Progress in Aerospace Sciences 125 (2021) 100726

Contents lists available at ScienceDirect

Progress in Aerospace Sciences

journal homepage: www.elsevier.com/locate/paerosci

Designing airspace for urban air mobility: A review of concepts and approaches

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ARTICLE INFO

Keywords:
Advanced air mobility
Urban air mobility
Airspace structure
Airspace design
Safety-capacity tradeoff
Public domain

ABSTRACT

The article brings together the academic and industry literature on the design and management of urban airspace. We analyze the proposed airspace concepts, identify their strengths and weaknesses, point to gaps in research, and provide recommendations for a more holistic approach to designing urban airspace. We first identify the structural factors that define the size, capacity, and geometry of urban airspace. These factors are grouped into four categories: safety-related factors, social factors, system factors, and aircraft factors. Second, we review different urban airspace concepts proposed around the world. Third, we assess the airspace concepts based on the identified factors. Most of the reviewed airspace concepts are idealized as abstract networks, with an emphasis on maximizing safety and capacity, and with little regard for factors such as technological complexity, noise, or privacy. Additionally, we find that the airspace structure directly influences the level of safety, efficiency, and capacity of airspace. On the one hand, air vehicles in less structured airspace have more degrees of freedom. They can freely choose their position, altitude, heading, and speed, which increases airspace capacity and reduces flying costs. However, these concepts require high technological capabilities, such as dynamic geofences and advanced sense-and-avoid capabilities, to maintain the required safety levels. On the other hand, airspace concepts with fewer degrees of freedom can accommodate less capable aircraft but require strict operation rules and reduced capacity to ensure safety. Finally, the proposed urban air mobility concepts require extensive ground infrastructures, such as take-off and landing pads and communication, navigation, and surveillance infrastructure. There is a need for a new branch of research that analyzes urban air mobility from the perspective of urban planning, including issues around zoning, air rights, public transportation, real estate development, public acceptance, and access inequalities.

1. Introduction

The idea of Urban Air Mobility (UAM), coupled with the technological development in automation and electricity storage, has spurred growth in the urban aviation industry. The concept of UAM comprises a set of rules, procedures, and technologies that enable air traffic operations of cargo and passengers in the urban environment. UAM is a part of the Advanced Air Mobility (AAM), a joint initiative of the FAA, NASA, and the industry to develop an air transportation system that moves passengers and cargo with new electric (i.e. green) air vehicles in various geographies previously underserved by traditional aviation [1]. Companies worldwide are racing to create urban aircraft prototypes and, in partnership with major aerospace suppliers, certify the technologies for urban flying. This push is putting pressure on cities and government agencies to create rules for using urban airspace, which is not an easy task considering the differences in air vehicle designs and sizes, maneuverability, speed, take-off procedures, automation, surveillance, and communication capabilities. These differences make it difficult for air vehicles to use the airspace safely and efficiently and require a standardized set of flying rules and procedures [2].

Today, unmanned aerial systems (UAS), also known as unmanned air vehicles (UAV), or colloquially, drones, are used in civilian applications such as recreation [3], traffic monitoring [4], disaster monitoring [5], fire detection [6], infrastructure inspection [7], mapping [8], forestry [9], and agriculture [10]. These operations, although numerous, are usually contained within specific geographic regions and still do not

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https://doi.org/10.1016/j.paerosci.2021.100726
Received 28 September 2020; Received in revised form 4 May 2021; Accepted 4 May 2021

pose a substantial risk to the everyday operation of the National Airspace System (NAS). However, proposed urban, suburban, and exurban air traffic is expected to create operational and safety challenges that might significantly impact the NAS.

Proposed operations will most likely be conducted by electric manned and unmanned air vehicles with vertical take-off and landing. Unlike a traditional helicopter, new air vehicles use multiple motors and propellers, electric engines, and lighter materials, which make them cheaper [11], quieter [12], and more efficient [13]. The operations are expected to cover both urban [14,15] and rural [16] regions. The operators will compete for the same limited space, which will push the industry to adopt smaller separation standards [17]. For this reason, several agencies are developing frameworks for managing urban airspace and ensuring safety.

This article aims to analyze the leading proposals for managing urban airspace, find their commonalities, and point to the best practices in airspace design. We seek to identify and analyze structural factors that define the physical structure of urban airspace. By "physical structure of urban airspace," we consider the position and size of airspace elements such as flying trajectories, tubes, corridors, and layers, as well as their associated rules of operations.

2. The need for urban airspace

The inability of the current air traffic management (ATM) system to manage urban airspace is the primary inhibitor of the development of urban air transportation [17]. Several challenges impede the integration of the existing NAS operations and urban operations: 1) higher number of operations, 2) greater density of operations, 3) lower altitudes of operations, and 4) varying performance of different operators and air vehicles [18]. These challenges stretch the capabilities of the current-day air traffic control (ATC) system and indicate the need for significant changes in the current system.

The International Civil Aviation Organization (ICAO) classifies airspace into controlled and uncontrolled airspace, using seven classes (A, B, C, D, E, F, and G), depending on air traffic services provided and flight requirements. Controlled airspace covers Classes A, B, C, D and E, while uncontrolled airspace covers Classes F and G. Each airspace class contains a set of rules indicating exactly how aircraft should fly and in what way ATC must interact with such aircraft. Therefore, ICAO defines each airspace class by the type of flight it services (instrument flight rules (IFR), visual flight rules (VFR)), provided separations (all aircraft, IFR flown aircraft from VFR flown aircraft, no separation), the type of air traffic service (ATC, traffic information about VFR flights, flight information service), speed limitation and altitude, radio communication requirements (continuous two-way, no communication), and ATC clearances [19].

ICAO, as a regulatory body, allows its member states to select airspace classes that fit their requirements. For example, in the United States (Fig. 1), controlled airspace consists of Class A and B airspace (where clearance from air traffic control is mandatory), Class C and D airspace (where two-way ATC communications are mandatory), and Class E airspace (where it is not mandatory to contact the ATC or to obtain clearance to enter). These five classes are further divided by altitudes: Class A, between altitudes 18,000 and 60,000 ft above sea level; Class B, around the nation's busiest airports; Class C, around medium-sized airports; Class D, around smaller airports with air traffic control towers; and Class E, around smaller airports without air traffic control towers. Uncontrolled airspace, defined as Class G, is airspace below 1200 ft, not equipped with any air traffic management service, where pilots rely on visual flight rules (VFR). Class F airspace is not used [20]. Within the classes of airspace, safety is preserved by maintaining a required separation between two aircraft.

Nearly all aircraft operations in controlled airspace today are managed under an airspace-based operation. In airspace-based operation, separation management and trajectory assignment are transferred from one sector to another and handled by controllers within each sector. Airspace-based operations are unlikely to be feasible for the UAM because urban flights are likely to occur in all airspace classes, except Class A [21]. One way of integrating UAM operations with the current system is to increase its capacity and enable ATC to control and manage all the operations within the respected airspace classes [21]. However, this approach requires a drastic overhaul in all aspects of NAS, which is a long and expensive process. It is more likely that UAM operations will be conducted within a separate, newly created airspace with a new set of rules and standards [22].

Such a system will be more complex than the airspace under ICAO's current seven classes of airspace. The difficulty of safely separating air vehicles in dense urban airspace can be reduced through the careful design of additional airspace structures as they can minimize complexity and increase throughput [23]. There is, however, no clear consensus on the type of airspace design that should be implemented. As presented in Section 4, several studies argue that predefined paths and zones are required to handle high traffic densities [1,22,24], while others argue that airspace should be unrestricted and open only to fully autonomous vehicles [25,26]. Most studies start from the proposition that the airspace structure should be optimized for capacity and safety. It is implied that the optimal airspace design is achieved by minimizing

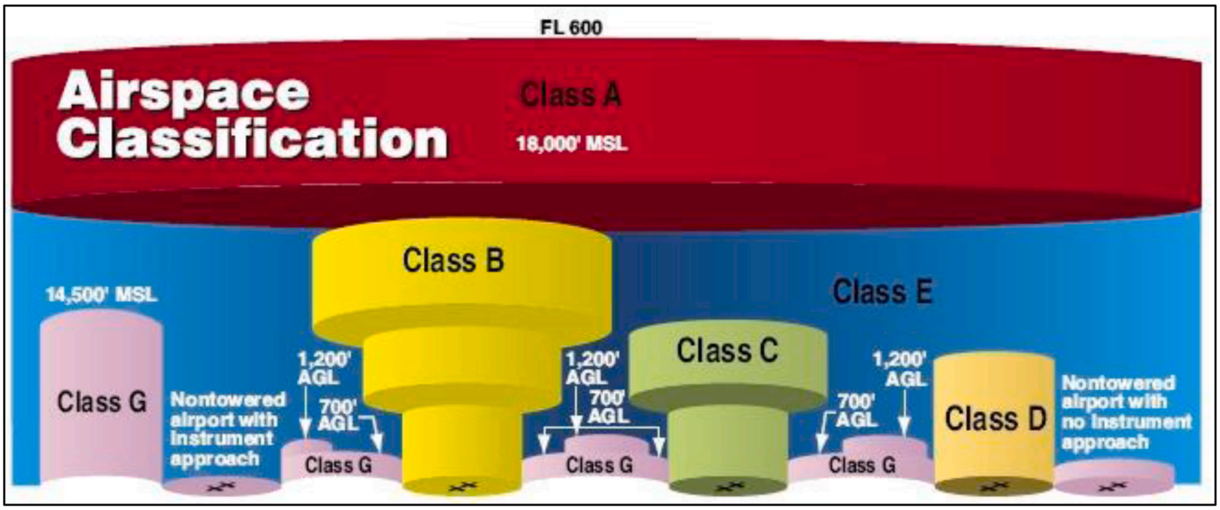


Fig. 1. Airspace classes in the US in accordance with ICAO guidelines [20].

damage (collisions with buildings and other aircraft) while maximizing capacity and throughput. In section 3, we show that safety and capacity are only two of the multiple variables required to design functioning urban airspace.

3. Factors that determine the geometry of urban airspace

We start by conceptualizing how different factors might have a physical effect on urban airspace. Safety considerations (and common sense) require aircraft to avoid collisions with buildings. Buildings are then the "no-fly" zones where flying is, understandably, prohibited. The space outside of the no-fly zone can be used for flying. A factor, in this case, safety, creates a spatial envelope, where everything inside the envelope is a no-fly zone, and everything outside it is open for flying, as presented in Fig. 2a. A step further would be to consider another factor, such as wind gusts, that create unsafe flying space in the proximity of tall buildings. Again, this unsafe space could be visualized by a clearance envelope that defines the outer boundary of the no-fly zone. As we add more factors, the clearance envelope expands, as does the no-fly zone. The resulting airspace fills the space beyond the no-fly zone, which is created by superimposing different clearance boundaries of all the considered factors (Fig. 2).

We use this logic to identify the factors that might restrict movement and influence the position of space open to flying. The factors are divided into four groups: 1) safety-related factors, 2) social factors, 3) operational factors related to the characteristic of the system, and 4) operational factors related to aircraft characteristics.

3.1. Safety-related factors

The Federal Aviation Administration (FAA) has identified the safety of people, vehicles, and property as the most important factor for the successful adoption of urban air mobility [1]. Safety can be improved by reducing risk. Risk is reduced by lessening the severity of the accident or lowering the likelihood that an accident will occur. In the context of airspace, risk cannot be eliminated altogether, but it can be reduced by avoiding objects, areas with turbulences, and areas with weather that can endanger the flight.

3.1.1. Object avoidance

The idea of defining urban airspace as a space free of buildings can be found in Refs. [25,27–29]. Control algorithms identify the obstacle space, while the remaining space is open to flying. Apart from avoiding buildings, aircraft also need to maintain a safe separation from other aircraft and minimize the probability of a mid-air collision [30]. Separation from other objects is the cornerstone of the safety of the traditional Air Traffic Management system. Present-day separation standards are unambiguous: two aircraft cannot be separated by less than 5 nautical miles (NM) en-route and 3 NM in the terminal area using radar wake vortex separation, or 1.5 min using time-based wake turbulence separation [31]. However, these distances are too prohibitive and not suitable for urban air traffic. The concept of separation in UAM is being reimagined since fixed distance spacing is proving to be too rigid for UAM operations. The literature suggests three distinct approaches to defining separation in UAM:

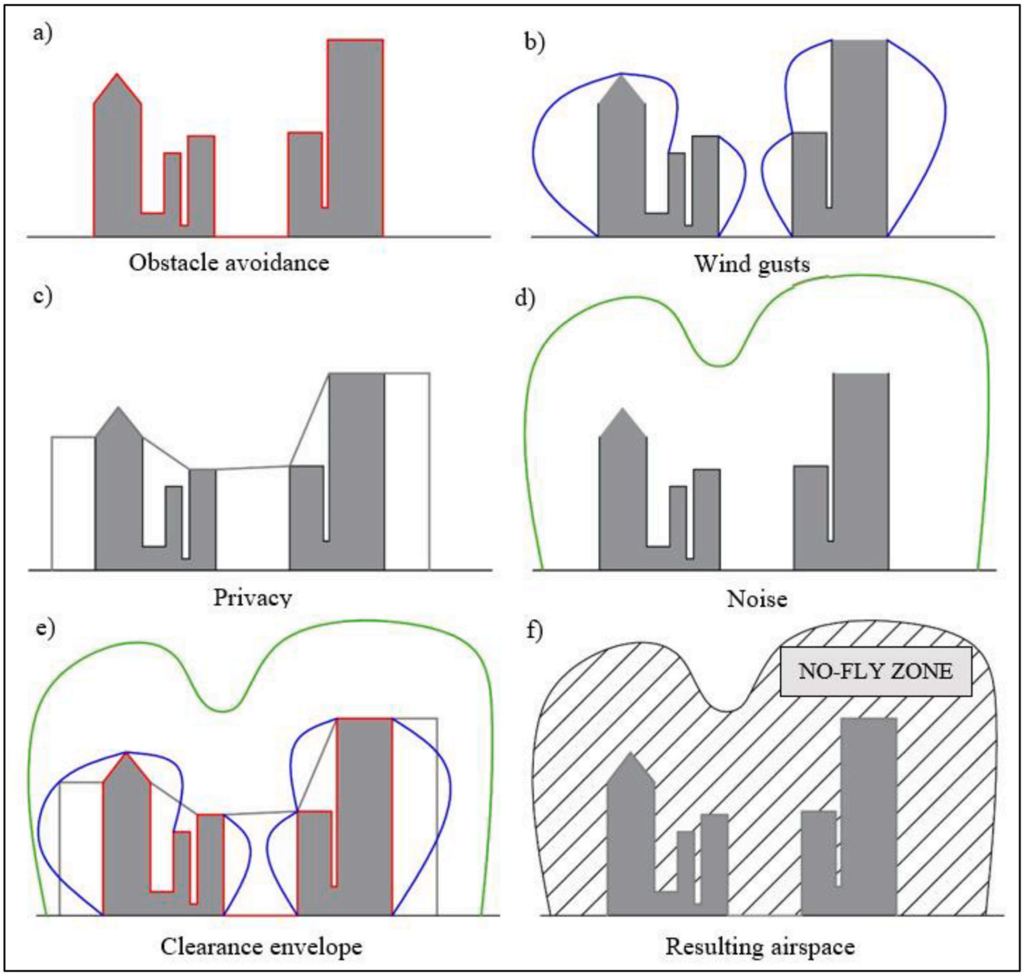


Fig. 2. Clearance depends on the selected variables: (a) obstacle avoidance; (b) wind gusts; (c) privacy; (d) noise; (e) clearance envelope; (f) resulting airspace.

1. Fixed separation - The traditional way of defining separation is to determine a distance all users must maintain. Since 3NM is too large for urban environments, some authors suggest smaller separation standards, such as 0.3NM, or even 0.1NM horizontal and 100 ft vertical separation [32], or 0.36NM horizontal and 450 ft vertical separation [33]. These authors argue that UAM aircraft are much smaller and nimbler, which allows reduced separation. As the systems become more mature, separation standards can change [34].
2. Dynamic separation - The second approach is so-called dynamic separation, a predetermined distance unique for each aircraft based on its class [35,36]. Each aircraft has different technological capabilities and characteristics. High-capability aircraft require smaller separations because they can detect and avoid nearby aircraft effectively, or their systems can predict the trajectories in advance and prevent the incident. In comparison, a poorly equipped aircraft may require larger separation due to limited maneuverability [26, 37]. Therefore, the capacity of airspace depends on the features of the aircraft within that airspace, and it changes as new users enter the airspace [27]. Some authors argue that distance-based separation needs to be abandoned altogether and replaced with time-based thresholds that account for aircraft performance and maneuverability [38].
3. No standardized separation - Currently, flights in Class G airspace do not receive separation guidance from the air traffic controllers [18]. Safety is ensured through the “see and avoid” approach, where the pilot visually maintains a safe distance from other aircraft. A technological equivalent to see-and-avoid is sense-and-avoid [39–41], a mix of hardware and software that enables UAV to detect obstacles and steer away from them. Smaller UAVs do not have the required payload or energy capacity to use radars or LIDARs, and most sense-and-avoid systems rely on cameras to scan their surroundings [37]. Although simple, this approach of avoiding collisions is essentially a greedy algorithm where each UAV looks only to resolve imminent conflict. In a dense traffic environment, uncoordinated “greedy” routing reduces airspace throughput and safety. Although sense and avoid cannot solve navigation and safety problems on its own, it is one of the prerequisites for safe urban flying [40–42].

Sense-and-avoid is not the only method of navigating through a dense urban environment. Strategic, trajectory-based collision avoidance is a necessary complement to the sense-and-avoid procedure, as it further reduces the likelihood of an incident [27–29]. Apart from the sense-and-avoid approach, collision avoidance can be done by strategic collision avoidance algorithms [28,43], avoidance maps [44], and path-planning [36,38,45].

In addition to separation, sense-and-avoid, and collision avoidance procedures, risk can also be reduced by using geofences. Geofence is a virtual airspace boundary that prohibits or restricts access to some or all aircraft to a specific part of airspace [46]. Objects on the ground, such as critical infrastructure (airports, high voltage pylons, hospitals) or protected areas (military bases, recreational areas, nature reserves) are the most likely candidates for geofences. Geofence concepts were proposed by The European Organization for Civil Aviation Equipment (EUROCAE) [47] and The National Aeronautics and Space Administration (NASA) [46], as shown in Fig. 3.

In more general terms, geofences can be static and dynamic. Static geofences can be used to define flying corridors [40] and support obstacle avoidance [49]. Dynamic geofences can be inserted into the airspace at any point as a result of ongoing events, emergency missions, or severe weather. Once the geofences are set, the remaining space is open for flying, and the resulting flying path may or may not consider additional factors such as third-party risk [50].

3.1.2. Wind gusts

According to the National Weather Service, a wind gust is a brief, sudden increase in wind speed. In urban environments, friction between wind and buildings creates eddies that cause sudden changes in wind speed and direction (Fig. 4). Aircraft’s energy consumption can increase due to the additional power required to maintain a steady flight. More importantly, wind gusts can cause loss of control and overcome the aircraft’s ability to maintain position, altitude, and stability [51].

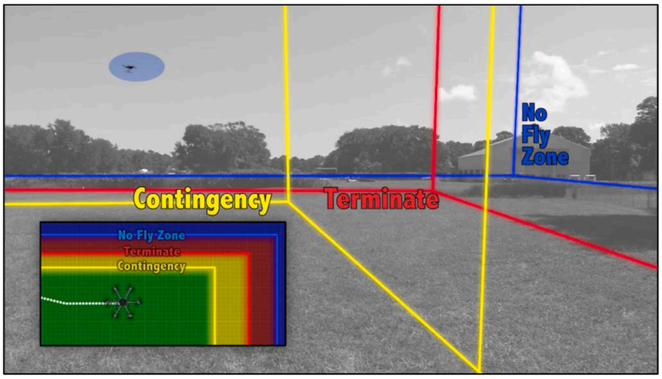


Fig. 3. Geofence “SafeGuard” developed by NASA [48].

Urban canyons and even individual buildings can cause flows with significant levels of turbulence [53–55], which can endanger the aircraft. Even the most advanced trajectory control algorithms cannot guarantee accurate navigation or object avoidance in unpredictable wind environments [56]. One of the reasons is that wind velocity is difficult to predict [57] and wind turbulences can happen in locations where they were not expected [58]. Studies show that wind gusts can affect the altitude [59,60] and position of urban aircraft [61,62] and that in these situations, the autopilot can “overcorrect” and deviate from the planned path [63], which can cause a collision. Some drone manufacturers specify that small air vehicle can tolerate a wind speed up to 10 m/s; however, initial tests by NASA show that small UAS cannot safely fly in wind flow with speeds greater than 5 m/s [64].

Should areas with wind gusts be avoided, or can high-precision algorithms and propellers maintain the control under sudden winds? Early experiments show that control cannot always be maintained [65] and that areas with wind gusts should be avoided [52].

3.1.3. Weather

In aviation, adverse weather conditions regularly cause delays and cancellations of airline flights. In any given year, between 25% and 50% of all aviation accidents are weather-related [61]. However, the severity of weather-related accidents has been steadily reduced due to better nationwide weather prediction and warning systems [66]. Although traditional aviation has benefited from these technological improvements, they are not accurate enough to provide real-time support to urban operations [67]. This gap is a severe constraint to UAM integration, mainly because the weather can disrupt urban air traffic through:

- Reduced mission endurance – Strong winds can decrease battery performance and interfere with the integrity of the flight. Precipitation can increase resistance to the movement of aircraft and cause the malfunction of onboard electronics. Low temperatures can decrease battery life. Icing can build up on airframes or propellers and increase the weight of the drone.
- Reduced safety – Wind and storms can be dangerous to low altitude aircraft due to the lack of space to correct position, heading, or altitude. Changes in barometric pressure can cause miscalibration of altimeter and cause altitude errors. Visibility and low ceiling could reduce the effectiveness of sense-and-avoid avionics.

Weather risks can be reduced by creating dynamic geofences that move with the weather. However, a dynamic geofence is only as good as the weather forecasts supporting it. Accurate forecasts are critical to

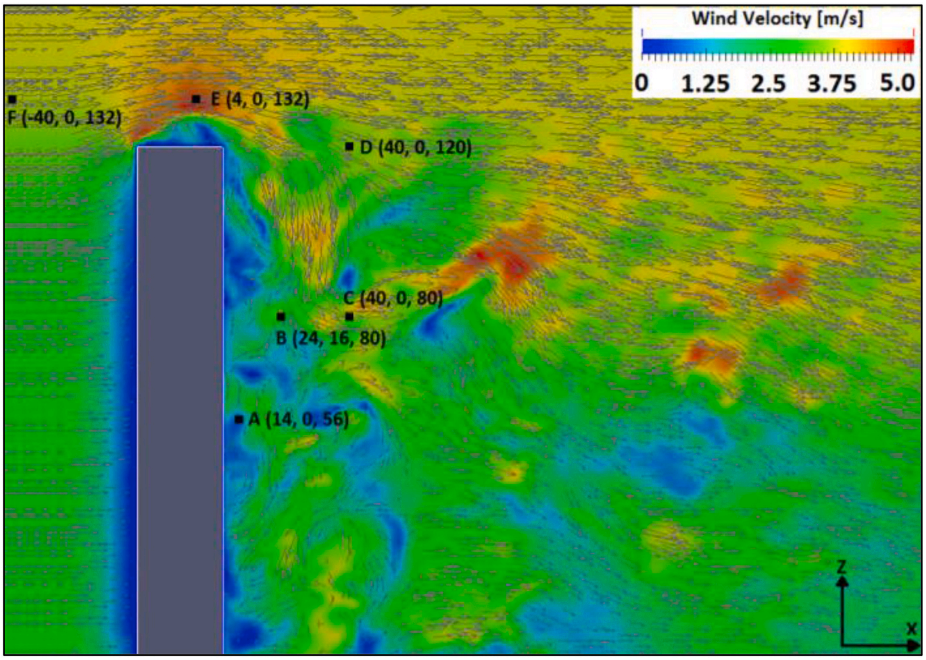


Fig. 4. Wind speed and direction around a building. Source: [52].

UAM safety [68] and route planning [69], especially because weather avoidance procedures decrease flight endurance of en-route aircraft [70].

3.2. Social factors

Local communities have increasingly influenced the operations of airlines and airports in their jurisdictions [71]. Flights occurring at low altitudes may expose individuals to negative externalities such as air pollution, noise, degradation of the living environment or reduction in property values [72]. UAM operations will most likely occur at lower flight levels and closer to residential neighborhoods than traditional airline operations, and thereby increase the likelihood of community opposition to the development of urban airspace. Studies suggest that UAM might be constrained by social factors such as the perception of safety, security, privacy, ownership, liability, regulation [73], noise, visual pollution, air pollution, and equity [74]. The final definition of airspace structures will mostly depend on noise, visual pollution, and privacy concerns.

3.2.1. Noise

Several studies have highlighted noise as the key constraint to the implementation of UAM [15,74–76]. The International Civil Aviation Organization (ICAO) has concluded that UAM noise will cause a significant level of annoyance [77]. Noise can interfere with daily activities and sleep, which causes stress-related symptoms [78]. Sleep disturbance reduces the quality of life and causes health issues [79–81]. Community opposition to noise is already a significant consideration for airports and airlines [82,83]. The FAA imposes noise limits for various types of aircraft, but it is anticipated that stricter standards will be required for urban aviation [84,85]. Adverse effects of noise in a community can be reduced by manufacturing quieter air vehicles or setting up flying routes that reduce noise exposure.

Reducing UAM noise will not be simple [86]. The volume and the frequency of a sound primarily depend on its source, which in the case of drones are motors, propellers, and airframes [87,88]. Although an electric engine in a modern multi-copter has significantly lower engine noise than a helicopter, the propellers create a high-frequency sound that cannot be easily eliminated [89,90]. The initial tests by NASA [91] show that, even at the same decibel levels, drones generate sound that is more annoying to the listeners than the sound generated by a car. Another study by NASA suggests that the listener’s annoyance may increase with the number of propellers [92] since a human ear is sensitive not only to volume but also to the frequency of sound. These results indicate that high-frequency noise produced by drone propellers might generate pushback even if the sound volume (in decibels) is within acceptable limits.

The volume and frequency of sound also depend on the listener’s distance from the source. Propeller sound decreases by about 6 dB with every doubling of distance from the source [87], which means that the level of noise exposure can be controlled by defining flight paths closer or farther away from the residential areas. Rather than relying solely on quieter engines to reduce community noise, operators will need to adjust flying paths to minimize the exposure to sound [93]. The adjustment of flying routes may be made proactively by designing airspace to reduce noise exposure or reactively in response to landowners’ lawsuits and community opposition.

3.2.2. Visual pollution

Visual disturbances in residential neighborhoods are likely to create localized pushback as low-level flights might be visually undesirable [94]. In one of the few articles on the subject [95], the authors conducted a text-mining semantic analysis to investigate a general sentiment toward drones and found that the public will likely be annoyed by small aircraft because they clutter the visual field and create shadows. A survey by Airbus found that 45% of respondents are concerned about visual pollution [96]. The way to combat it would be to create routes that fly over less-populated areas or water. A whitepaper by Uber [15] points out that visual pollution concerns can be addressed via trip route modifications to avoid particularly sensitive vistas or by consolidating traffic to existing transportation corridors such as above highways. Social scientists argue that drones can be viewed as usurpers taking over people’s right to the city and air [97]. In popular literature and media, dystopian urban environments are usually presented as spaces cluttered with small aircraft (Fig. 5), which might influence real-world public sentiment and UAM acceptance.

Fig. 5. Dronepolis: a dystopian view of UAM [98].

3.2.3. Privacy

Issues of privacy are exacerbated in residential and business areas. A successful airspace concept should ensure that air vehicles do not create a sense of intrusion on the human environment [99,100]. In a democracy, a person does not have to justify the desire for privacy, the state must justify its violation. Legal scholars agree that the argument that "no privacy problem exists if a person has nothing to hide" is not valid [101]. Saying you do not care about privacy because you have nothing to hide is to say you do not care about freedom of speech because you have nothing to say [102]. It is to assume that no one has anything to conceal, including political and religious beliefs, immigration status, or health records. In addition to recognizing the importance of privacy, it is important to understand that there are multiple types of privacies that should be safeguarded: privacy of the person, of behavior and action, of communication, of data and image, of thoughts and feelings, location and space, of association [103]. The specific privacy type associated with UAM is difficult to define, given drones' diverse capabilities and applications. For example, aircraft equipped with cameras can capture images that can provide information about people's location, behavior, and activity patterns [103].

The arguments for safeguarding privacy might sound outdated. After all, people relinquished privacy when they bought a smartphone. However, the issue of UAM acceptance is less about the ownership of private data and more about the *perception* of privacy. UAM operations, which occur in low altitude airspace, may accentuate annoyance over the proximity of the flights and the *perceived* privacy loss [104]. And experience from airport development shows just how powerful annoyed citizens can be. The main two factors expected to affect the perception of privacy are the number of flights and their altitude. These factors are nearly entirely dependent on the decisions about the design of airspace.

3.3. Operational factors – system

The scalability of air traffic control is one of the critical constraints for the operation of UAM [17]. The FAA estimates that there are 1.7 million drones in the US at the end of 2020 [105], seven times larger than combined airline and general aviation fleets. Accommodating such traffic requires new and innovative system-wide solutions in air traffic management, communication, navigation, and surveillance.

3.3.1. Air traffic management system

The main challenges in air traffic management are airspace integration, separation, contingency management, capacity, traffic flow management, and scheduling [106]. If aircraft in urban airspace can freely select their routes, speed, and altitude, the air traffic management system needs to be technologically advanced to facilitate that selection.

There are two approaches to thinking about managing urban air traffic. The first, proposed by the FAA and NASA [1,2], argues that the air traffic management system should be centralized and technologically able to accommodate aircraft of all levels of performance. The second approach, promoted mainly by the industry, argues that aircraft should select their preferred routes while maintaining safety with onboard technology, such as sense-and-avoid. It follows that aircraft with inadequate technological capabilities would not be able to enter the airspace. The advantages of one approach over the other depend on, among others, the maturity of the system. NASA proposed stages of the development of UAM, called NASA's UAM Maturity Levels [107], presented in Table 1. In the early stages, when both aircraft and management systems' technological capabilities are limited, it is reasonable to expect limited operations constrained to selected regions [108]. A government aviation agency (such as the FAA in the US) will maintain its regulatory authority, but the operations will not be managed by air traffic control. As technology advances, higher integration between the operator and management system could be achieved.

3.3.2. Communication, navigation, and surveillance

Significant technological improvements are required in all three aspects of the communication, navigation, and surveillance (CNS) system. The existing UAVs mainly rely on simple point-to-point communication over the unlicensed band, which is unreliable, insecure, and can only operate over a very limited range. Technologies currently not used in traditional aviation, such as LTE and 5G-and-beyond cellular services, as well as satellite links will be required to facilitate communication between aircraft and traffic control. However, wireless communication face many challenges, including availability, latency, use-of-power, and security issues. Further developments are needed to enable safe UAM operations. For a detailed review of the emerging communication technologies in UAM, see Refs. [109,110].

The availability and accuracy of GPS can also be a problem. In the urban environment, buildings can block satellites from direct line of site to the GPS receiver, which can cause errors in navigation or completely block the signal. Moreover, atmospheric conditions can cause a variation in the precision of GPS positioning. An experiment [111] measuring a flight path precision of a drone in an urban environment showed that the drone deviated up to 2 m from the expected flight path. However, in a few situations, the drone deviated 5 m or more. Other studies on GPS accuracy found that in city canyons the positioning drift can be over 20 m due to signal blockage [112]. While there are no official FAA standards on the maximum allowable difference between the estimated position and the true position of a drone, some authors argue that the error should not exceed 3 m [113], which indicates that either GPS needs to be improved, or new technologies need to be developed to sustain higher technical capability levels of UAM.

Higher positional accuracy could be achieved by using an image-based navigation system, cooperative navigation, or signals and additional ground infrastructure. For example, a combination of GPS and cellular networks can reduce error down to 15 cm [114], or in some cases, even down to 2 cm [112]. Only experiments and experience will show which level of navigational precision is required for safe UAM. Reducing error from 5 m to 1 m will undoubtedly improve the safety of

Table 1
NASA's UAM maturity levels (UML) [107].

State	UML	Description
Initial	1	Early operation exploration and demonstrations in limited environments.
	2	Low-density and low-complexity commercial operations with assistive automation.
Intermediate	3	Low-density, medium-complexity operations with comprehensive safety assurance automation.
	4	Medium-density operations with collaborative automated systems.
Mature	5	High density and complexity operations with highly-integrated automated networks.
	6	Ubiquitous UAM operations with system-wide automated optimization.

the system. However, even the most precise GPS systems are for naught if the signal is not available. The improvements in accuracy should be followed by improvements in availability.

Traditional radars are inadequate for the surveillance of low-altitude UAM operations. Some operators propose the use of automatic dependent surveillance-broadcast (ADS-B); however, in high-density environments, the ADS-B frequency band will likely be oversaturated [115]. Advanced surveillance systems that overcome ADS-B limitations should be developed [116]. Higher freedom of flight will require more sophisticated CNS technology, and organizations that present new concepts for urban air traffic need to explicitly address the shortcomings of current technologies.

3.3.3. *Capacity*

Government agencies agree that airspace should be able to accommodate all air vehicles, regardless of their capabilities and sizes [1,2,117]. Decisions and projections about capacity will determine the design of airspace. These decisions include the layout of airspace geometries, air traffic control, traffic mix, and separation. The consequences of inadequate capacity are ground delay, airborne delay, increased cost of entering the airspace as well as a possible prioritization of airspace for specific classes. However, capacity is constrained by safety, as well as other factors presented here, and should be determined as one of the many variables in a multivariant optimization.

3.4. *Operational factors – vehicles*

The design of airspace depends on the characteristics of aircraft that use airspace. These aircraft differ in size, speed, maneuverability, autonomy, and CNS capabilities. The resulting airspace will need to reconcile these differences.

3.4.1. *Aircraft type and aircraft mix*

In traditional aviation, the size and maneuverability of an aircraft are important factors in airport planning. They set the dimensional requirements of airport infrastructure and flying procedures. Similar to traditional aviation, the design of landing and take-off pads and airspace structures depends on the type of aircraft. Characteristics such as weight, wingspan, speed, range, materials, maximum altitude, and endurance provide a basis for classification and identification [8,118]. As the new air vehicles emerge, it is crucial to identify their differences and similarities with the existing aircraft and to determine how the mix of these vehicles impacts the constraints of airspace. As the industry of aircraft manufacturing advances, airspace needs to be flexible to accommodate and integrate new types of vehicles.

3.4.2. *Level of autonomy*

Automation could overcome some of the deficiencies of the air traffic management system or CNS system and could increase the robustness of the system against interference. As the level of autonomy increases, it is expected that urban airspace will be able to accommodate an increasing number of aircraft. However, there are multiple definitions of levels of autonomy. For example, DroneII [119] proposed six levels (Table 2), The North Atlantic Treaty Organization (NATO) [120] defined four levels (Table 3), The National Institute of Standards and Technology [121,122] proposed a framework of five levels (Table 4), and Air Force Research Laboratory [123] proposed ten levels of autonomy (Table 5).

The first step in creating a single UAM airspace would be to adopt a single classification for aircraft autonomy and, based on it, create procedures and rules of flying. Despite many classifications and levels, the common features that define the level of autonomy are control, perception (situational awareness), decision-making, and communication/cooperation [123]. These features could be a start in defining a single classification system. There will likely be a transitional period where the airspace will accept both manned and unmanned aircraft of different levels of autonomy. To accommodate this traffic, the controllers or the designers of the system will need to separate their operations.

Table 2
Levels of autonomy by DroneII [119].

LEVEL	DESCRIPTION	CONTROL	USE
0	No automation	Pilot in full control.	Recreational drones
1	Pilot assistance	Pilot in control, drone controls at least one vital function.	Inspection and maintenance, photography, monitoring
2	Partial Automation	Pilot is responsible, drone controls heading, altitude and speed.	Mapping, surveying, spaying and seeding in agriculture
3	Conditional Automation	Pilot is a backup; drone performs all functions given a set of conditions.	Mapping, surveying
4	High Automation	Drone in control under a fixed set of rules. Human may not be needed.	Photography, filming, delivery
5	Full Automation	Drone in control, no expectation of human intervention.	Passenger transport

Table 3
Levels of autonomy by NATO [120].

LEVEL	DESCRIPTION	CAPABILITY
1	Remotely controlled system	Actions depend on operator input.
2	Automated system	Actions depend on fixed built-in functionality (preprogrammed).
3	Autonomous non-learning system	Actions depend upon a fixed set of rules.
4	Autonomous learning system with the ability to modify rules	Actions depend upon a set of rules that can be modified for continuously improving goal directed reactions.

Table 4
Levels of autonomy by National Institute of Standards and Technology [121,122].

LEVEL	DESCRIPTION	CAPABILITY
1	Remote control	No tactical behavior.
2	High-level human input	Low-level tactical behavior in simple environment.
3	Mid-level human input	Multi-functional missions in moderate environment.
4	Low-level human input	Collaborative, high-complexity missions in difficult environment.
5	No human input	All missions in extreme environments.

3.4.3. *Energy efficiency*

The endurance of batteries imposes severe constraints on the operational time of an electric UAM aircraft. Several solutions have been proposed, including a more efficient rotor configuration [124], the use of novel lightweight materials [125], and dumping exhausted battery modules out of the aircraft in flight [126]. A most realistic option, however, is to select trajectories that minimize energy consumption [12,127–129]. In Ref. [127], the authors proposed an energy-efficient path-planning strategy for a hexacopter. The authors found that the best results are achieved by flying at lower altitudes and by flying a shallower descent. Another study found that cruise efficiency drops with an increase in cruise altitude [12].

What is evident is that the operators and individual aircraft will look to optimize their paths to minimize energy consumption. Given the findings that energy efficiency drops with cruise altitude, the goal of minimizing energy consumption conflicts with other goals of reducing noise exposure or increasing capacity. A common theme emerges: optimizing for a single factor might provide a sub-optimal system

Table 5
Levels of autonomy by Air Force Research Laboratory [123].

LEVEL	DESCRIPTION	CAPABILITY	SEPARATION
0	Remotely piloted vehicle	Altitude sensing.	Several miles
1	Execute preplanned missions	Flight control and navigation sensing. All actions are preplanned.	Several miles
2	Pre-loaded alternative plans	Automatic trajectory execution. External commands.	Several miles
3	Limited response to real time events	Automatic trajectory execution. Ability to compensate for limited failures.	Several miles
4	Robust response to anticipated events	Automatic trajectory execution. Ability to compensate for most failures.	Hundreds of yards
5	Event adaptive vehicle	On-board derived vehicle trajectory. Ability to compensate for most failures. Ability to predict onset of failures.	<100 yards
6	Real time multi-vehicle coordination	Detection of other aircraft in local airspace. On-board collision avoidance.	<100 yards
7	Real time multi-vehicle cooperation	Continuous flight path evaluation. Trajectory optimization. On-board collision avoidance. Off-board data sources for deconfliction & tracking	Not required
8	Multi-vehicle mission performance optimization	Detection & tracking of other air vehicles within local airspace. Operation in controlled airspace without external control. On-board deconfliction & collision avoidance.	Not required
9	Multi-vehicle tactical performance optimization	Detection & tracking of other air vehicles within airspace. Full decision making capability on-board. Full independence.	Not required

solution. Therefore, the design of airspace structures and routes should carefully consider energy consumption in the context of efficiency, but also other critical factors, such as safety and community acceptance.

The list of the studies presented in this chapter can be found in Table 6, grouped by the relevant factors. These factors are used to assess the airspace concepts presented in Section 4.

Table 6
List of relevant studies grouped by the factors that impact airspace design.

Group	Factor		Studies
Safety	Object avoidance	Separation	[32–36,130]
		Sense-and-avoid	[39–41]
		Aircraft avoidance	[30,35,43]
		Static Geofence	[25,34,45,131–135]
		Dynamic Geofence	[25,34,38,132,135]
	Wind gusts		[51,52,59,60]
	Weather		[67–70]
Social	Noise		[15,74–76,84–86]
	Privacy		[25,103,104,137]
	Visual pollution		[94–97]
System	Air Traffic Management		[21,106–108]
	Communication, Navigation, and Surveillance		[109–114]
	Capacity		[1,18,22,117]
Vehicle	Aircraft type		[8,118]
	Autonomy		[119–123]
	Energy efficiency		[12,127–129]

4. Review of urban airspace design concepts

This section assesses the most important government- and industry-led urban airspace design initiatives around the world, and then summarizes and evaluates the most relevant factors, which are classified into four groups: safety, social, system, and vehicle factors.

4.1. Government-led initiatives

4.1.1. FAA-NASA UAS traffic management (UTM)

The UAS Traffic Management (UTM) [1,138,139] is a project by NASA that aims to enable small, unmanned drones to access low-altitude airspace beyond visual line of sight (BVLOS) with minimal impact to the existing aviation system (Fig. 6). The low-altitude airspace is defined as airspace below 400 ft, where the UTM operations are segregated from other airspace users. The development of UTM is sequenced in four Technical Capability Levels (Table 7), with the simple, remote, and rural operations in the first phase, and dense urban operations in the fourth phase [139]. In the initial stages, the existing technology and separation procedures will be used to facilitate operations, while the improvement of technologies such as detect-and-avoid, in-flight separation service, and contingency procedures will enable future phases.

Although UTM is envisioned as a low-altitude region in uncontrolled (Class G airspace), NASA does plan to integrate UAS operations in other airspace classes [140]. In the controlled airspace, UAS are segregated from controlled air traffic by creating transition tunnels, or blocks of airspace reserved for UAS operations. Alternatively, UAS operations can be integrated into the controlled air traffic flows where they will behave the same as traditional aviation [140].

The operators (drone pilots) are responsible for submitting a flight plan and for maintaining separation from other aircraft. The plan contains information about the airspace volume, times, and locations of the operation. While UTM provides advisories, weather information, and other observations, the operator is responsible for the planning and execution of the safe flight, identification of unexpected operational conditions, or hazards that may affect their operation. The stage-four UTM will provide authentication, geofencing, capacity management, airspace corridors, weather integration, trajectory management, contingency management, and the dynamic adjustments of the system. The FAA will maintain the link between UTM and NAS and create real-time airspace constraints for UAS Operators [140].

The existing technologies used currently for NAS and in the initial phases of UTM for surveillance and navigation are ADS-B and GPS. Although the initial tests showed that these technologies could be used for UTM, experiments by NASA show that ADS-B can be used for surveillance only in a limited scope, at very low power, low traffic, and short distances. At higher traffic densities, the use of ADS-B will adversely affect manned aviation surveillance [141]. Despite these limitations, the goal for initial UTM implementation is to minimize development time by utilizing existing technologies [142].

In the initial phases, UTM will not provide much airspace structure, as aircraft will fly on user-selected pre-approved routes. While the UTM project does raise concerns about social factors, the selection of routes is currently not constrained by social factors.

4.1.2. FAA urban air mobility (UAM) concept of operations

The FAA forecasts increased demand for alternative modes of air transportation enabled by the progress in electric aircraft technology and vertical take-off and landing capabilities. New vehicles can be incorporated into airspace by creating new airspace structures. Fig. 7 illustrates the FAA's approach to the relationship between UAM, UTM, and ATM operations within different airspace classes.

Under the FAA's proposal, UAM operations are conducted in UAM Corridors without ATC separation services. The corridors are the mechanism of separation between UAM and other operations. Within the corridors, separation is maintained by UAM operators, which in the

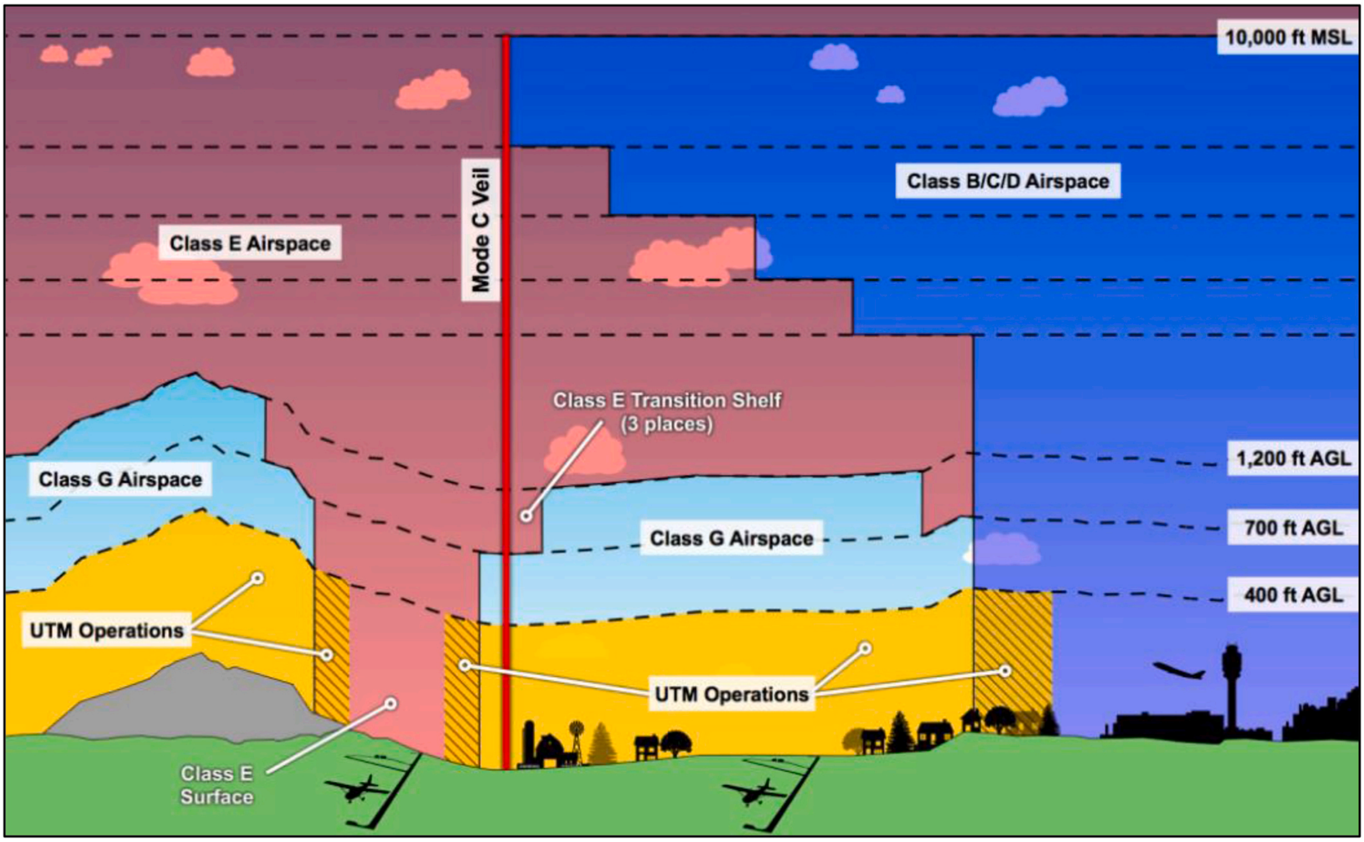


Fig. 6. NASA's UTM system would integrate UAS operations in the airspace above buildings and below traditional aviation operations [139].

Table 7
NASA's Technical Capability Levels [139].

Technical Capability Levels (TLC)				
	TCL 1	TCL 2	TCL 3	TCL 4
Population	Remote	Sparse	Moderate	Dense
Traffic density	Low	Low	Moderate	High
Application	Rural	Industrial	Suburban	Urban
Other	Notification based operation	Tracking procedures	V2V communication	Large-scale contingency management

initial phases of UAM operation, includes pilot on board. Each corridor will have performance requirements (such as maneuverability or sense-and-avoid capabilities) to ensure more efficient operations. Different corridors may have different requirements. Initially, the corridors will connect two UAM aerodromes to support point-to-point operations. In the later stages, the FAA expects the development of more complex and efficient networks that move away from point-to-point operations.

The FAA posits that corridor design criteria should include 1) Minimal impact on the existing NAS operations, 2) Public interest considerations, such as noise, safety, and security, and 3) Customer needs. Within the corridor, additional structure - "tracks" may exist. The "tracks" enable additional separation of aircraft with different technological capabilities (Fig. 8).

Centralized air traffic management services provide weather, terrain, and obstacle data. UAM operators are also responsible for constantly monitoring weather and winds prior to and throughout the flight. If the performance of aircraft is inadequate to maintain safety in the forecasted weather, the flight should be postponed.

4.1.3. NASA UAS traffic flow control (UTFC) in urban areas

In another concept proposed by NASA [22], the urban airspace is divided into multiple layers (Fig. 9). Each layer contains an airspace structure located above a street, which creates multi-level networks between densely located tall buildings (Fig. 10). Three types of airspace structures are considered: sky-lane, sky-tube, and sky-corridor. Each structure provides a different number of degrees of freedom. Sky-lanes are the most restrictive in terms of altitude, heading, speed, and position, whereas sky-corridor allows the most freedom. The UAS traffic flow control (UTFC) controls density and throughput, supervises directional flows of traffic, provides traffic information, identifies unauthorized flights, and sends safety advisories.

The structures are designed to assure the level of safety while minimizing investments in infrastructure and technology. More structure provides more predictable operations and thus requires less technical support. Additionally, with more structure, it is easier to segregate aircraft based on their capabilities, which increases safety and reduces the number of potential conflicts. Finally, more structure provides robustness to system failure and scalability [22].

The same study [22] tested different structures, and the results show that more structure (sky-lanes) provides a safer and simpler environment. However, more complexity reduces capacity and increases delays. The corridors provide less structure which increases capacity but also increases the probability of loss of separation. The comparison of these structures is presented in Table 8.

In this concept, each vehicle is responsible for maintaining separation and avoiding collision within the lane or while changing lanes, turning, or exiting the lane. The authors do not include considerations about social factors, or the technologies needed for the concept to work.

4.1.4. MITRE

MITRE proposed a concept of augmented Visual Flight Rules

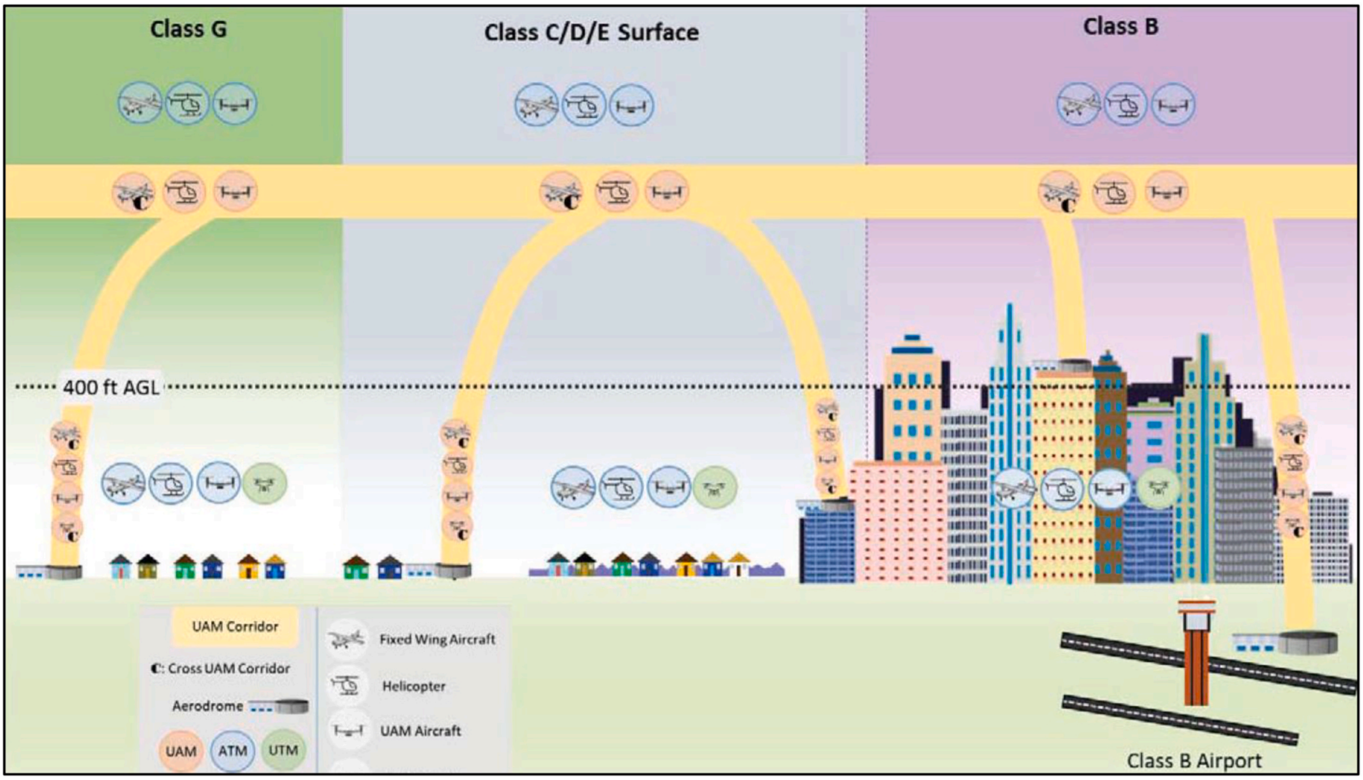


Fig. 7. UAM, UTM and ATM Operating Environments [1].

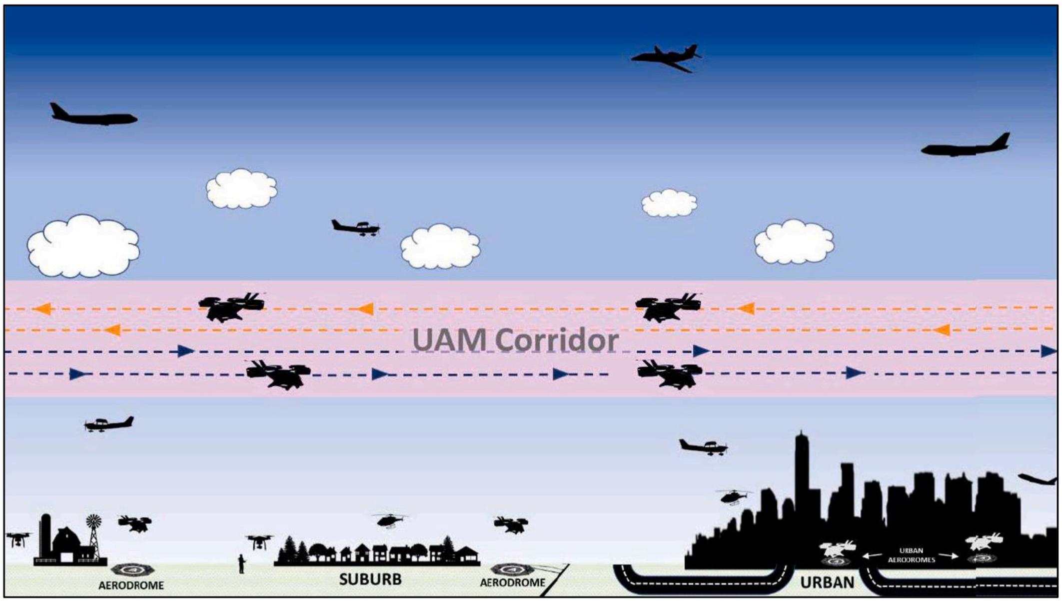


Fig. 8. FAA's UAM Corridors with tracks [1].

operations [143], which enables UAM aircraft to operate in Class G airspace under the existing Visual Flight Rules by using detect-and-avoid capabilities. If the aircraft needs to enter controlled airspace, the Dynamic Delegated Corridors are created. The Dynamic Corridor allows UAM aircraft to fly in busy airspace by defining specific tunnels in NAS and segregating traffic (Fig. 11).

Aircraft will need to be equipped and supported by a wide variety of decision support tools, as the onboard technology will be responsible for maintaining separation and conducting avoidance maneuvers. Additionally, these tools will provide information such as traffic conditions, corridor position and heading, weather advisories, and airspace flight rules. The air traffic management system and architecture will be similar to UTM, with more stringent safety standards.

The priority will be given to aircraft with better technology, such as advanced detect-and-avoid, noise reduction capabilities, navigation precision technology, and vehicle-to-vehicle (V2V) communication technology. More capable aircraft will be able to fly the most efficient preferred routes. The hope is that under this approach, the operators will have an incentive to improve capabilities which would increase airspace capacity and safety. However, the impacts of mixed-equipage operations

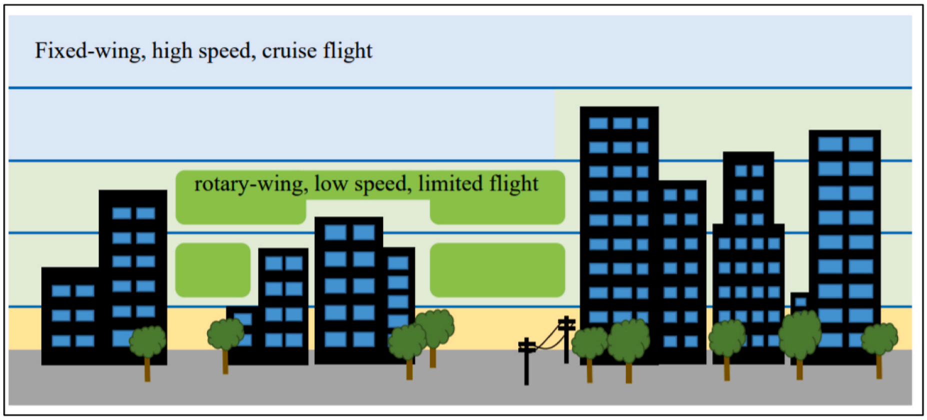


Fig. 9. NASA UAS traffic flow control: Vertical layers of the airspace in urban areas.

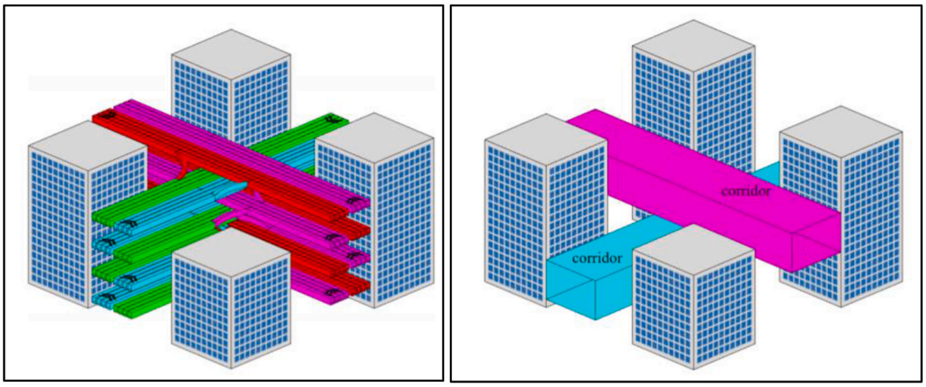


Fig. 10. NASA UAS traffic flow control: Composition of airspace structures: sky-lanes (left) and corridors (right) [22].

Table 8
Comparison of airspace structures in UTFC [22].

Structure	Advantage	Disadvantage
Sky-lane	Reduces traffic complexity, similar to roads on the ground.	Increases delay; Vulnerable to a wind gust; Requires traffic control signals, low capacity.
Sky-tube	Simple, flexible flight.	Requires traffic flow control.
Corridor	Flexible flight, high capacity.	Requires rules for separation assurance and collision avoidance.

on the system should be carefully investigated and understood.

4.1.5. *SESAR U-SPACE*

U-space is a project initiated by the European Commission to allow drones to operate in low-level airspace, at an altitude of up to 150 m [144]. U-space provides a framework to support routine drone operations and creates rules for interactions with manned aviation. Initially, flights will be allowed to operate only in small parts of reserved airspace. However, as technology improves, the operations will spread to other parts of airspace in four stages:

- The first stage provides basic services such as identity (ID) registration and static geofencing to identify drones and inform operators about restricted areas. The majority of operations will happen in low-density regions. However, some visual line of sight (VLOS) operations in the urban environment are allowed.
- The second stage connects drones to the ATC and manned aviation. Where appropriate, the existing infrastructure will be used, but new technologies, such as 5G, and mix of 5G and ADS-B, will also be implemented. The range of VLOS operations in uncontrolled and controlled airspace will be increased. Operations will be approved automatically, and some beyond the visual line of sight (BVLOS) will be allowed.
- The third stage introduces operations in high-density and high-complexity areas. Detect-and-avoid, as well as reliable means of communication, will enable an increase of operations in all environments. Interactions with ATM/ATC and manned aviation will become routine. New operations, such as urban air mobility, are expected to occur.
- The fourth stage fully integrates unmanned with ATM/ATC and manned aviation by leveraging high levels of automation.

In addition to stages, airspace is partitioned in X, Y, and Z airspace (Fig. 12). Airspace X is low-risk airspace with few basic requirements from the operator. The pilot remains responsible for collision avoidance, and only visual-line-of-sight operations are allowed. In Airspace Y, an approved flight plan is needed, the pilot needs to be trained for Y operations, and BVLOS operations are allowed. Airspace Z also requires a pre-approved flight plan, provides centralized capacity management and coordination between aircraft.

Under U-Space rules, social acceptance indicators such as noise, privacy, and visual impact must be considered. For example, under U-Space rules, the aircraft will be issued noise certificates that attest compliance with noise regulation. However, the airspace is not designed in a way that can address these issues.

4.1.6. *DLR U-SPACE*

The concept proposed by The German Aerospace Center - Deutsches Zentrum für Luft-und Raumfahrt (DLR) [146] integrates new airspace

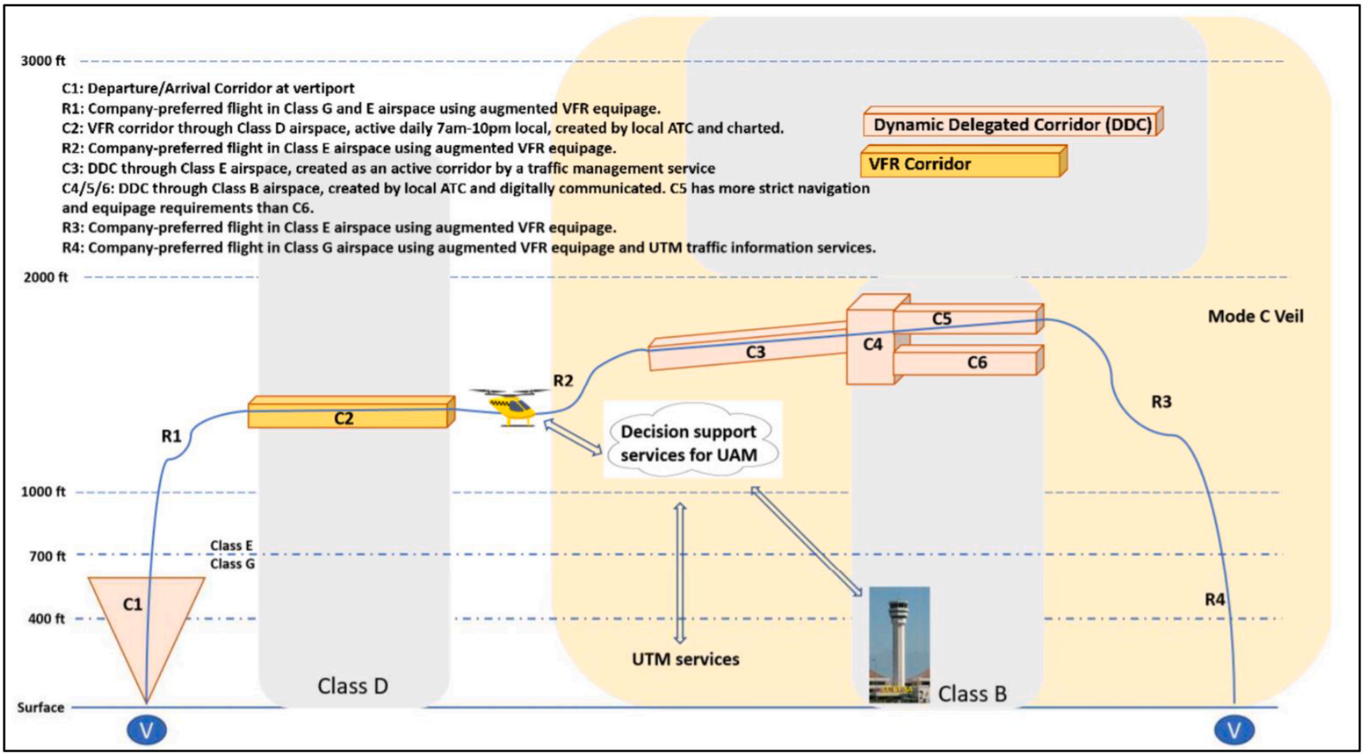


Fig. 11. Airspace integration concept by MITRE [143].

users, such as UAS and air taxis into uncontrolled airspace (Class G). The airspace is segmented into regions ("cells") for users of similar characteristics. Characteristics such as aircraft level of autonomy and equipage, availability of U-space traffic control, and occurrence of VFR-traffic are considered, and airspace is segmented so that vehicles of similar characteristics are flying in the same cell. Within a cell, each aircraft is modeled by an ellipsoid based on its performance parameters, such as automation, navigation, communication, and surveillance capabilities (Fig. 13). The lower the capabilities, the larger the safety ellipsoid around the aircraft. As a result, a cell capacity might be reached with only a few air vehicles with a large ellipsoid, or by more aircraft with smaller ellipsoids. Vehicle operators must maintain the separation between two air vehicles. The air traffic management system creates geofences, which can be static, such as terrain and ground obstacles and permanent no-fly zones, or dynamic, such as temporary closure of airspace due to weather or special event. While the U-Space concept does not explicitly mention wind gusts, it does leave the possibility to create a dynamic geofence in the case of severe weather events, such as heavy winds or rains.

The role of the traffic management system is to segment the airspace, set up the geofences, and approve flight paths within predefined time slots in a first-come-first-serve fashion. On the tactical level, ATC monitors position, altitude, and heading of aircraft and sends traffic, geofence, or weather advisories to aircraft. The surveillance is achieved by ADS-B and through the LTE network. Communication to the aircraft could be conducted through LTE, Open Glider Network, or very high frequency (VHF) data link, depending on the aircraft's capabilities and equipage. A special segment of airspace is dedicated to VFR flights with limited communication abilities.

From the user perspective, the advantage of the proposed concept is that it opens the airspace equally for aircraft with low and high technical capabilities and provides safety by segregating them. This approach minimizes complexity, but it also reduces the capacity of overall airspace since some cells might be underutilized. At low density, air vehicles have a lot of freedom in terms of route selection, but at high densities, they are required to follow predefined trajectories. The management system monitors the airspace requirements and the planned aircraft missions and updates the segments accordingly over time.

The concept of cells does not explicitly consider social factors, such as noise, or privacy, as social factors do not explicitly constrain the position or size of the cell. This issue could be solved by creating a geofence.

4.1.7. METROPOLIS

The authors of the project Metropolis [24,147] proposed four different types of urban airspace for unmanned aerial vehicles (UAVs) and personal air vehicles (PAV): full mix, layers, zones, and tubes. The minimum cruise altitude for all four concepts is 300 ft above ground and 100 ft (UAVs)/500 ft (PAVs) above the highest building. Flying between buildings is prohibited due to noise and privacy concerns. The maximum altitude is 6500 ft to prevent mixing with traditional aviation.

Safety is achieved by maintaining minimum separation and equipping aircraft with sense-and-avoid capabilities. The minimum separation corresponds to a 1-min spacing, which for PAVs equals 250 m. Vertical separation is proposed to be 50 m. Aircraft are autonomous, and human pilots may only be needed in emergency situations. Additionally, aircraft are equipped with ADS-B, which reports location to surrounding aircraft. The operational factors, such as capacity and efficiency, depending on the type of airspace, are:

- Full Mix (free flight) – All air vehicles share the airspace and move without barriers. Air Traffic Control does not require flight plans; it only manages the capacity of the airspace and sets up the geofences, while tactical collision avoidance tasks are delegated to each aircraft. The difficulty in resolving conflicts is the highest in the Full Mix concept since aircraft have four degrees of freedom: speed, altitude, and X and Y coordinates. On the other hand, this freedom reduces distances traveled by aircraft, thus reducing associated trip costs. The path planning algorithm determines the optimal trajectory and executes it. If a conflict arises, priority is given to the aircraft with poorer maneuverability, and cruise is prioritized over climb or descent.

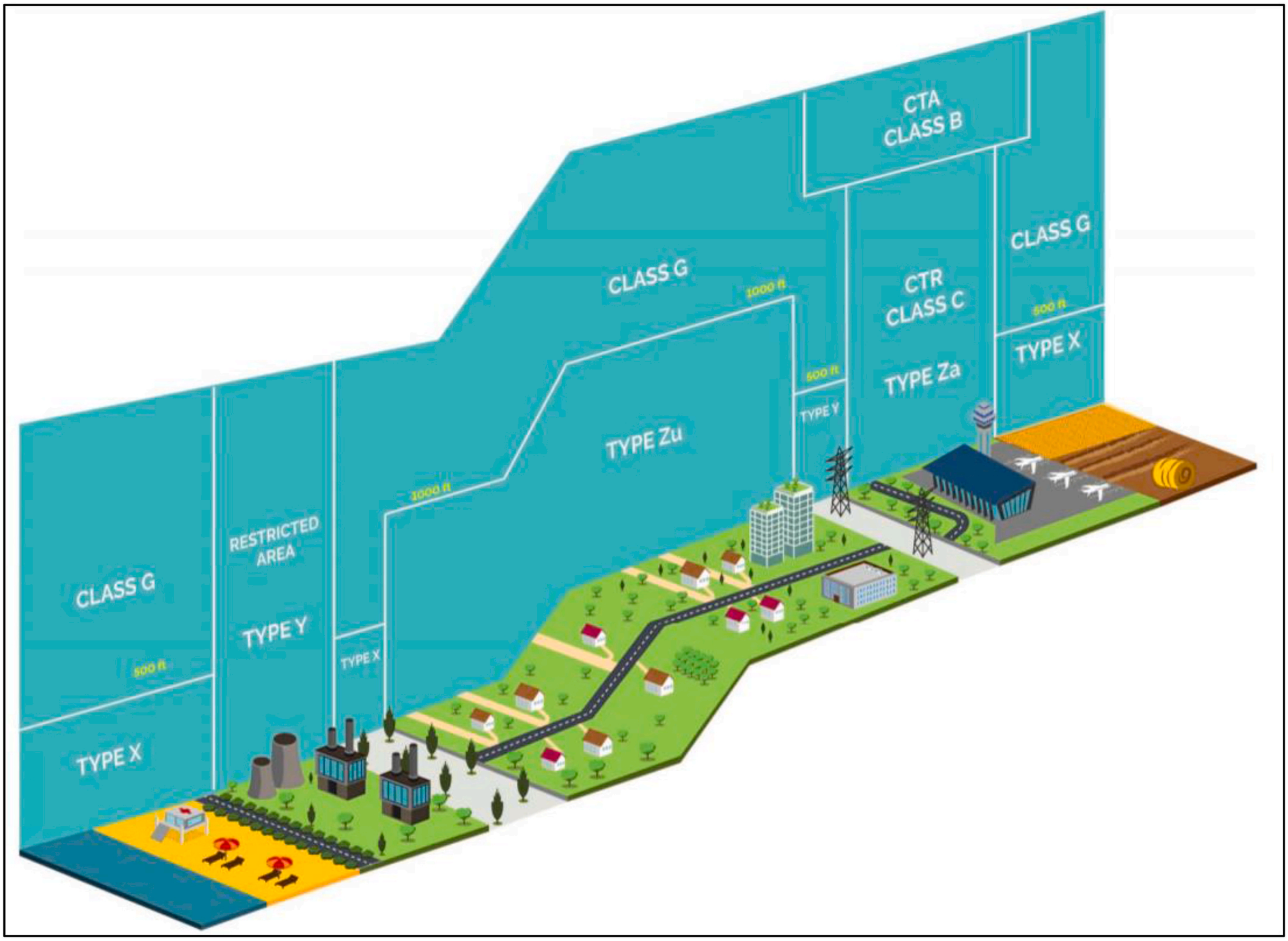


Fig. 12. SESAR's U-Space airspace concept [145]. X – low risk, Y – medium risk, Z – highest risk.

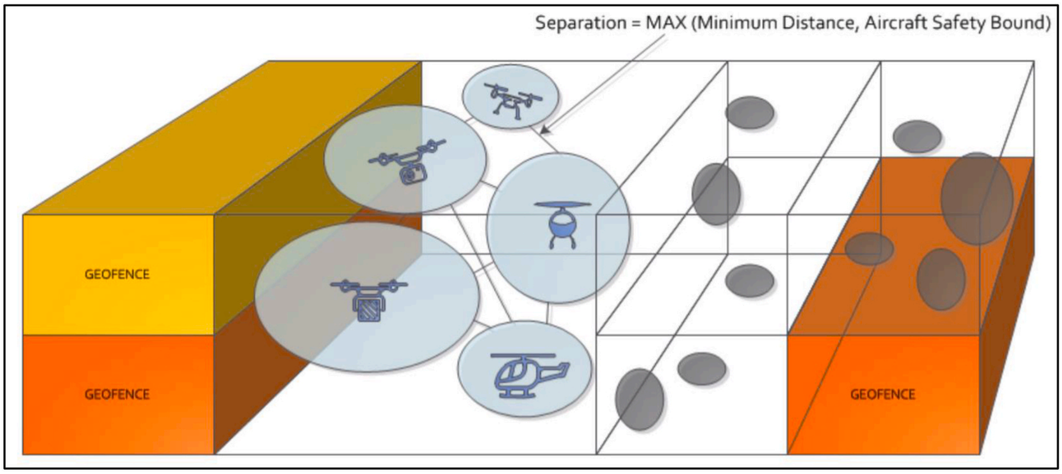


Fig. 13. DLR's airspace concept with cells [146]. The lower aircraft performance – the larger the ellipsoid.

- Layers – Airspace is divided into layers where every altitude band corresponds to a heading range (Fig. 14). Layered airspace aims to facilitate separation and increase safety. The airspace is portioned into the feeder layer, UAV layer, and PAV layer. The feeder layer is the lowest layer, and it is used for climbs and descents. Above it is a layer reserved for small unmanned drones, followed by a separation layer and a PAV level layer system (see Fig. 15).

The altitude thresholds will depend on the height of the buildings in the city. Since PAVs have to accelerate to a certain speed to enter the PAV layer, take-off procedures will not completely be vertical. These

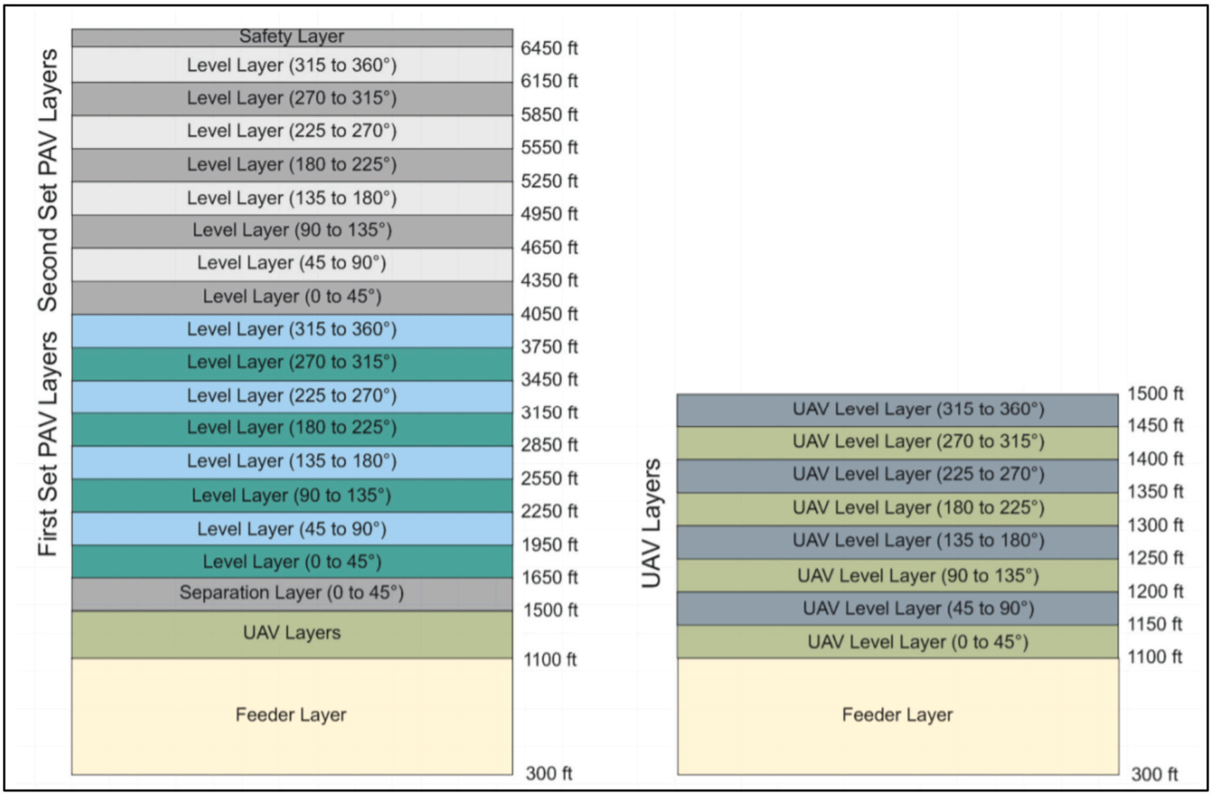


Fig. 14. Flight levels in layered airspace [24].

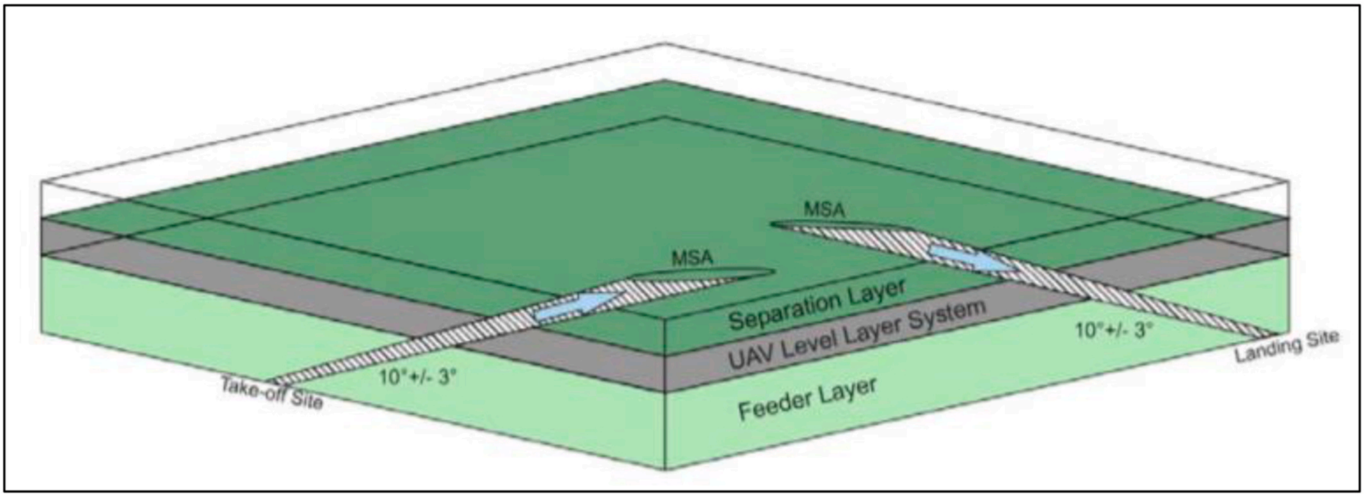


Fig. 15. Take-off and landing cones for Personal Air Vehicles in layered airspace [24].

"cones" are implemented only to pass the UAV layer system safely. It represents a protected zone that is prohibited for UAVs. ATC is in charge of collecting flight plans and creating cones.

- Zones – Airspace is partitioned into zones for different types of vehicles, based on their characteristics, such as speed, maneuverability, level of autonomy, as well as global directions to aid separation between vehicles. Two types of structures can be discerned: circular and radial zones (see Fig. 16). The circular zones are used similarly to ring roads, while the radial zones serve as connections between concentric zones. There is no vertical segmentation. Instead, altitude is selected flexibly, based on the planned flight distance between origin and destination.
- Tubes provide a fixed route structure presented in Fig. 17. Aircraft can only follow the tubes and maintain an equal speed as the other aircraft in the airspace, which offers the advantage of channeling traffic in a safely separated manner. By creating multiple layers of tubes, it is possible to segregate aircraft based on their speed, heading, and size. This increases the throughput and safety of the system. Short flights utilize a dense grid at the lower levels, while longer flights benefit from long straight tubes in the upper layers of the topology, allowing them to travel longer distances at higher speeds.

The study also created simulations and compared the performance of different airspace topologies. The summary is presented in Table 9.

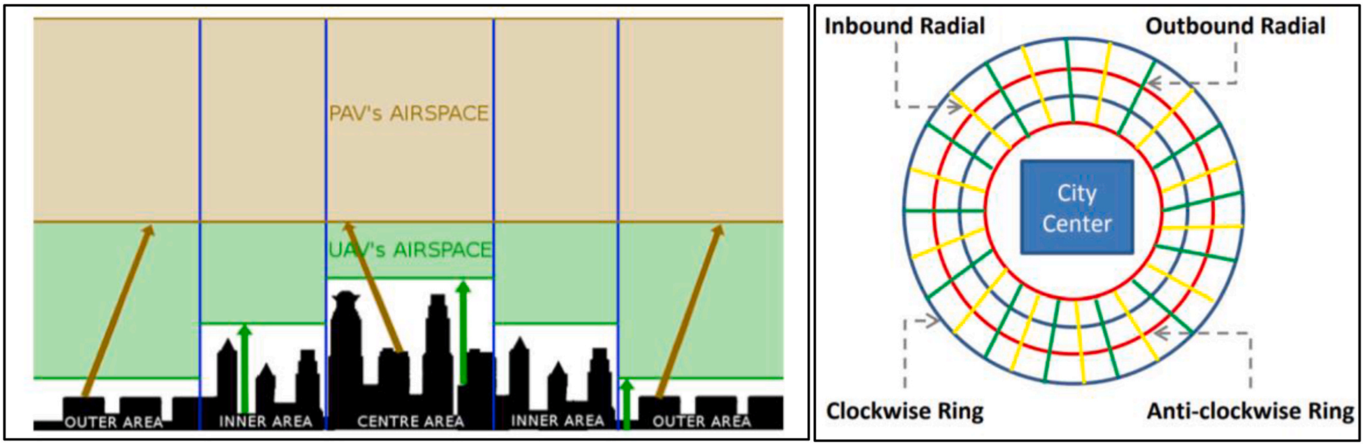


Fig. 16. Zones: vertical (left) and top-down (right) view [24].

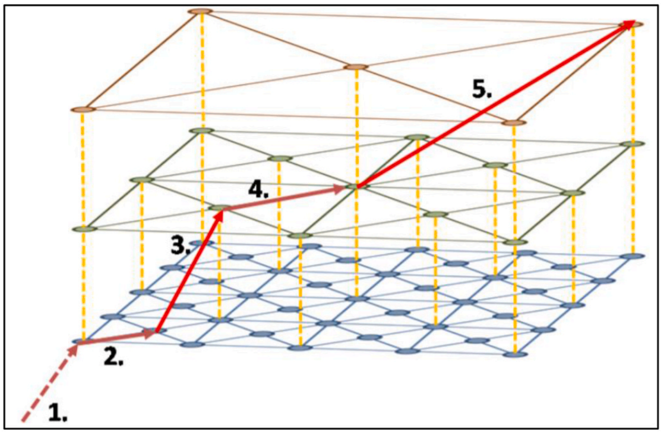


Fig. 17. An air vehicle taking-off and climbing to the appropriate tube [24].

Based on the results of the simulations, the study found that Free flight increases robustness by distributing conflict resolution tasks, increases flight efficiency with direct routing, and reduces the probability of conflict. However, there are some concerns over the uncertainties of aircraft positions and their impact on safety. In terms of the number of UAV-PAV conflicts, the best performing structure is Layers, while Tubes yield the highest number and severity of conflicts. The tube creates the highest delays and the longest flights, concluded that the best structure in terms of safety versus capacity is the layered airspace [24]. Additionally, the study concluded that pre-planning and prevention of conflict routes are difficult to perform and that at least some airspace structure is needed to provide separation. A trade-off to structure is capacity, as more structure reduces capacity.

4.1.8. ONERA's low-level Remotely Piloted Aircraft System (RPAS) traffic management system (LLRTM)

French research agency ONERA proposed a Low-level Remotely Piloted Aircraft System (RPAS) Traffic Management System (LLRTM) [148] to monitor piloted drone traffic, manage it in uncontrolled airspace below 500 ft, coordinate it with ATC in controlled airspace, and provide ground-based detect-and-avoid functions. The service is based on the network of ground receivers and onboard ID and tracking devices. The resulting system performs traffic detection and conflict resolution [149]. The main goal of LLRTM is to reduce the risk of collision between two drones, as well as collisions between drones and traditional aircraft.

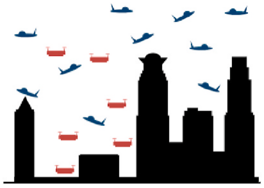
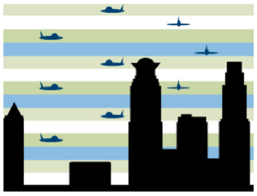
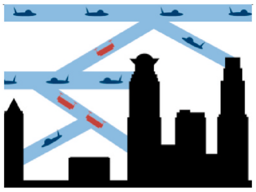
The airspace is segmented in vertical layers separated by buffer zones. The heights of layers are defined by the aircraft cylinders. A cylinder is a 500 feet wide horizontal and 200 feet wide vertical region around the aircraft used for maintaining separation, as shown in Fig. 18.

All aircraft must have electronic identification and tracking technology. Although ADS-B is commonly used by commercial aviation, its operating frequency does not have a sufficient capacity to be used by drones. Instead, the authors propose FLARM (Flight Alarm) transceivers, which broadcast the ID, position, altitude, heading, and speed every second. The next stages of the development of this concept will include 4D trajectories, automation, and the best-equipped/best-served approach.

4.1.9. Singapore Nanyang Technological University's UTM concept

The Nanyang Technological University from Singapore proposed a concept of managing urban air operations [150] by defining two-way traffic lanes that are horizontally and vertically separated (Fig. 19). The lanes are placed so that they avoid areas with dense populations to

Table 9
Comparison of airspace structures by ranked characteristics 1-best, 4-worst.

	Full Mix	Layers	Zones	Tubes
				
Safety	2	1	3	4
Third party risk	2	1	3	4
Capacity	1	2	3	4
Efficiency	1	2	3	4
Noise	2	1	4	3

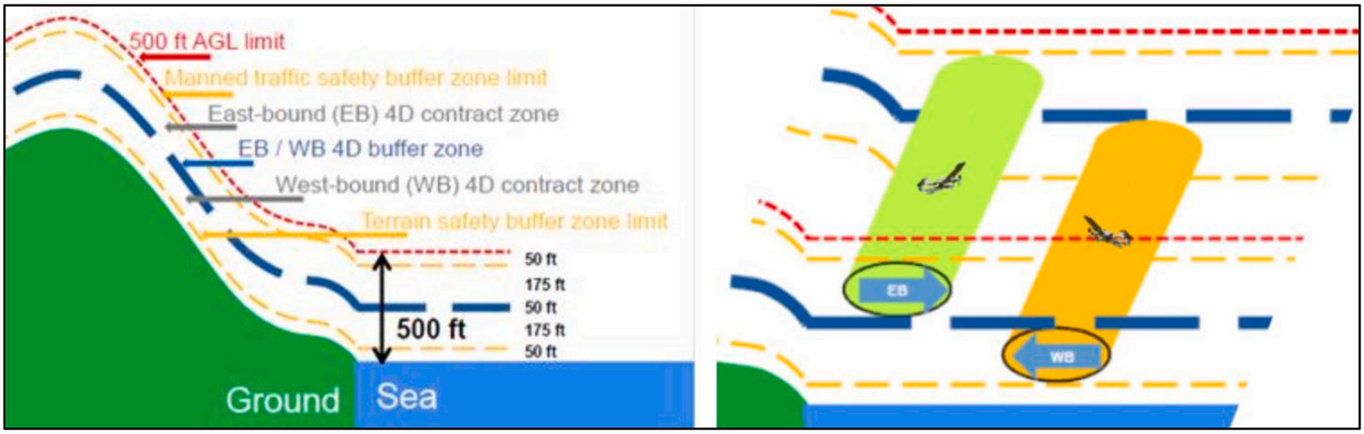


Fig. 18. Separation guidance under LLRTM proposal [148].

minimize risk. In the initial phases of the airspace development, the lanes are positioned above ground infrastructure - railways and roads. The operations are restricted based on time, such as non-peak hours. Certain rooftops will be designated for take-off and landing, while the air in the vicinity of these rooftops is reserved for the climb and descend.

Additionally, airspace is divided into zones, as presented in Fig. 20: no flying zone (NFZ), business zone (BZ), and residential zone (RZ). The goal of zones is to create constrained airspace where a single UAS control station manages flights within the zone. The authors envision travel and delivery operations from one rooftop within the zone to another within the same zone. Flying to another zone is possible, but the control needs to be transferred to another air traffic control, similar to the airspace-based operations in today's airspace.

Within a zone, aircraft can also use the predetermined flight tubes to simplify the complexity of managing the traffic and create a more predictable environment. Every aircraft is equipped with advanced detect-and-avoid technology. The technological requirements for aircraft in this airspace include detect-and-avoid capabilities, vehicle-to-vehicle and vehicle-to-ground communication links, GPS localization, and remote piloting.

The authors argue that social factors, such as privacy, should not be limiting factors, but should be included in the broader assessment of costs and benefits of the technology. If the benefits of the technology outweigh the privacy and noise concerns, the operations should be allowed [150].

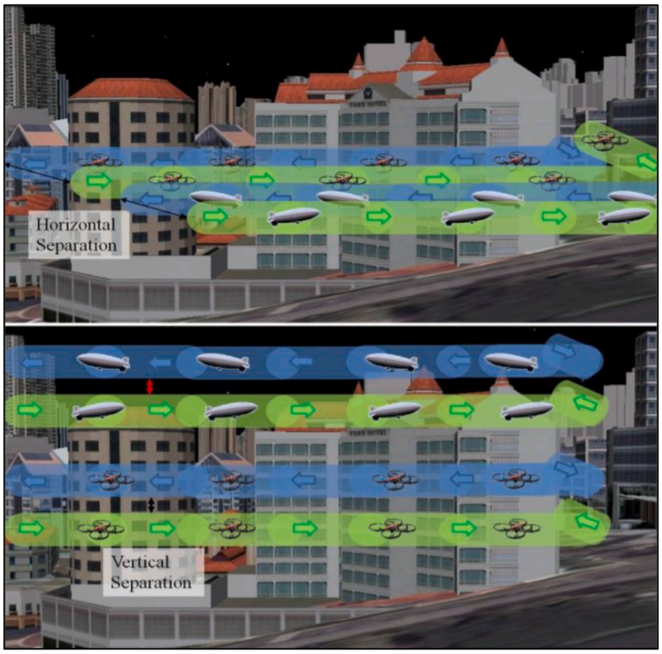


Fig. 19. Horizontally and vertically separated flight lanes in Singapore [150].

4.1.10. *China's civil UAS Aviation Operation Management System (UOMS)*

UAS Aviation Operation Management System (UOMS) [151] is an air traffic management system that enables drone operations in low-level airspace. UOMS provides static geofencing, dynamic geofencing, flight plan approval, traffic capacity and flow management, and flight surveillance and warning system. UOMS segregates aircraft into different flight levels based on their characteristics (Fig. 21).

In China, general aviation has its own management system, called General Aviation Flight Service (GAFS). It is intended that both UOMS and GAFS operate in the same area. UAS flights and general aviation are not segregated, and UOMS and GAFS share all information.

All drones in UOMS airspace are connected to the cellular network. Tests on communication networks show that the 4G network provides coverage below 300 m, and 5G network can support flights up to heights of 1000 m. The precision of location reporting is enhanced by using communication networks since GPS has reliability issues [151].

4.1.11. *JAXA UAS traffic management*

Japan Aerospace Exploration Agency (JAXA) proposed a concept of the UAS traffic management (UTM) system for traffic management of UAS operations [152]. UTM collects flight plans of all manned and unmanned flights, sets geofences, and provides information on traffic, weather, and geofenced areas. Individual traffic management service providers coordinate with central airspace management service, coordinate with it, and ensure the safety of operations by separating drones in their control from drones of other providers (Fig. 22).

The development of UTM is sequenced in four stages, starting from the remotely piloted VLOS operations in the first stage, to the automated BVLOS operations in urban areas. In-flight traffic management functions are transmitted using a mobile communication network (LTE) over the air [153].

4.2. *Industry-led initiatives*

4.2.1. *Amazon*

In a proposal by Amazon [154] airspace below 500 feet is segregated into layers (Fig. 23). Four layers are suggested:

- Low-Speed, Localized Traffic - area below 200 feet is reserved for applications such as recreation, surveying, inspection, surveillance,

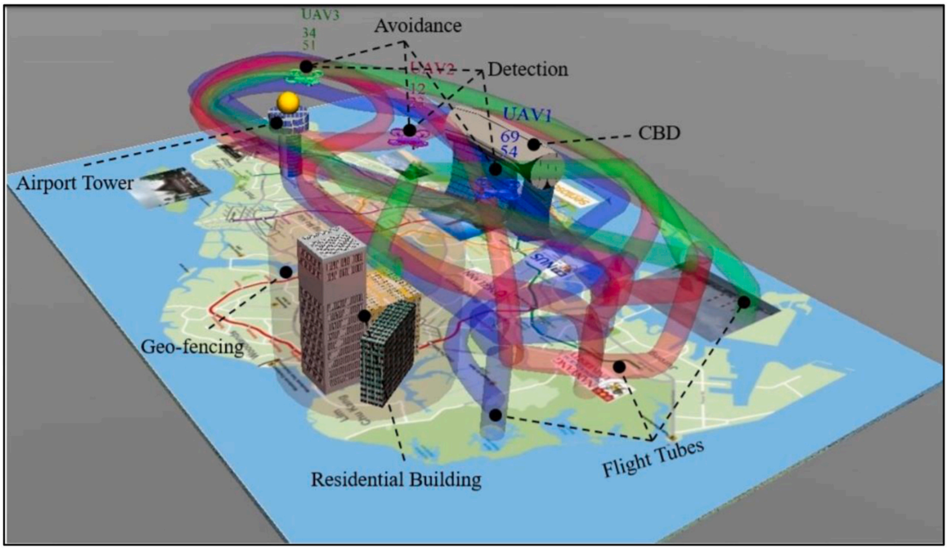


Fig. 20. Airspace in Singapore [150].

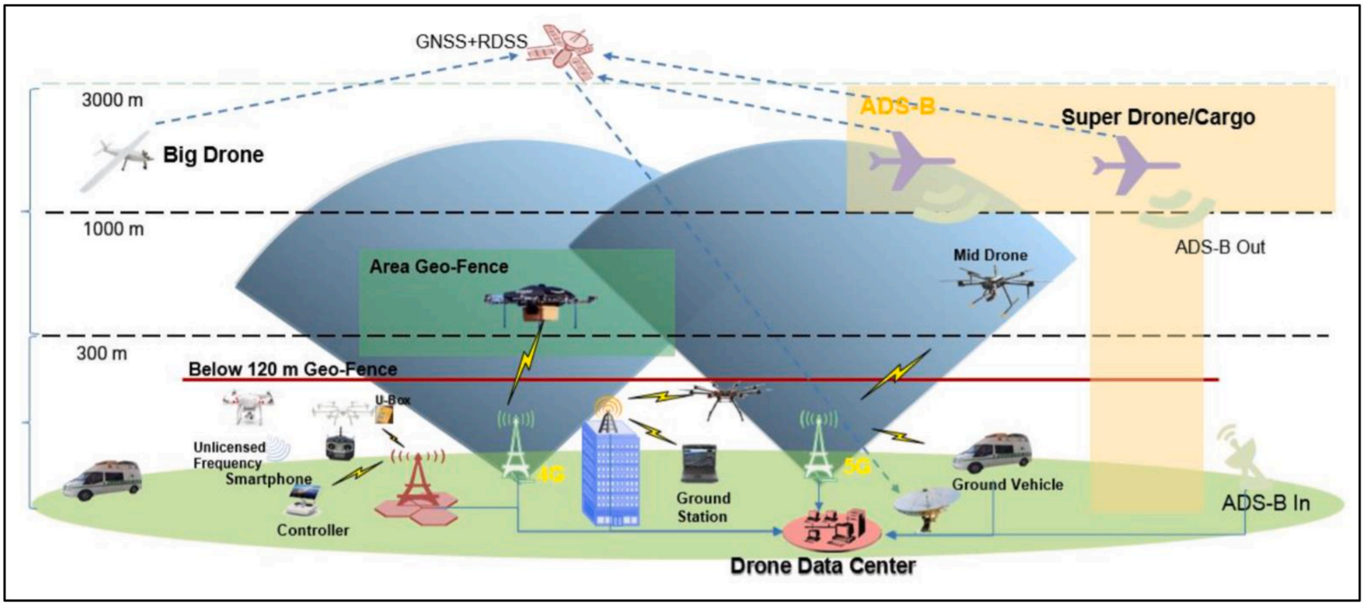


Fig. 21. UOMS in China [151].

and videography, as well as low-tech aircraft without detect-and-avoid technology.

- High-speed transit - includes levels between 200 and 400 feet, and is reserved for well-equipped autonomous aircraft vehicles that operate beyond the line of sight. Technological capabilities required for this layer include detect-and-avoid capabilities, vehicle-to-vehicle (V2V) communication, and collision avoidance.
- No Fly Zone - is the area between 400 and 500 feet, and,
- Predefined Low-Risk Locations - area established by aviation authorities.

The vehicle would be able to access different layers of airspace based on equipage and capabilities. Operators with a lesser-equipped vehicle may fly safely in a remote area. However, the only aircraft with sophisticated technology will be able to operate in an urban or dense environment. The equipage levels and access are presented in Table 10.

A central management entity controls off-line coordination and performs auditing; however, the majority of traffic management is performed by operators in a federated fashion. Those operators would coordinate by following established protocols, using vehicle-to-vehicle, vehicle-to-operator, and operator-to-operator communication. This approach will entail a distributed network comprised of local/regional air operations centers and remote vehicle operators. This new system is essential given the highly automated nature of future UAS.

Highly equipped UAS will be capable of navigation, merging and sequencing, communication, maintaining safe self-separation, collision avoidance, and deconfliction in congested airspace without operator assistance. Collision avoidance must be achieved with both collaborative and non-collaborative objects. Collaborative detect-and-avoid collision avoidance is enabled by vehicle-to-vehicle communication. On the other hand, non-collaborative collision avoidance is enabled by sensors, which recognize non-collaborative entities such as manned aircraft, birds, and balloons.

4.2.2. *Airbus*

Airbus proposed four concepts (Fig. 24) of designing airspace: Basic

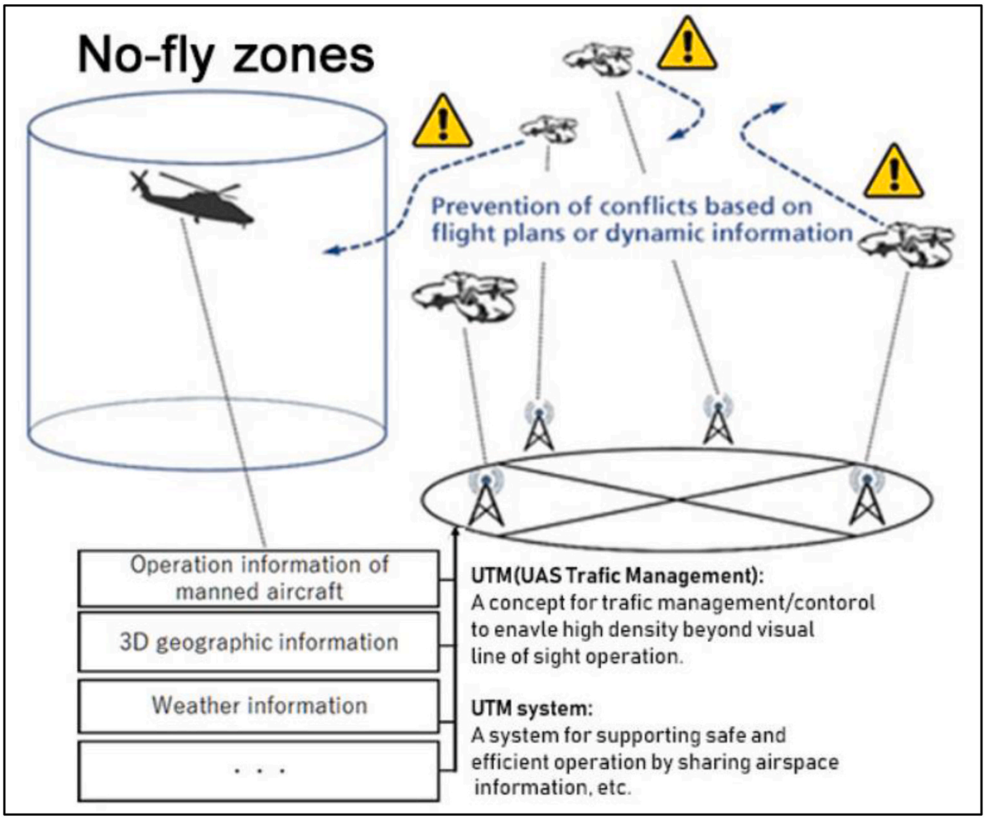


Fig. 22. Japanese UTM [152].

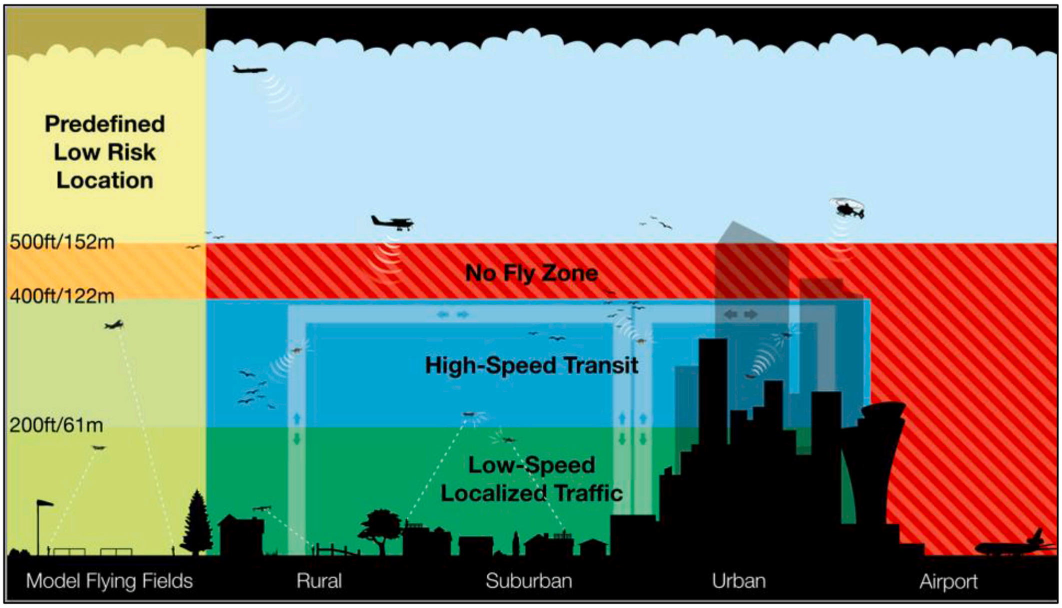


Fig. 23. Urban airspace concept by Amazon [154].

Flight, Free Routes, Corridors, and Fixed Routes [156]. In Basic Flight, both manned and unmanned aircraft are responsible for self-separation and must maintain it at all times. If all aircraft select a direct route without coordination, the safety decreases as the number of conflicts increases. In the Free Route, aircraft can fly any path as long as the path is pre-approved, deconflicted from other routes, and approved by a traffic manager. This approach provides flexibility while maintaining an acceptable level of safety. The trajectories are less-than-optimal since the flight plan can be rejected. Corridors are predefined volumes in space, used in high-demand situations. This concept is similar to the waypoint procedures used in traditional aviation. Fixed Routes are used to ensure safety when there is a mix of aircraft capabilities and high traffic density. These routes are constructed and modified dynamically based on risk, traffic, and weather.

Airbus proposes new flight rules that would accommodate unmanned operations. For example, Basic Flight Rules (BFR) would cover

Table 10
Equipage and airspace access under best-equipped, best-served model proposed by Amazon [155].

Class	Equipage	Airspace Access
Basic	Radio Control	Line of sight flight in predefined low-risk locations.
Good	Transmission of ID and location via V2V, ability to receive air traffic and weather data, internet connection via ground infrastructure, GPS and Wifi capabilities, geospatial data.	Operations below 200 feet in rural areas.
Better	Avoidance based on collaborative V2V, onboard internet connection, ADS-B Out.	Operations below 200 feet in suburban operating areas.
Best	Non-collaborative detect-and-avoid, onboard internet connection, ADS-B In/Out, 4D trajectory planning and management, alternate landing execution.	BVLOS operations below 400 feet in all areas, in all conditions.

manned flights that operate independently. They would be responsible for maintaining separation, routing, and safety. On the other hand, Managed Flight Rules (MFR) would cover operations that coordinate their path with a traffic management system and follow its separation guidance.

Real-time two-way communications report position and status so that traffic managers can coordinate with their aircraft. Around airports, ATM and UTM services work together. For example, they coordinate the direction of local traffic flows between fixed-wing aircraft and unmanned drones at local airports based on weather conditions. Traffic management services provide basic information to pilots and autopilots about conditions in the airspace, regulation, and nearby traffic. Managed aircraft use this information as input for tactical self-separation and collision avoidance.

Aircraft will also need to meet navigation performance standards. Navigation may be assisted by GPS, ground-based beacons, or other technology (see Table 11). Aircraft may need to maintain precise navigation in areas like urban canyons, where multipath effects degrade traditional navigation accuracy. With traffic management services maintaining separation for managed drones, detect and avoid is a backup. Simulations show that it works well in low-density regions, while strategic and tactical management works better at higher densities.

4.2.3. Boeing

Boeing proposed a concept of free-flight, performance-based routes for low altitude trajectory operations [157]. These routes would be managed by a 4D trajectory-based separation management system that would maintain safety, including during approach and departure for operations around hubs and terminal locations.

The technological requirements include onboard algorithms for real-time flight planning and in dense traffic environments. Traffic, weather, and other operational restrictions will be shared in real-time, and the aircraft will dynamically adjust its flight plan and route. Advanced detect-and-avoid systems will provide safety assurance and collision avoidance during the flight.

4.2.4. Embraer-X

Embraer-X proposed a concept called Urban Air Traffic Management (UATM) [158]. The UATM airspace is positioned between lower-level

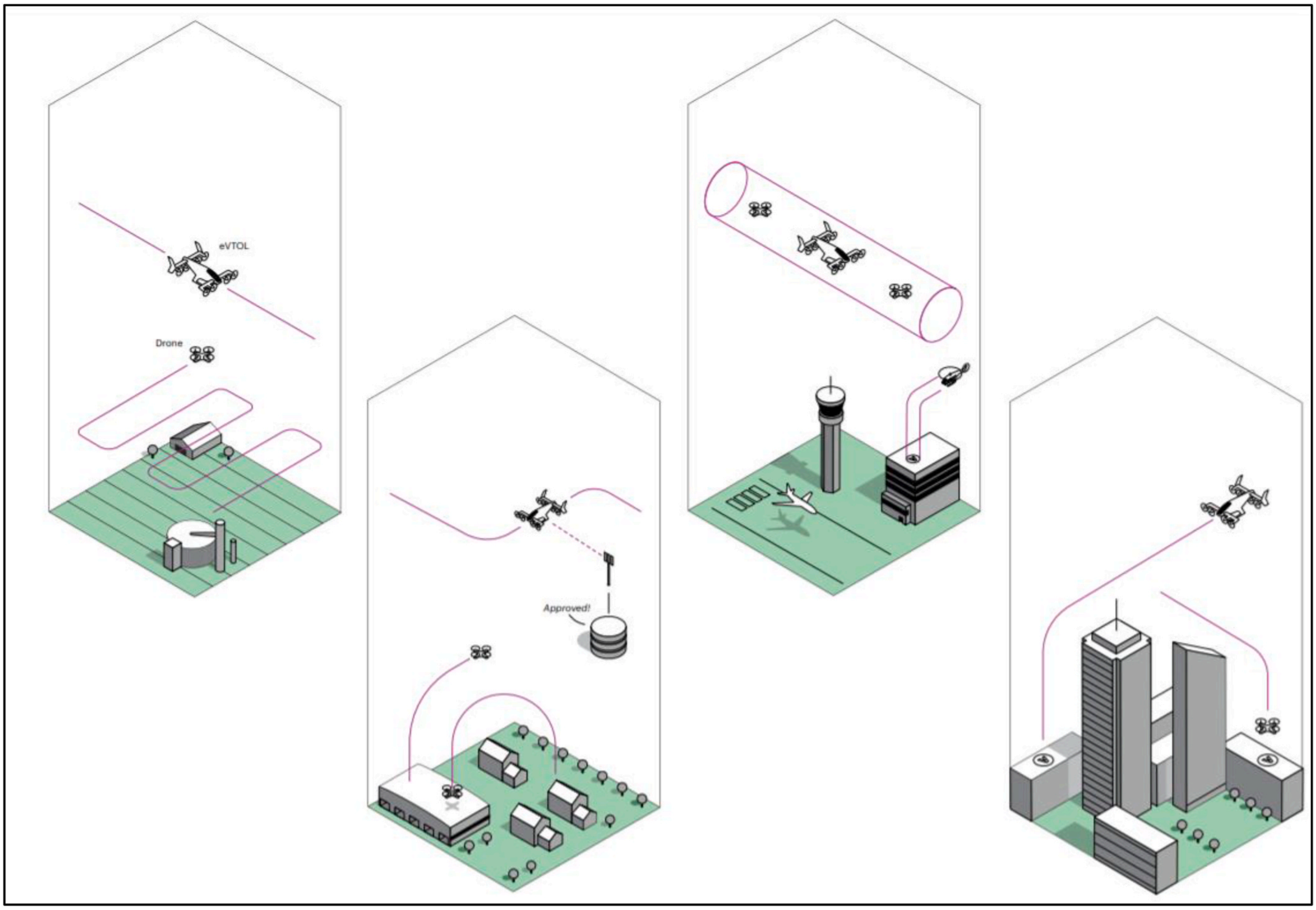


Fig. 24. Airspace structures by Airbus (left to right): Basic Flight, Free Route, Corridors, and Fixed Route [156].

Table 11
Services offered based on the level of automation in Airbus proposal.

Automation	Level 1	Level 2	Level 3	Level 4	Level 5
Operations	VLOS	Autonomous BVLOS in low-density airspace	Integration of BVLOS in controlled airspace	Fleet operations	On-demand autonomous operations in high-density airspace
Airspace	VFR corridors, altitude restrictions, automated geofencing	UAS tracking, automated approvals	Unmanned procedures, corridor configurations	High-density controlled airspace	Dynamic and performance-based rules for access to airspace
Services	SWIM System-Wide Information Management	Network manager	ATM-UTM coordination, digital traffic manager	Specialized traffic management	ATM integration, congestion avoidance

airspace reserved for small UAS (sUAS) operations, and traditional ATM airspace (Fig. 25). Within the UATM airspace, the aircraft use routes and corridors. Routes are linear trajectories defined by waypoints that accommodate a single vehicle, while corridors accommodate multiple vehicles. Given the complex mix of aircraft capabilities, routes and corridors are critical for managing traffic efficiently. Different rules apply to different structures and access to some corridors or routes may be restricted. The combination of layers and structures provides access to aircraft of different capability levels while maintaining safety.

The operator files a flight plan to the central traffic management authority that authorizes the 4-D trajectory and ensures it is deconflicted, and that the requested routes, corridors, and airspace will be available at the designated time slot. The traffic management system dynamically manages routes, corridors, and geofences based on traffic, weather conditions, emergencies, or other restrictions. Additionally, the system ensures that flights conform to the flight authorizations and assigned routes.

To develop UATM, Embraer-X relies on the development of new technologies. For example, the report indicates that the foundation for surveillance will be GPS supported by a new technology that would serve as a redundancy in case of a GPS failure. However, as shown by NASA, GPS failure is not as big of a problem as GPS accuracy, which can be off by as much as 5 m [136]. Additionally, tracking will also depend on ADS-B-like devices that will have its benefits, and communication will be conducted on the 5G LTE network.

The report indicates that the positioning of routes and the design process must consider communities that will be affected by the negative externalities of air traffic. Well-designed airspace structures will reduce risks, maintain efficient traffic flow, and ensure community acceptance when traffic reaches high volumes, which is the reason why all stakeholders should be included in the design process as soon as possible [158].

4.2.5. *Uber elevate*

Uber took a more modest approach of integrating its on-demand VTOL operations into the existing framework of air traffic management. They don't directly specify airspace structure but listed the recommendations for the successful operations of their on-demand VTOLs [15]. Although Uber's proposal relies on the existing technologies and NASA UTM proposal, it does present a discussion about the principles of designing urban airspace, especially in terms of social acceptance, which is not odd given that Uber's success relies on the positive acceptance of its users.

The proposed safety level is twice that of driving a car based on the number of fatalities per passenger-mile. Using Part 135 operations as a proxy, Uber argues that the current safety level in air-taxi aviation is worse than driving (about 0.15 deaths per 100 million passenger miles).

In the initial phases, the existing technologies such as ADS-B and radio-based voice communication will be used for operations of VTOLs with a human pilot onboard. However, to achieve a higher density of

Fig. 25. UATM concept by *Embraer-X* [158].

operations, new technologies, specifically developed for low-level airspace, will need to be developed. The whitepaper calls for the extension of NASA's UTM above 500 feet to accommodate intended VTOL operations and create seamless integration with airports and terminal areas. Additional technologies needed are 1) digital air traffic control communication, 2) a UTM system expanded to higher altitudes that can manage a mix of VTOLs and General Aviation aircraft, and 3) traffic management system that can integrate VTOLs and airline approaches and departures near airports.

Uber argues that stringent standards for reducing noise should be adopted, including noise objectives for vehicles, long-term and short-term annoyance. Using these metrics, and real-time tracking of site noise as inputs, the minimum-noise flight path should be selected.

4.3. *Assessment of urban airspace concepts*

The summary of the proposed concepts is presented in Table 12 and Table 13. Each concept is evaluated according to the dimensions presented in Section 3: safety, social, system, and vehicle factors. Most concepts focused on the limited notion of safety, which includes avoidance of physical objects, but less on safety impacts of weather or wind. The most frequent, sometimes unstated assumption is that the technology required to support UAM operations exists and is ready for implementation. However, technologies such as detect-and-avoid, advanced communication, navigation, and surveillance are still inadequate to facilitate safe operations.

Social factors are largely ignored, which is not uncommon in the initial phases of developing new engineering solutions. While the abstraction of the physical nature of a city into a mathematical network is a useful tool for the ideation of possible solutions, the customer (i.e., the public) should be introduced into the process sooner rather than later.

It is noticeable that private companies are promoting airspace concepts that do not require centralized air traffic control or management system. While this approach might seem quicker, it increases complexity, which might ultimately reduce the trust and safety of air mobility.

Overall, the proposed concepts can roughly be divided into three groups. The first group includes the most realistic proposals that rely on the existing technologies, and that could be implemented today. These are the proposals by NASA, FAA, SESAR U-Space and to a measure, DLR U-Space. Under these proposals, drones fly in G Class airspace, below the altitude of 400 ft and leverage the existing air traffic management system, which provides identity registration, as well as weather and obstacle (geofence) data. The pilots are required to fly the drones in the line of sight and maintain separation from the other traffic according to the existing airspace rules. The operations are kept separate from the controlled airspace. If there is a need to go through controlled airspace, UAV operator can use segregated corridors with the permission of air traffic control. Although future phases require more advanced technologies, the first phase could be implemented today.

The second group of airspace concepts proposes dedicated UAM traffic control and the creation of airspace structures, such as layers, tubes, lanes, etc. This group includes the majority of proposals, including UTFC, MITRE, METROPOLIS, ONERA, Singapore UTM, Airbus, and Embraer-X. To properly function, these concepts require improvement of several technologies, most importantly, improvement in high-capacity communication networks, and improvement in the precision of surveillance systems which would enable remote path planning and conflict resolution. These concepts propose static separation requirements and may or may not be complemented by advanced sense and avoid systems.

The third group of concepts, such as those from Amazon and Boeing, rely on the development of technologies that would enable UAVs to be highly independent of any air traffic control. The vehicles are expected to carry high-quality cameras, LIDAR, and some version of RADAR, and

Table 12
Review of airspace concepts.

Concept			FAA UAM v1.0	NASA UTM	NASA UTFC	MITRE	SESAR U-Space	DLR U-Space	Metropolis-a	Metropolis-b	Metropolis-c	Metropolis-d
Country/Region			USA	USA	USA	USA	EU	Germany	Netherlands	Netherlands	Netherlands	Netherlands
Structure			Corridors	Preapproved Trajectories	Skylanes	Preapproved Trajectories	Preapproved Trajectories	Cells	Full mix	Layers	Zones	Tubes
Safety	Object avoidance	Static Geofence	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Dynamic Geofence	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Sense and avoid	Not required	Not required	Required	Required	Not required	Not required	Required	Not required	Not required	Not required
		Separation	Static	Static	Static	Static	Static	Dynamic	Static	Static	Static	Static
	Wind gusts		✓	x	x	x	x	✓	x	x	x	x
	Weather		✓	✓	x	✓	✓	✓	✓	✓	✓	✓
Social	Noise		✓	x	x	x	x	x	x	x	x	x
	Privacy		x	x	x	x	x	x	x	x	x	x
	Visual pollution		x	x	x	x	x	x	x	x	x	x
System	Airspace Management		Centralized	Centralized	Centralized	Centralized	Centralized	Centralized	Centralized	Centralized	Centralized	Centralized
	CNS		Not specified	GPS, ADS-B	Not specified	Not specified	LTE, FLARM, ADS-B	LTE, FLARM, ADS-B	LTE, FLARM, ADS-B	LTE, FLARM, ADS-B	LTE, FLARM, ADS-B	LTE, FLARM, ADS-B
	Capacity		Medium	High	Low	High	High	High	High	High	Medium	Low
Vehicle	Automation	Manned	✓	x	x	✓	✓	✓	✓	✓	✓	✓
		Unmanned	x	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Critical aircraft		Various	sUAS	sUAS	Various	Various	Various	Various	Various	Various	Various
	Energy-efficient paths		x	✓	x	✓	✓	x	✓	x	x	x

Table 13
Review of airspace concepts (continued).

Concept			ONERA	Singapore	UOMS	JAXA	Amazon	Airbus	Boeing/Aurora	Embraer-X	Uber Elevate
Country/Region			France	Singapore	China	Japan	USA	EU	USA	USA	USA
Structure			Layers	Lanes	Layers	Corridors	Layers	Basic flight, Free routes, Corridors, Fixed routes	Tubes	Layers with routes and corridors	Preapproved Trajectories
Safety	Object avoidance	Static Geofence	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Dynamic Geofence	x	x	✓	x	x	✓	✓	✓	✓
		Sense and avoid	Not required	Required	Not required	Required	Required	Not required	Required	Required	Not Required
		Separation	Static	Static	Static	Static	Dynamic	Static	Dynamic	Static	Static
	Wind gusts		x	✓	x	x	x	x	x	x	✓
	Weather		x	x	✓	x	x	✓	✓	✓	✓
Social	Noise		x	x	x	x	x	x	x	✓	✓
	Privacy		x	x	x	x	x	✓	✓	✓	✓
	Visual pollution		x	x	x	x	x	x	x	✓	✓
System	Airspace Management		Centralized	Decentralized	Decentralized	Centralized	Decentralized	Centralized	Decentralized	Centralized	Decentralized
	CNS		FLARM, LTE, ADS-B	GPS, V2V Comm	4G/5G LTE	Precision mapping, RADAR, GPS	WiFi, ADS-B, V2V	ADS-B, V2V Comm	ADS-B, Internet, Blockchain	Next generation GPS and ADS-B	Next generation technologies
	Capacity		Medium	Low	High	High	Medium	Varies	Medium	High	Not specified
Vehicle	Automation	Manned	✓	x	✓	x	x	✓	x	x	✓
		Unmanned	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Critical aircraft		Various	UAS	Various	Various	Various	Various	Various	Various	VTOL
	Energy-efficient paths		x	x	x	x	x	✓	✓	x	x

have the potential to collect, process, and transmit large volumes of data. The UAVs will have the capability to sustain this heavy payload while not jeopardizing endurance and range, which implies improvement in battery technology. The concepts rely on advanced sense-and-avoid systems.

5. Discussion

The first step in the process of designing airspace is to determine its structure. Air vehicles in less structured airspace have more degrees of freedom and can freely choose their position, altitude, heading, and speed, which allows them to fly cost-effective routes. However, these concepts, although least prohibitive, require high technological capabilities, including advanced detect-and-avoid systems, vehicle-to-vehicle communication, and more advanced ADS-B and GPS services. On the other side of the spectrum (Fig. 26), concepts with the most structure can accommodate various levels of equipage but require strict rules and route following to ensure safety.

Less structured airspace has been shown to allow for higher traffic densities by reducing traffic flow constraints and structure. Here, aircraft can fly user-preferred (often direct) routes, while separation responsibility is delegated to individual aircraft using onboard conflict resolution technologies [24,157]. Energy consumption is lower due to more efficient routes. However, free flight is possible only if vehicles are autonomous, and the concept is not inclusive of aircraft with lesser technological capabilities. Free flight concepts usually do not consider social factors in selecting their routes, as this would require higher levels of coordination and structure. The collision risk is high since the detect-and-avoid system is the only barrier that prevents an accident, and flights can have multiple collision points along their trajectories. Third-party risk is also high since user-selected routes might be located above high-density neighborhoods. These findings are supported by the Metropolis study (Table 9) and the Altiscope study that showed that increasing disorder in airspace leads to lower safety levels [159]. The concept of free flight is popular as it does not require a centralized traffic management system; it is achievable solely by developing higher-level autonomy. However, it can only be implemented in limited, constrained geographic areas where there is little chance of contact with other aircraft or objects. The performance of these different factors for free flight, as well as for the other more complex structures, is qualitatively presented in Fig. 27.

Other concepts aim at changing the airspace structure specifically for integrating small UAS, for example, by introducing specialized UAS traffic management (UTM). One step further is to segregate aircraft of different capabilities into different layers. The study [160] has shown that layers reduce the probability of a collision in three ways: by creating vertical separation between operations, by segregating flights according to the direction and speed, which reduces the number of conflict points, and by separating according to the aircraft capabilities. The concept of layers also performs well in terms of capacity [160], third-party risk [147], and inclusivity [156].

Some structures can be beneficial in terms of traffic separation, but too much structure only reduces performance. As flight paths become constrained, capacity, efficiency, and safety decrease. Since multiple aircraft are guided to the pre-set waypoints or structures, the number of potential conflicts increases, compared even with free flight [147]. Highly structured airspace has an advantage in that it can accept aircraft of different technological capabilities, i.e., it is inclusive.

The structure comes from the need to separate operations without imposing too many technological requirements. Rotorcraft wake vortex propagates downward and does not create the same issues as wake vortices in traditional aviation [22]. Therefore, the horizontal separation for rotary-wing UASs is only influenced by the need to avoid conflict, which means that the separation standards mainly depend on a vehicle's speed, maneuverability, sensor system technology, and autonomous decision-making capability.

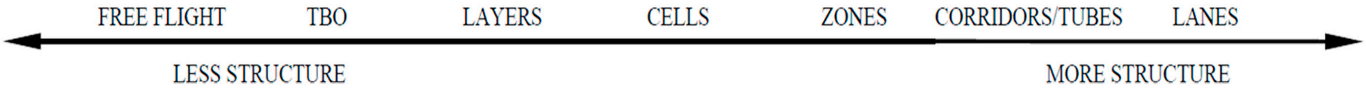


Fig. 26. Airspace structure and design concepts.

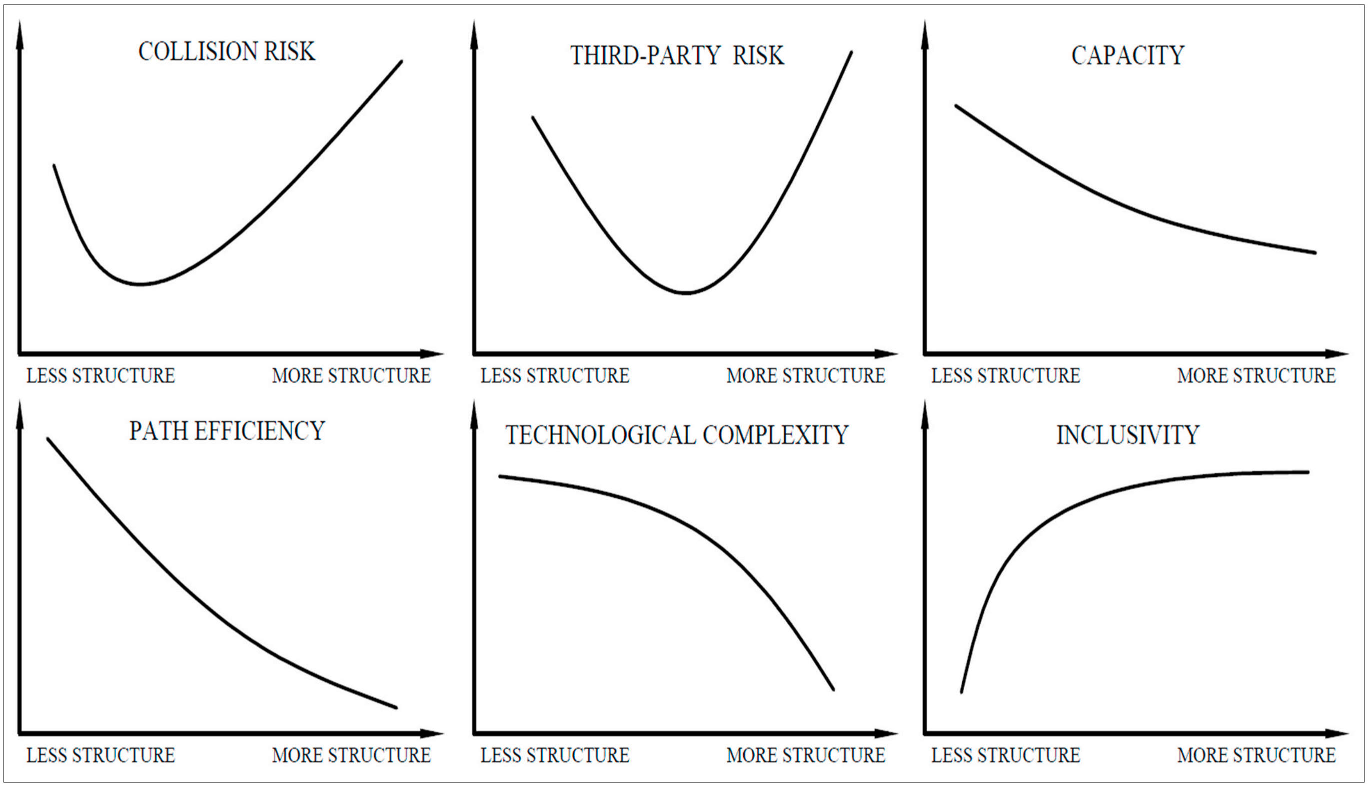


Fig. 27. Performance vs. Airspace structure.

The technology required to provide such capabilities is still not sophisticated enough. For example, although advances in detect-and-avoid systems have been made, it cannot be relied upon for safety assurance [161]. The GPS can provide accuracy up to 5 m, which is not adequate for high-precision navigation in unstructured airspace [111]. ADS-B, required for tracking and surveillance, lacks frequency bandwidth to support high-density UAM traffic [115] and should be replaced with more advanced surveillance systems [116]. For these reasons, it is reasonable to predict that in the short- and mid-term, more segregated airspace will be developed.

Finally, the collection of these concepts shows that social factors usually come as an afterthought, which is a mistake since noise is one of the most severe capacity-limiting factors [162]. The focus of the research efforts presented in this article is placed on the trade-off between safety and capacity. However, the assumptions for these concepts are based on an abstract network, with a particular emphasis on efficiency over other outcomes. Idealized networks usually ignore risks such as bird strikes and realities on the ground.

Urban air mobility, as a new mode of transportation, is there to serve the public. But currently, there is a little public debate over what UAM should look like, and the average city resident seems to be unfamiliar with the concept of UAM. Urban air has been seen as a common good, with a little contestation over rights to it. However, as the privatization of the air proceeds, it is naïve to expect that it will simply be appropriated by the aviation industry without pushback from state and local legislatures, private citizens, communities, and other interests. Traditionally, areas around airports were the only areas affected, and the wider population had no contact with air traffic operations, mainly because air transportation networks do not have physical manifestation on the ground. Aviation and the cities were able to coexist without much contact. However, urban aviation is manifesting itself on the ground, by physically changing the built environment and altering the living environment, which impacts the interests of communities, real-estate developers, politicians, citizens, and interest groups.

Even a policy taken for granted by researchers, such as drone identification, poses challenges when implemented in the real world. Remote Identification of Unmanned Aircraft Systems Rule [163] is a proposed rule that would require all drones to have remote identification capabilities. However, the proposal has faced an uproar by the hobby model aviation community, claiming that the new rules would effectively wipe out the community and the supporting $1 billion industry. A simple piece of legislation is facing serious opposition. The issues such as air rights, land appropriation, land use, and zoning will be much harder to solve.

The UAM is in the “honeymoon” phase, similar to where autonomous vehicles were in the early 2010s. New aircraft prototypes are here, and the industry is enthusiastic. However, there is still a long way to go in terms of technology, regulation, and public conversation. The ramifications of rolling out too quickly, especially in passenger transportation, are severe. By rushing to start UAM passenger transport, the unexpected safety issues and public opposition might stop the UAM development and force cities to ban UAM. Traditional aviation has been dealing with public opposition for over five decades, mainly due to aircraft noise imposed on communities near airports. However, most commercial airports are currently located in the suburbs, whereas vertiports will mostly be located in more densely populated areas. Since commercial airports developed mechanisms for dealing with public concerns in suburban environments, these same mechanisms may not fully apply to vertiport and city environments.

The aviation agencies around the world will likely have more difficulties in enacting their solutions in the space where there are so many stakeholders and will need to reach out to a wider audience than today.

6. Conclusion

This study presents a review of urban airspace design concepts and creates a framework that can be used to assess the proposed concepts. We define four groups of factors that impact the physical structure of airspace: safety, social, system, and vehicle factors and then analyze airspace proposals based on these factors. The analysis shows that most proposals 1) focus on the limited notion of safety, 2) rely on technologies that are still not available, and 3) do not address social factors adequately.

Additionally, we find that the structure and restrictiveness of airspace can influence capacity, safety, and efficiency. Less structured airspace, such as the concept of Free flight, allows greater capacity and route efficiency but requires greater technological capabilities and reduces safety. On the other hand, more restrictive structures, such as tubes and lanes, enable the operations of less-equipped aircraft but increase delays.

Recommendations for further research on the topic of urban airspace include:

- Research of risk, including accident scenario planning, bird strike risk, loss of control, and risk due to wind gusts.
- Research and discussion about data usage, rights, anonymization, and de-identification of data collected by aircraft in the urban environment.
- Research on new technologies, especially ADS-B, detect-and-avoid, technology for taking over control if the geofence is breached, and a safety protocol under which new tech can be inspected.
- Research into psychoacoustic effects of drone noise on humans and airspace concept development that has noise at the core of its design.
- Research of community input and design, including visual pollution and privacy concerns.
- Research on the impact of ground infrastructure on urban planning, including landing and take-off sites, real estate, zoning, planning issues, inequalities, and air rights.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Glossary

ADS-B: Automatic dependent surveillance-broadcast
ATC: Air Traffic Control
ATM: Air Traffic Management
BFR: Basic Flight Rules

BVLOS: Beyond visual line of sight
BZ: Business zone
CNS: Communication, Navigation and Surveillance
DLR: Deutsches Zentrum für Luft und Raumfahrt
EUROCAE: European Organization for Civil Aviation Equipment
FAA: Federal Aviation Administration
FLARM: Flight Alarm
GAFS: General Aviation Flight System
GPS: Global Positioning System
ICAO: The International Civil Aviation Organization
ID: Identity
JAXA: Japan Aerospace Exploration Agency
LLRTM: Low Level RPAS Traffic Management System
LTE: Long-Term Evolution
MFR: Managed Flight Rules
NAS: National Airspace System
NASA: National Aeronautics and Space Administration, The
NATO: North Atlantic Treaty Organization, The
NFZ: No Flying Zone
ONERA: The Office National d'Etudes et de Recherches Aérospatiales
PAV: Personal Air Vehicles
RPAS: Remotely Piloted Aircraft System
RZ: Residential Zone
sUAS: small UAS
SWIM: System Wide Information Management
TLC: Technical Capability Levels
UAM: Urban Air Mobility
UAS: Unmanned Aerial Systems
UATM: Urban Air Traffic Management
UAV: Unmanned Aerial Vehicle
UML: Urban Air Mobility (UAM) Maturity Levels
UOMS: UAS Aviation Operation Management System
UTM: Unmanned Aerial Systems (UAS) Traffic Management
V2V: Vehicle-to-vehicle
VDL: Very High Frequency (VHF) Data Link
VLOS: Visual-line-of-sight
VTOL: Vertical Take-off and Landing