one, drone threats and events, concerns threats that may impact the UAS set (drone, ground station, and pilot) and compromise the safety of an operation. The second one is UAM threats and events, which include risks that can compromise the safety of UAM services. Drone-related threats can be divided into four main groups: technical/mechanical failures, meteorological or environmental events, human-related and operational threats, and security (Abdalla, 2020).

Technical and mechanical failures include datalink loss (telemetry & FPV, telecommand) (Thipphavong, 2018), voice link with ATC or with a second pilot for E-VLOS failure, and failure of cameras or sensors (both as payload and used for control). It can lead to a lack of connection among drones, operators, and service (Perez-Castin et al., 2020). Another risk in this category is the failure of the position emitter or receiver. Additionally, the availability and accuracy of GPS in urban environments can be challenging (Thipphavong, 2018; Bauranov, 2021; Castro, 2021). Buildings that block the GPS receiver's direct line of sight to satellites can cause navigation errors. Directional loss can also be caused by compass, IMU, or altitude sensor failure (CORUS, 2019). Another safety risk is unintentional loss of altitude (Perez-Castin et al., 2020; Bauranov, 2019) that can occur due to engine failure, drained energy sources, ESC failure, or propeller failure. Failure of the flight control computer leads to decreased (or no) ability of the operator or autopilot to control the flight. Parachute failure in the circumstances of a parachute recovery results in damage or loss of the vehicle due to ground impact.

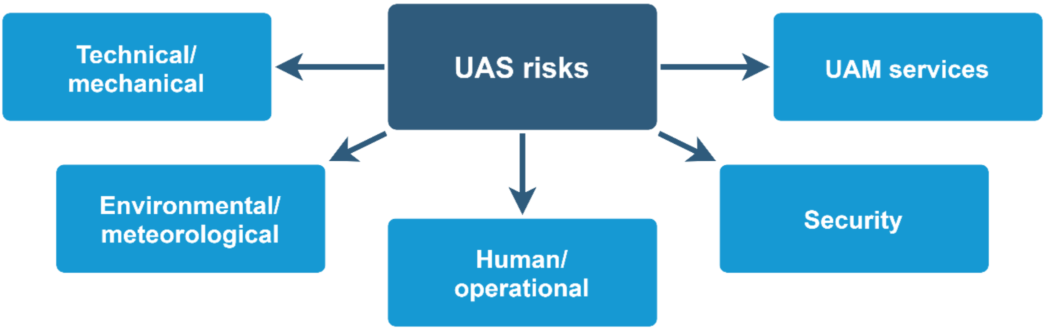

Fig. 2. Categories of UAS-related risks

Table 1. Technical/mechanical UAV-related threats and events

Technical/ mechanical	Datalink loss
	Voice-link failure
	Sensor or camera failure
	Position emitter or receiver failure
	Directional loss (e.g., GPS malfunctions)
	Unintentional loss of altitude
	Flight controller failure
	Parachute failure
	Loss of payload
	Total loss
	Erroneous data, latency, and processing error
	Emissions of radiated energy or toxic chemicals
	Automation error, unexpected automation behavior

Other threats identified in this category are loss of payload (e.g., when cargo or a passenger is insufficiently restrained), a drone sending erroneous data to services, high latency in sending the relevant information, or a processing error resulting in the derivation of faulty results. Potential emissions of radiated energy and toxic chemicals that exceed safe limits have also been identified as an issue. It concerns situations in which the cabin environment becomes toxic or when emissions within enclosed spaces (e.g., hangars) exceed limits. Technical threats can also result from automation errors or unexpected automation behavior.

Table 2. Environmental/meteorological UAV-related threats and events

Environmental/ meteorological	Animal collision
	Inappropriate or severe weather
	Icing
	Electromagnetic interference
	Corrosive environments
	Noise, pollution
	Sand or dust

Another safety risk category is related to meteorological and environmental factors, such as animal collision, e.g., bird strike (Bauranov, 2019; CORUS, 2019), inappropriate or severe weather, e.g., rain, hail, snow, fog, gusty wind in urban canyons, and lightning strike (Castro, 2021; SESAR JU, 2021). Strong winds and extreme temperatures can reduce battery performance; precipitation can cause malfunctioning of onboard electronics and increase vehicle resistance to movement. Electromagnetic interference can also be a challenge in some environments, particularly in urban areas with high traffic density or tall buildings. Operations in corrosive environments cause damage, and the ingestion of dust or sand into engines can result in complete engine failure.

Human-related and operational threats include mission planning error (Bauranov, 2019), violation of minimum separation in flight (Graydon et al., 2020), or inadvertent entry into flight-excluded areas, e.g., due to insufficient geo-fencing (Ellis et al., 2020). All can lead to collisions with other UAS, manned aircraft, or other obstacles such as trees, buildings, people, or terrain (European Union Aviation Safety Agency, 2015). Another challenge is related to immediate give-way events, e.g., an emergency helicopter, a manned vehicle emergency landing, or a first-aid drone, when the mission trajectory needs to be dynamically adjusted (CORUS, 2019). There are also safety risks to passengers on board, such as passenger interference with vehicle operations, passenger illness during flight, or vehicle motion exceeding limits for occupant health and comfort. Several factors related to human operators' performance also need to be considered. Some risks, e.g., VLOS loss, can result from inadequate operator training for maintaining safety margins, loss of situation awareness, or distraction during manual flight. All can lead to human errors, such as inadvertent use of flight controls, wrong responses to emergencies, or perception errors. Other dangers can result from operators who do not comply with requirements, breach the operational plan, or engage in aggressive maneuvers.

Table 3. Human/operational UAV-related threats and events

Human/ operational	Mission planning error
	Violation of the minimum separation in flight
	Inadvertent entry into flight-excluded areas
	VLOS loss
	Collisions with other UAS
	Collisions with manned aircraft
	Obstacle collision
	Immediate give-way events
	Passenger interference with vehicle operations
	Passenger illness during flight
	Vehicle motion exceeding comfort limits
	Inadequate operator training for maintaining safety margins
	Operator distraction during manual flight
	The operator does not comply with the requirements.
	Insufficient understanding of advanced systems
	Obsolete equipment

An interesting and demanding issue in this category concerns establishing UAV operator training and licensing standards. Unmanned aviation presents human factors considerations distinct from those of manned flight. Various types of UAS, sometimes supplied with advanced automation aids, are becoming increasingly accessible. It is anticipated that recreational pilots will operate many drones within a brief time. UAS technology is advancing rapidly, enabling diverse innovative features such as sophisticated sensors and remote, pre-programmed, or autonomous flight control that can operate differently depending on flight conditions.

Unlike professionals, who undergo comprehensive training and testing to operate systems safely and efficiently, most amateurs have limited knowledge of the automated systems in their drones. They might be unaware of the possibilities and limitations of such systems, or unable to respond appropriately to automation failures or unexpected behavior. The lack of training and experience can lead to complacency or incorrect automation use, resulting in inconsistent performance by recreational pilots and increasing operational risk. Some operators might not have the proper understanding of how they affect the operations of other airspace users. This aspect should be considered when establishing the minimum standards for operator training and designing automation capabilities.

The successful integration of state-of-the-art UAV technologies into urban environments requires advanced city services, including high-speed Internet connectivity, drone communication, dedicated infrastructure (vertiports, corridors, tubes) enabling high throughput, and various support systems. The potential consequences of the failure of any component of such a complex system are unknown and need to be explored. Additionally, there is a risk that some people will use obsolete technology or unregistered UAVs that can, intentionally or unintentionally, mislead the advanced automated systems used by newer UAVs. It is still unclear whether advanced systems can operate safely alongside UAVs using outdated technology. Systems that do not meet current requirements and users who do not comply with the regulations could pose a significant risk to others operating in the airspace and people on the ground.

Table 4. Security-related UAV threats and events

Security	Intentional collision
	Intentional interference
	Trespassing

The fourth risk category includes security-related hazards such as intentional collision and intentional interference (Bauranov, 2019; Perez-Castin et al., 2020), as well as cyber-attacks, e.g., undetected hijacking of the C2 link (Thipphavong et al., 2018). There is also a sensitive concern about people using drones for surveillance or flying over private property to transmit images.

Table 5. UAM services-related threats and events

Services	Lack of transactional integrity
	Datalink loss
	Loss of data, processing error, and latency
	Lack of available infrastructure
	Inadequate ground crew training
	Degradation of ground control station capability

One of the challenges in the UAM services-related category is maintaining transactional integrity, meaning, for example, that flight plan services should not create conflicting flight plans even when several users file their flight plans simultaneously. Several technical threats were identified as well, e.g., datalink loss, data loss, processing errors, latency, no ATC, or no monitoring system available. Another issue is a lack of infrastructure, e.g., the availability of vertiports and low throughput. Inadequate ground crew training, dispatch understaffing, or degradation of ground control station capability (e.g., displays) can lead to insufficient ground support and, as a result, impair operations, e.g., delayed flight planning (Thipphavong, 2018). Another challenge is to ensure that the airspace infrastructure is usable by vehicles of varying performance and capability (Perz, 2024). There is a need to establish a minimum set of requirements for the use of dedicated airspace structures. Among the identified risks, especially challenging ones, are those unique to UAS operations, because mitigating them will require entirely innovative solutions.

3.2. Hazardous events and long-term challenges

Having discussed various safety hazards related to UAV operations, two diverse groups of challenges can be identified. The first one would comprise threats related to everyday drone operations, incidents that can happen quite commonly and usually affect only the UAV itself without causing much harm to the overall system. This category includes datalink loss, sensor failure, loss of control, collisions, blocked GPS signals, or unfavorable weather conditions such as wind gusts or low temperatures that affect battery performance. In most cases, relevant technological solutions must be developed and applied to mitigate these risks, e.g., detect-and-avoid systems.

The other group includes long-term challenges related to the growing density of UAV operations and UAM development. As UAV capabilities expand over the next few years, society and law enforcement must anticipate emerging risks and develop solutions. Safety requirements should be adjusted to the operational risk of a given mission depending on mission goal, operational complexity, geographic factors, and environmental constraints. Since most UAM services have not yet been implemented, many limitations and challenges remain unknown. Some of these concerns are related to drone missions performed by inexperienced pilots who have poor training. Autonomous aids are being developed to allow unskilled operators to operate a UAV. Relevant qualification criteria for UAV operators need to be established. Advanced technologies will enable a single pilot to manage multiple drones simultaneously. Such a transfer of role from operating a single UAV to simultaneously monitoring multiple systems poses an unknown safety impact.

Another issue that needs to be addressed is noise and visual pollution associated with high UAM congestion. Noise is a key factor, given that UAM operations will be conducted in densely populated environments. Due to low-level flight over urban areas, UAM is expected to meet a stringent noise standard. These concerns can be addressed by modifying flight routes to avoid particularly sensitive areas, e.g., by consolidating traffic to existing transportation corridors. High density of UAM operations can also result in low vertiport availability and negatively affect throughput. As already mentioned, it is necessary to develop innovative solutions in air traffic management, communication, navigation, and surveillance to ensure the safe operation of various types of vehicles with different hardware and software. Obsolete, low-cost, or DIY equipment in the airspace must be adjusted to advanced systems. Designing safety systems and providing regulations to ensure safe operations in various conditions is crucial.

It is anticipated that UAS will need to handle a significant amount of data used by onboard systems. Multiple, heterogeneous data sets will likely need to be analyzed in real time to enable the effective operation of mission-related systems. Challenges related to data quality, management, and processing must be considered. Certification requirements for data-driven, especially non-deterministic AI systems, should be established. Some emergency scenarios need to be created to mitigate the risk entailed by potential datalink loss, latency, or low data quality.

The NASA ConOps document (Ellis et al., 2020) discusses data-driven strategies for a safety system that could detect and mitigate various safety-critical risks. An IASMS would collect data on aircraft status, air traffic management systems, airports, and weather, then assess the data and detect or predict elevated risks to undertake mitigation actions. The design of safety systems should account for the growing use and complexity of automated systems, increasingly complex operational environments, poor operator skills, and airspace management involving mixed aircraft and equipment. The document discusses several safety risks, describes the known and well-understood ones — e.g., unsafe proximity to people on the ground, air traffic, or property — and critical system failures, and identifies the unknown ones that require additional attention. The distribution of authority and autonomy between humans and machines is an emerging challenge. The authors suggest that it may be necessary to develop the capability to quickly ground all UAS during a system-wide emergency to mitigate risks associated with rogue operations. In addition to the previously mentioned emerging challenges, the areas identified in the NASA ConOps need to be further explored.

4. General Aviation vs. Unmanned Aircraft Systems

4.1. General Aviation

The aviation sector is tightly regulated to guarantee a uniform, high level of air transport safety. There are strict requirements for pilot licensing, airworthiness, or aircraft type approvals. Over the years, the NTSB has thoroughly investigated every aviation accident in the U.S. to determine the probable causes and issue safety recommendations to prevent future accidents. Safety requirements and the regulatory framework have been built over decades, ensuring the sustainable development of civil aviation. Implementations of significant technological advancements were preceded by profound risk assessment and the introduction of adjusted safety measures. In the manned aircraft domain, commercial pilots responsible for safely transporting large numbers of people are held to the highest level of experience and training. Human-crewed aircraft have strict quality and redundancy requirements that have been developed over decades. Establishing safety requirements is considered the highest priority of the general aviation industry because any negligence can be hazardous and result in loss of human life.

4.2. Unmanned Aircraft Systems

On the contrary, the rapid development and proliferation of cutting-edge technology in the unmanned aviation industry are outpacing existing regulations and control mechanisms. To maintain the current safety level of airspace operations, it is crucial to anticipate emerging challenges and adjust rules and standards accordingly. Some UAV rules could be derived from safety procedures and regulatory guidelines in manned aviation, e.g., by introducing drone operations categories, airspace, vehicle classes, or registration requirements. However, the manned aircraft framework generally cannot readily be applied to drone operations. Some requirements, such as rigorous certification standards, could completely block drone operations, preventing the implementation of advanced aviation innovations. Redundancy requirements would excessively increase their price and, as a result, decrease their accessibility. A similar approach applies to drone operators' training and licensing. As unmanned aircraft become increasingly affordable and easy to fly, it is almost impossible to impose on drone operators the same regulatory restrictions as those applied to civil aviation pilots. However, considering the growing community of airspace users, it is essential to ensure that all of them are familiar with aviation and airspace regulations and willing to comply with safe operating practices. Thus, it is necessary to find a middle ground that preserves current airspace safety standards while allowing small, uncrewed aircraft to operate at a reasonable cost.

The risk associated with most UAV operations is lower than in the manned aviation sector. In non-urbanized areas, drone operations can be implemented safely and efficiently. However, the possible applications are still quite limited. UAVs can be used for specific, well-defined missions in environments where the risk of flying over people or collisions with other aircraft is significantly reduced. Considering the nature and circumstances of such operations, they can be performed without implementing rigorous safety regulations. UAS has been successfully used for military applications, precision agriculture, border patrol, and forest surveillance. The risk of such operations is much lower than the potential hazards in urban environments. However, the experience and solutions developed to support such missions could benefit the development of UAM implementation strategies. They can help identify some challenges and ways to overcome them.

The UAM operations in complex, congested, and unpredictable urban settings could be much more dangerous. These operations bring many challenges. Even though some advanced technologies and concepts enabling drone operations in cities have already been developed and are likely ready for implementation, there is concern about their safety. Although autonomous systems offer various benefits (e.g., increased mobility, reduced congestion, reduced fuel emissions, and energy savings), they are not readily accepted by society. Vehicle- and system-level safety requirements must be established to ensure a safe and viable integration of autonomous missions into urban settings. Autonomous operations are especially challenging when determining who is legally responsible for the operations and any potential damage they cause.

5. Adaptable solutions

To ensure high levels of safety, some risk mitigation solutions from manned aviation (both civil and military) could be incorporated into drone regulations; some will need to be appropriately adjusted, and new technologies must be developed. That is why it is necessary to identify the UAV-related risks and assess which could be mitigated by transferring existing safety solutions from manned aviation. In their case, there are already some guidelines to follow. The hazards unique to advanced UAV operations will require the development of new mitigation strategies. The table below summarizes some scalable UAM-related aspects that could be addressed in line with safety guidelines for manned or non-urban UAV operations.

The extent to which the existing solutions are transferable is unknown and must be explored. However, some general rules could be adjusted to regulate complex UAM operations. A good example of transferring some ideas from the domain of manned aviation is the UAS classification presented in European Commission regulations. By analogy to manned aircraft classification (determining aircraft categories based on size and maneuverability), three categories of UAVs were defined. Each of them can be associated with various levels of operational risks. Depending on the category, the operator must comply with different requirements and safety standards. For a small drone, the consequences of a low-altitude crash are usually negligible, affecting only the drone itself. Larger and heavier ones pose a bigger risk; therefore, in their case, the quality of the individual components becomes a greater concern.

Table 6. Scalable aspects of airspace operations

no.	Aspects od the airspace
1.	Aircraft classification
2.	Airspace classes
3.	Pilot/operator training and licensing
4.	Certification/registration
5.	Security systems
6.	Weather, icing

In some cases, applying existing solutions is unreasonable and might even be dangerous. Some advanced technologies are outpacing the development of the necessary infrastructure, and existing concepts are incompatible with the new equipment and operations. Adapting existing solutions can introduce new risks. A good example of such misalignment is when the first cars were introduced, but the environment was not ready, and the city's infrastructure was not prepared for car traffic. Roads suitable for horseback riding proved too narrow for cars, leading to many accidents.

Searching for new solutions to address emerging risks and needs is necessary to mitigate the incompatibility between new technologies, environments, and infrastructure. An interesting example of such an approach is how Tesla addresses the challenges of using Autopilot mode in their cars in cities. Tesla autopilot performance can be affected by poor visibility (heavy rain, snow, fog), bright light (oncoming headlights, direct sunlight), narrow, high-curvature, or winding roads, interference from other equipment that emits ultrasonic waves, extremely hot or cold temperatures, etc. Due to these limitations, autopilots might not work correctly in urban areas. A new traffic approach was proposed – underground tunnels providing stable conditions, ensuring high safety. Such innovative concepts are needed to address specific UAS–related challenges, including large-scale operations, compatibility of the onboard systems (software, sensor standards), complexity of urban environments (wind, GPS), data transfer, centralized vs. distributed traffic management systems, or cybersecurity.

Some UAM risks are difficult to define and mitigate. Some are related to airspace division and traffic management. These could be inspired by road traffic or manned aircraft solutions. Still, additional UAS-specific features (e.g., corridors, layers, chimneys) will need to be introduced alongside UAS regulations and standardization. Official rules and standards are required to regulate UAV maintenance, hardware and software certification, and UAV interactions to prevent collisions. Another domain to be explored is the airspace organization around the airports and the decentralization of data management. It is assumed that the ATM should use only general information about UAV operations, and traffic should be based on local sensors and software. Various risks arise from insufficient cybersecurity measures, including package interception or drone hacking. Dedicated safety features need to be developed to mitigate them.

6. Air Traffic Concept

6.1. Layers conception

The whole mixed concept assumes that the airspace is essentially unstructured. Traffic is only subject to physical constraints, e.g., weather, static obstacles, and terrain. The vehicles use a direct route between their origin and destination, with optimized flight altitudes and velocities. The layered concept segments the airspace into layers of specific vertical dimensions. Each altitude layer limits horizontal travel to a specified heading range. Such an approach is expected to reduce the probability of conflicts by reducing relative velocities between aircraft at the same altitude (Sunil et al., 2015).

To enable smooth tactical deconfliction, each travel layer for standard transit can be accompanied by a deconfliction layer that allows a UAS to fly over a potential existing path and avoid a traffic conflict.

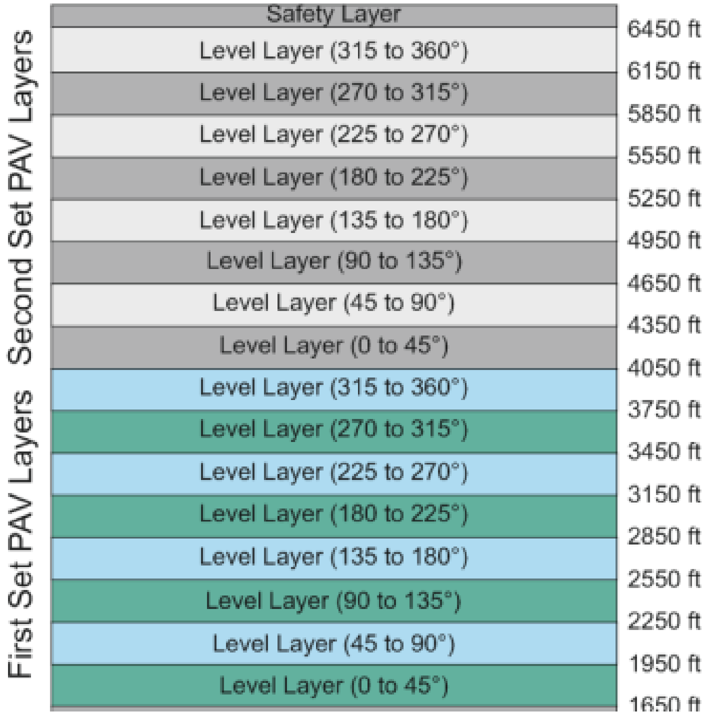

Fig. 3. Schematic view of the Layers concept (Federal Aviation Administration, 2020)

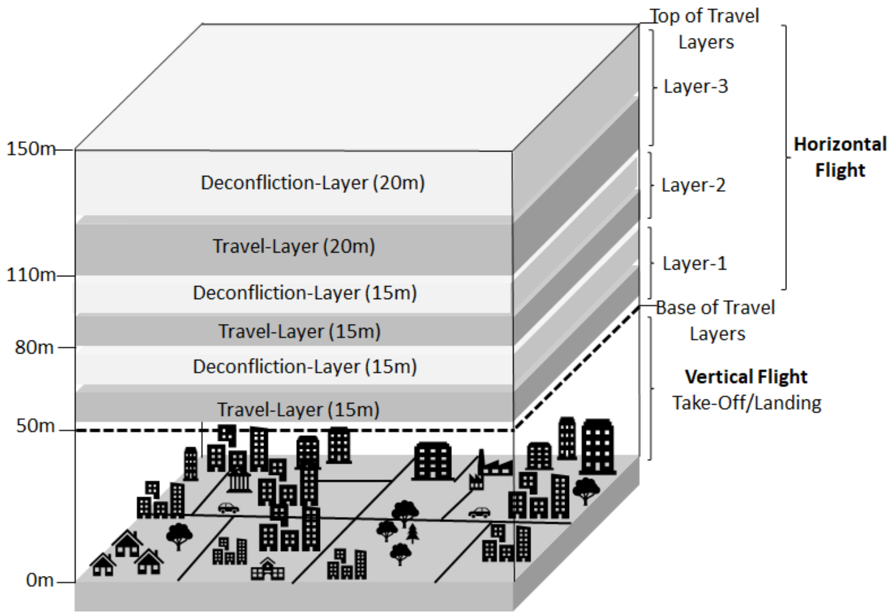

Fig. 4. Schematic of airspace layering structure with three pairs of travel/deconfliction layers (McCarthy et al., 2020)

6.2. Zones

The zone concept segments traffic based on travel direction similarity, taking the city's layout into account. Two zone types can be discerned: circular and radial.

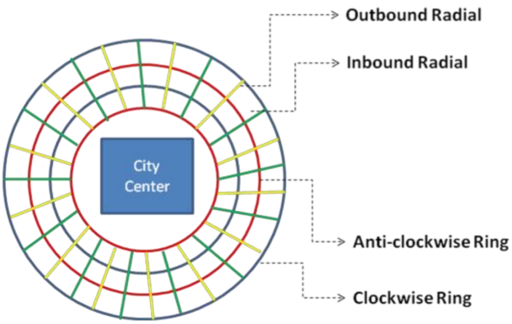

Fig. 5. Top-down view of the Zones topology (National Aeronautics and Space Administration, 2015)

The former ones are used similarly to bypass roads in cities. The radial zones serve as connections between these circular zones. They enable traffic towards and away from the city center. There is no vertical segmentation—altitude is selected flexibly based on the planned flight distance between the origin and destination.

6.3. Sky-lanes

Airspace above an urban street is sectioned into multiple layers by altitude. Sky-lanes represent an extension of a conventional road system into each layer. A road system in the air is formed with lanes. In each layer, a group of parallel lanes is placed at a given altitude and serves as a road strip. Vehicles can change their lanes laterally. They can also migrate to other layers or cross strips via left- and right-turns. Lane arrangements and the configuration of intersections/interchanges distinguish different sky-lane design variants.

Table 7. Sky-lane design variants (Sunil et al, 2015)

Design	Features
A1	Sky-lanes, coherent lanes, fused crossing
A2	Sky-lanes, coherent lanes, exclusive crossing
A3	Sky-lanes, alternating lanes, exclusive crossing

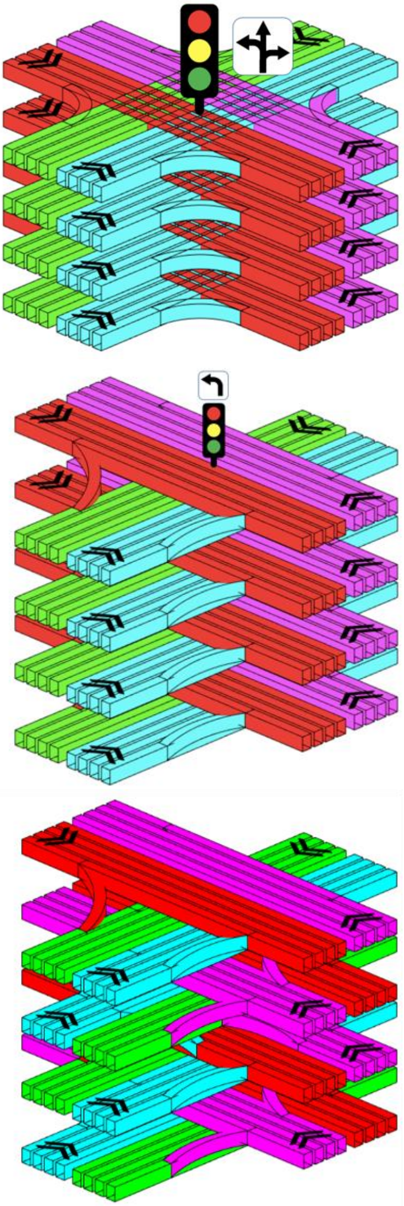

Fig. 6. Sky-lane design variants: A1, A2, and A3 (Jang et al., 2017)

In the first variant (A1), the roads share the same layer at intersections, so the lanes of the strips are fused there. A traffic control signal is required since intersecting road strips share the intersection space at each layer. The traffic control service can be provided via radio communication. As an alternative to an intersection, roundabouts can be used at junctions with multiple sky lanes (Sacharny, 2019).

The second and third design variants use exclusive stacking of crossed strips. There are no direct intersections because the crossing strips do not share the same layer. Both designs assume that right turns can be facilitated by using a ramp from the rightmost lane in each strip. The lane directions across different layers can be coherent (as in the second design) or alternating (as in the third design). In sky-lane systems, lateral and vertical separations are given by the design of airspace structures. Vehicles maintain level flight along the reference centerline of a lane unless they move into neighboring lanes or other altitude layers. The main issue is longitudinal separation along the lane direction. If two vehicles, a predecessor and a follower, are cruising in the same lane, the follower is responsible for collision avoidance. If the predecessor suddenly changes its behavior (e.g., decelerating to stop), the follower must ensure a safe distance to prevent a collision.

6.4. Sky-corridors

According to the corridor design described by (Sunil et al. 2015), each vehicle manages its flight within a corridor. The vehicles can move freely in any direction within the corridor, provided safety is ensured. Vertical separation is assured by vehicles.

In a multi-layered air corridor model (Sacharny, 2019; Muna et al., 2021), layers are used to enable safe and efficient operations. The top layer accommodates south-bound and north-bound traffic, while the bottom layer accommodates eastbound and westbound traffic. When making a turn, the vehicles should move to a middle layer to hover there when waiting to execute a safe turn maneuver. The middle layer is available at all intersections. Its primary purpose is to prevent collisions while vehicles change flight direction. When a vehicle needs to change direction, it should move to the middle layer, change its heading, and then go to the target level. Before moving to the target level, the vehicle needs to verify whether the next position is occupied. The UAV hovers in the middle layer until the target level becomes available.

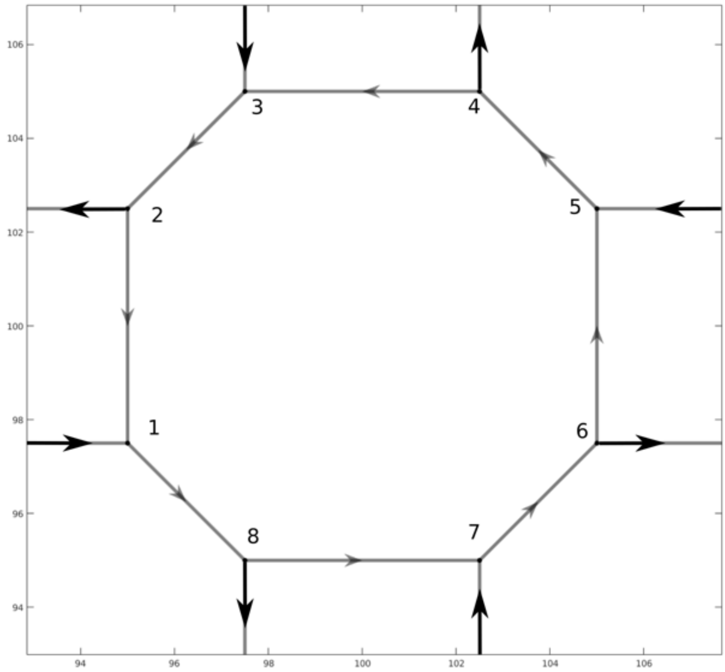

Fig. 7. Airway Roundabout (Muna et al., 2021)

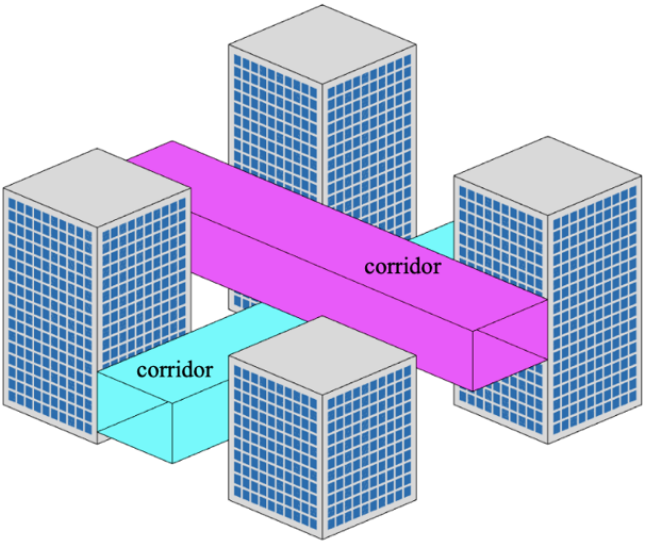

Fig. 8. Air-corridors (Jang et al., 2017)

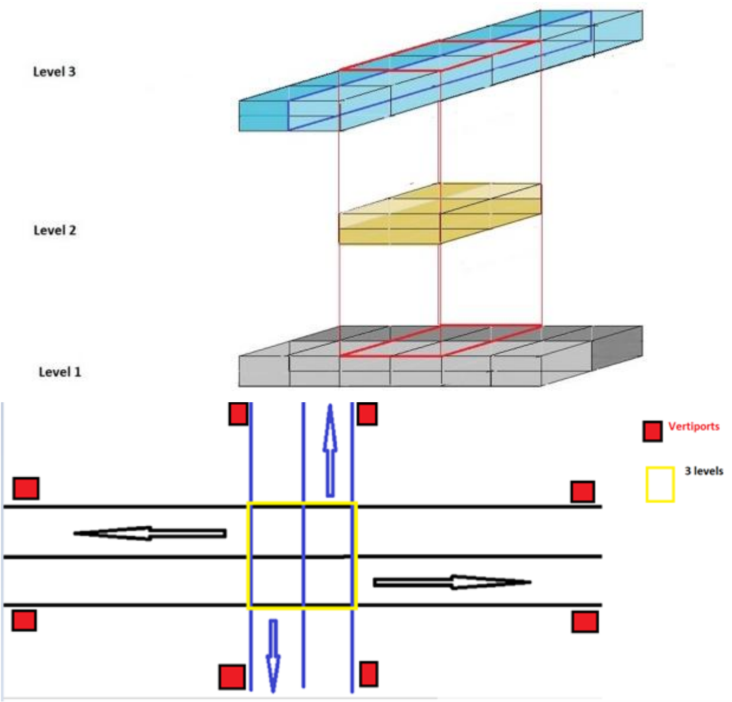

Fig. 9. Air-Multi-layered Air Corridor: side view of an intersection, top view of an intersection (McCarthy et al., 2020).

7. UAS classification

The next step in the research was to define and develop a simplified classification of UAS based on the literature and existing descriptions. The literature and law research revealed several ways to determine automated systems and UAS. The classification of the UAS may be compared to the automation levels that have existed in engineering research over the years (Table 8).

Table 8. Sheridan's levels of automation (Federal Aviation Administration, 2020)

Automation Level	Definition
1	The computer offers no assistance; humans must do it all.
2	The computer offers a complete set of action alternatives, and
3	Narrows the selection down to a few, or
4	Suggests one, and
5	Executes that suggestion if the human approves, or
6	Allows the human a restricted time to veto before automatic execution, or
7	Executes automatically, then necessarily informs the human, or
8	Inform him after execution only if he asks, or
9	Informs him after execution if the computer decides to
10	The computer decides everything and acts autonomously, ignoring the human.

UAV systems may be compared not only by weight and application, which is the most common way to classify UAVs. The UAV systems are mainly classified due to:

- size,
- mass,
- range,
- velocity,
- endurance,
- propulsion system,
- mission type.

The other approach is to group them by level of autonomy. The simulation implemented the following classification by comparing various systems and methods.

Table 9. Kopyt's levels of UAS autonomy (Kopyt et al., 2024)

Autonomy Levels	Description
0	Full manual
1	Automatic Flight Control (waypoint navigation: A -> B)
2	Small UAS: Automatic Flight Control + Collision Avoidance
3	Large cargo UAS: Automatic Flight Control + Collision Avoidance
4	Fully Autonomous

8. Urban Air Mobility Simulation Tool

One of the most important outcomes of the literature review was that the potential of air traffic management must be incorporated into airspace regulation. This point reminds one of road traffic (vehicles). Thus, tests and simulations must be performed before running them in a real environment. To meet those expectations, the research team developed a simulation tool to model various aspects of Urban Air Mobility. The tool allows creating various scenarios and applying different ATM or algorithms. The goal of the simulation is to visualize some of the main risks identified in the first part of the research. The first step was to identify the most critical risks to consider.

For simulation, the Warsaw area was selected. The Polish Aviation Authorities designated the area as a future urban air mobility control area. The square size is 30 x 30 [km], see Figure 11. In a simulated environment, the five groups of UAVs (Table 9) were implemented with varying numbers and proportions, depending on the scenario. One of the most significant conclusions from the first part of the research was that the ATM system needs to be decentralized due to the vast quantity of data, despite some aspects, such as UAV and operator registration and path planning. The simulation tool was developed in the MATLAB environment (Kopyt et al., 2024).

Fig. 11. Warsaw area with no-fly zones

Since many government institutions are in the Warsaw area, a large no-fly zone was selected (marked as 2), and the circle represented a Frontex building (the EU agency for border security). Those areas are where it is impossible to fly with any UAV. Despite the various Air Traffic controls that will be implemented, the no-fly zones were a must-have in the simulation, as this aspect will always remain valid. Consequently, limited fly zones have been introduced, as traffic over dense areas was assumed to be kept to a minimum to reduce the risk of failure. Those areas allow UAS to enter, but it must reach the destination using the shortest path using the dedicated algorithm (Kopyt et al., 2024; Kopyt et al., 2025).

The first simulations were simple trajectories from A to B (Point-to-Point paths). This group of UAVs is presented as group 1. These may be represented as small delivery drones with limited sensors and computing power, low levels of autonomy, and poor risk response. This kind of UAV was a good reference point for starting the simulation. For the first scenario, the 100 UAVs were selected from random points (takeoff and landing spots). The UAV's range was parametrized, and the first simulation was set to 10 [km]. UAS fly along paths composed of waypoints. The first and last waypoints correspond to the takeoff and landing points. If the straight path between the first and last waypoints crosses airspace (no-fly zone), additional nodes are added at the vertices of the airspace. The best (shortest) route is determined between all possible nodes using the A* graph traversal algorithm. Currently, a departure or destination point lies within the no-fly zone. In that case, the departure/destination waypoint is moved to the closest airspace vertex (i.e., the airspace boundary). The additional nodes generated at the vertices of an airspace are not generated directly at the vertices. Still, they are translated away from the airspace by a specified amount (which might differ for each drone). Some of the consequent modifications led to implementing a better map and a more effective way to present the data.

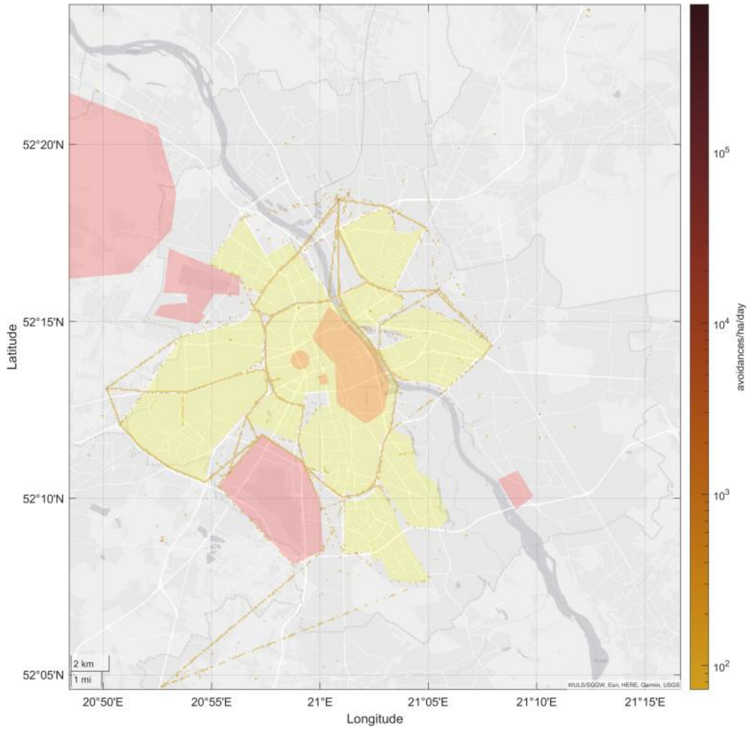

Fig. 12 Warsaw area with no-fly zones and limited fly zones

Based on similar tools, such as Flight Radar or Maritime Radar, the heatmap was generated to track the trajectory of each UAS (Figure 13) (Jacyna-Gołda et al., 2014; Szałtys, 2023). Within this approach, areas covered by UASs appear more clearly. In the following figure, it is easy to see that above the no-fly zone, a significant concentration of systems may pose risks, i.e., collision—based simulation with no-fly zones.

To make the visualization more realistic, the probability of takeoff and landing spots was related to the population density in each Warsaw district. Based on official data, the population probability was applied to the system; the UAS do not start randomly across the whole area, but rather according to the data. Improvements allow more simulations to be run in the simulation tool.

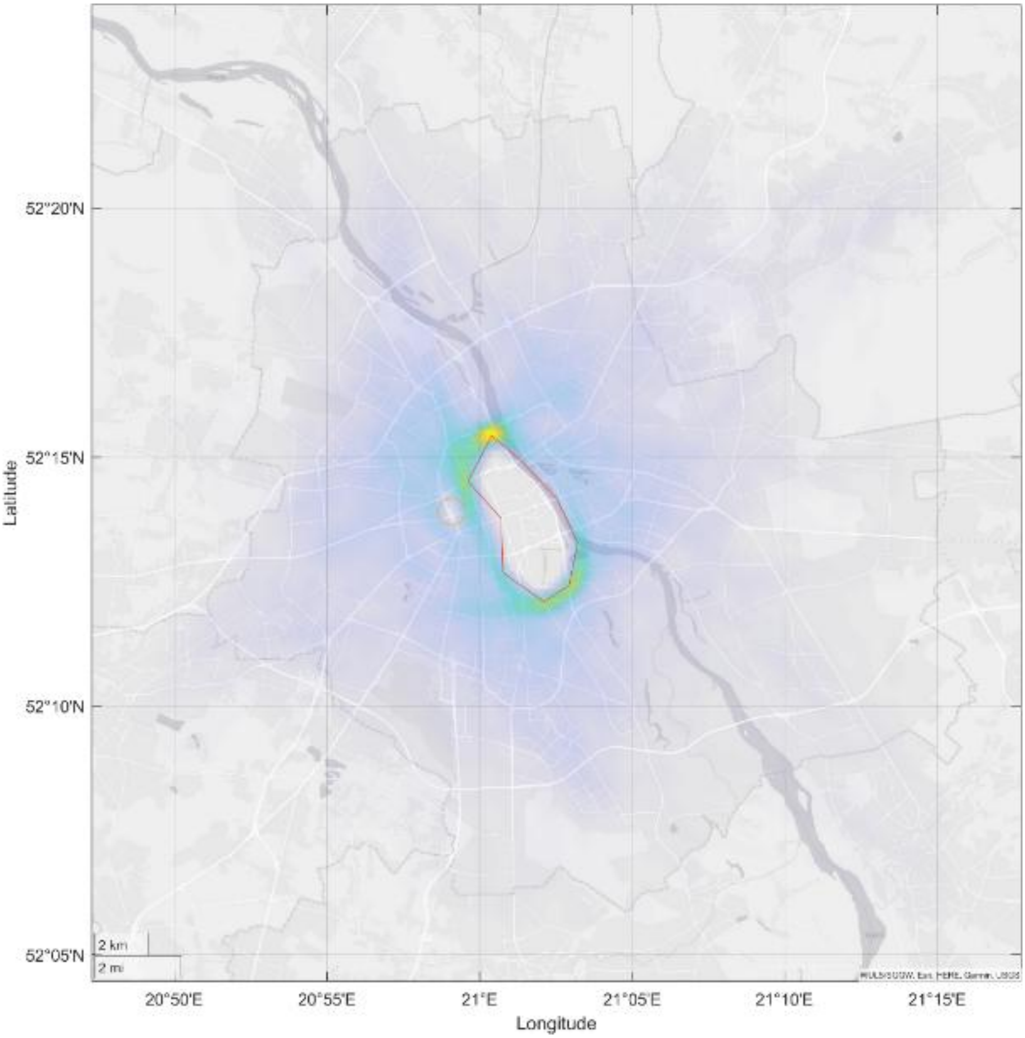

Fig. 13 Heatmap for 3000 UAVs traveling from point to point

8.1. Distinct types of scenarios

Currently, the research is focused on testing a set of Air Traffic Management approaches, specifically sky regulation, to determine how drones should behave in potential trajectory conflicts. The following section presents examples of UAM traffic simulations over Warsaw, Poland, involving 73,167 VTOLs with varying levels of autonomy and diverse route types (e.g., point-to-point taxis, multi-point parcel deliveries, recreational loitering). The number of VTOL used in the simulation was estimated based on statistical data (Kopyt et al., 2025; Główny Urząd Statystyczny, 2023) and on a statistical analysis of delivery volumes for 2023. This figure corresponds to the current number of deliveries (food and packages) using traditional transport methods, such as cars and scooters. It is assumed that these services will soon transition to the air, so the authors adopted this value for the simulation. To make potential conflicts more visible, the VTOLs were enlarged in the simulation. The selected cases are presented below:

- Hubs are defined as points, random VTOLs' altitude distribution,
- Hubs extended, random VTOLs' altitude distribution,
- Hubs extended, dedicated altitude bands for each VTOL family, random altitude distribution,
- Hubs extended, dedicated attitude bands for each VTOL family, controlled altitude distribution,
- Hubs extended; VTOL’s altitude is associated with its course.

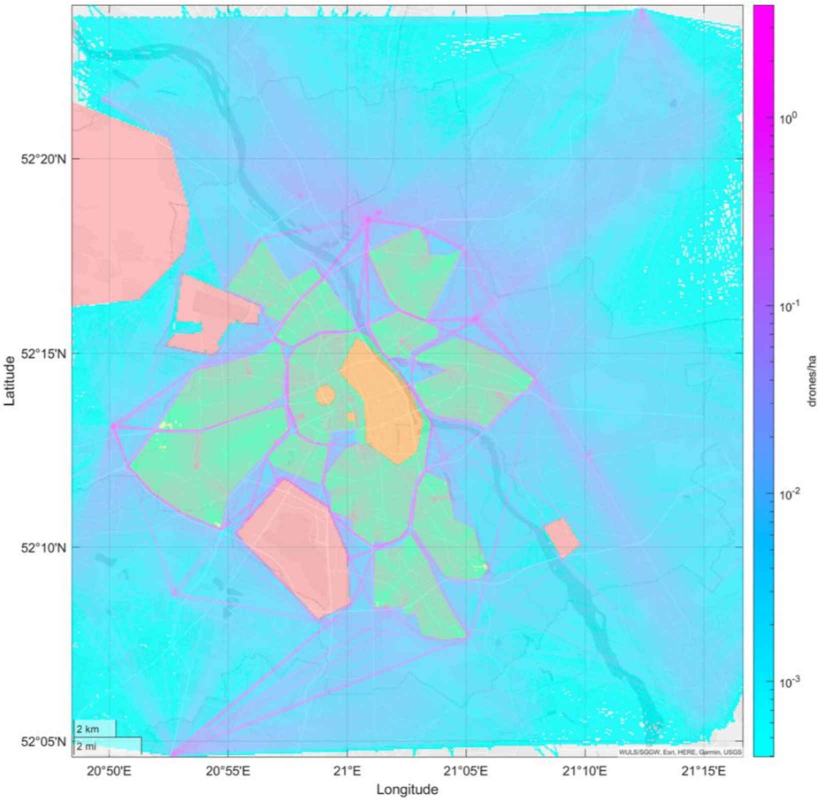

Fig. 14. Heatmap for simulation with various hubs

In Fig. 14, the traffic distribution is presented as a heat map. The more intense color indicates that more VTOLs take the same path within the interval. The red areas are the no-fly zones defined by Kopyt et al. (2024), and the yellow/light green areas are limited-fly zones. VTOL can only fly through the area with takeoff or destination points within the zone. The flight must be performed along the shortest path to minimize the time spent within the zone. Those limited-fly zones were added to the simulation to reduce VTOL traffic over certain city regions, so VTOLs do not fly indiscriminately over Warsaw. Therefore, no-fly zones were deliberately established to avoid densely populated areas (e.g., buildings or public spaces) and to reduce risk. It was assumed that organizing traffic above the streets is preferred for safety reasons (e.g., uncontrolled descent resulting in a VTOL collision with obstacles or the ground). Thus, the implemented zones yield specific VTOL trajectories, enabling VTOLs to avoid densely populated areas. The simulation results showed the importance of altitude division for various UAS, increasing safety while reducing the number of platforms. This optimization cost must be considered in future corridors and airspace capacity calculation plans.

8.2. Vertiports and hubs

The simulation begins by configuring all key parameters, including UAS characteristics and vertiport dimensions (Arnedo, 2024; Kopyt et al., 2024). By default, the vertiport is modeled as a circular area, which can be modified if needed. After setting these parameters, a grid of valid landing positions is generated within the vertiport to determine safe landing zones for UASs. The simulation considers two types of UASs: small ones designed for food deliveries and larger ones for handling bulkier packages. As the simulation progresses, UASs are introduced dynamically, ensuring that the minimum separation distance based on their wingspans is maintained to avoid collisions. Each UAS is assigned a specific service type, and its operational cycle, including takeoff and landing, is simulated to mimic real-world conditions. Throughout the process, the states of all UASs are monitored and visualized to track their performance. The results include the total number of UASs the vertiport can accommodate, the average service rate (UASs per minute), and the peak service rate achieved during the simulation. The simulation allows for the modification of key parameters, such as:

- Vertiport Diameter.
- Percentage of Large UAS.
- Separation as a percentage of wingspan between UASs used to initiate the grid.
- Flight mission durations.
- Percentage of UASs leaving the airspace.
- Time after which UASs permanently leave the airspace.

Small UASs have a wingspan of 2 meters, large UASs have a wingspan of 6 meters, and each UAS is modeled as a perfectly circular circle for simplified 2D analysis. Two mission types — short (30 minutes) and long (60 minutes) — are randomly assigned to UASs, but the simulation is flexible enough to accommodate new or modified mission durations. Parameters also account for UASs departing the vertiport to land elsewhere, ensuring they do not occupy vertiport space after takeoff and enabling simulations of increased UAS activity from ground launches. Conversely, scenarios where UASs appear mid-air, simulating arrivals from other vertiports, are feasible but require more sophisticated modeling to comply with EASA regulations (EUROCONTROL, 2020) by controlling the conditions under which new UASs enter the airspace. The case study allows us to calculate the vertiport's capacity regarding its parameters (Kopyt et al., 2024). Figure 15 presents an example of a circular vertiport with separate zones for various platforms.

8.3. Sound impact

Another principal factor that needs to be verified is the impact of the UAS-generated noise on densely populated areas. Their distinct high-frequency sound, often perceived as more intrusive than traditional urban noise, can lead to increased stress, annoyance, and sleep disturbances, potentially contributing to long-term health issues like elevated blood pressure. Strategies such as designing quieter propulsion systems, establishing operational restrictions (e.g., no-fly zones or curfews), engaging communities in planning, and monitoring noise levels in real time are being implemented to mitigate these effects. This aspect was also a research subject. Like most cities, the Warsaw Area has its sound map developed yearly (Urząd Miasta Stołecznego Warszawy, 2024; World Health Organization, 2011). The sound impact of cars, trains, and planes could be examined on those maps. Having a similar result for future airspace over Warsaw could be beneficial for authorities, as it would help them learn how sound propagation is changing due to UAS traffic management. Currently, the sound model and its propagation are being implemented in the simulation tool, and the equivalent results will be delivered soon for comparison.

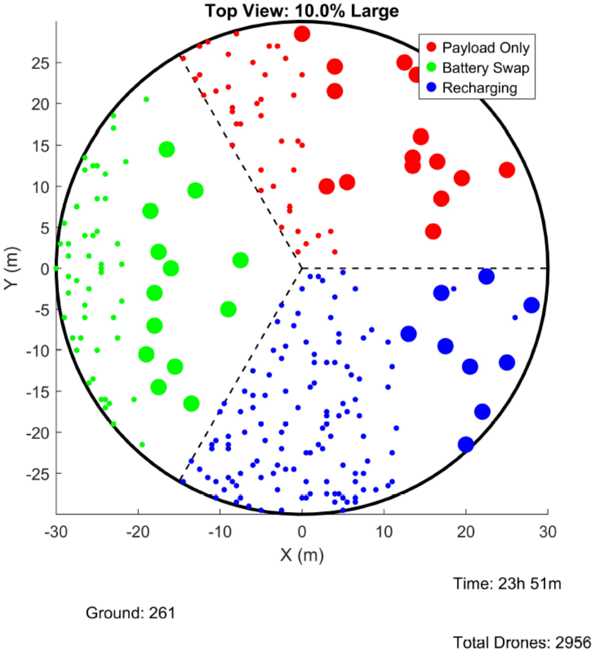

Fig. 15. Vertiport divided into UAV sections

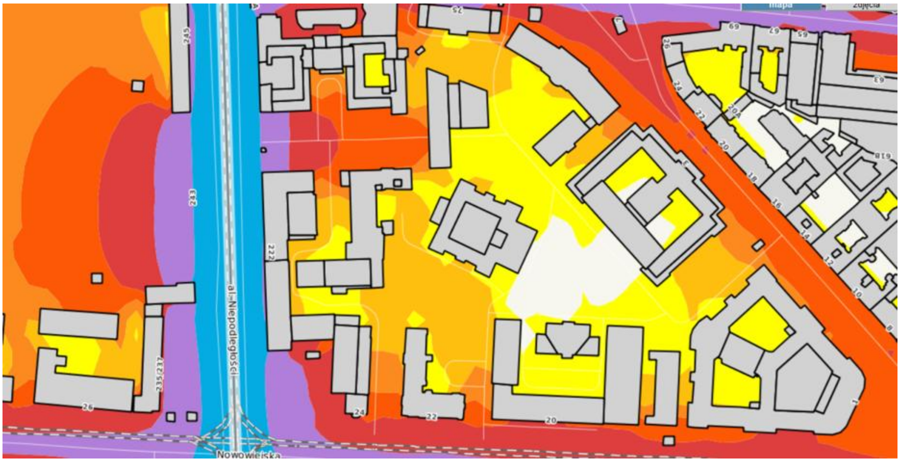

Fig. 16. Acoustic map of part of the Warsaw area

8.4. Simulation validation

Various aspects of the simulation should be validated using data acquired during tests in a real environment. Some elements are relatively easy to implement in the accurate models. The architecture of the simulator was developed in a way that.

9. Conclusions

The rapid development and integration of Unmanned Aircraft Systems and Urban Air Mobility into urban environments present opportunities and challenges. While technological advancements have made UAS operations more feasible, they bring significant safety, regulatory, and operational risks, particularly in densely populated areas. The research identifies various risk categories requiring innovative mitigation strategies, including technical failures, environmental factors, human errors, and security concerns.

Simulation tools developed in this study may be critical in identifying, analyzing, and addressing these risks. By replicating urban airspace scenarios, these tools enable testing potential solutions and ensure the safety and efficiency of UAM operations. Key strategies include implementing layered airspace designs, dedicated corridors, and vertiport hubs to manage traffic effectively. Moreover, considerations such as noise pollution and the integration of outdated and advanced systems into a cohesive airspace framework remain areas of focus. The simulation tool showed the possibility of testing and validating various aspects of UAM. The presented cases are only a few examples that should be modeled and investigated further.

Adopting scalable safety measures from manned aviation and developing UAS-specific regulatory frameworks is essential for fostering a safe and sustainable UAM ecosystem. The findings emphasize the need for collaboration among stakeholders, rapid regulatory adaptation, and continued innovation to meet the growing demand for urban air mobility services. This research contributes significantly to understanding and mitigating the risks associated with UAM, paving the way for its safe integration into urban environments by 2050.

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