Airspace Designs and Operations for UAS Traffic Management at Low Altitude

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Abstract: As the usability of and demand for unmanned aerial vehicles (UAVs) have increased, it has become necessary to establish a UAS traffic management (UTM) system for efficient UAV operations at low altitudes. To avoid collisions with ground obstacles, other UAVs, and manned aircraft, in building a safe path, the UTM needs to determine the time and space allocated to each flight. Ideas for discretizing and structuring airspace in various forms have been proposed to enhance the efficiency of system operation and improve traffic congestion through effective airspace allocation. Additionally, various methods of allocating UAVs to structured unit spaces have been studied in the literature. In this paper, the methods and structural designs for allocating airspace that have appeared in related studies are classified into several types, and their strengths and weaknesses are analyzed. The structured airspace designs are categorized into three models: Air-Matrix, Air-Network, and Air-Tube, and analyzed according to their sub-structures and temporal allocation methods. In addition, a quantitative analysis is conducted by re-categorizing the structured airspace and operation methods and building their combinations.

Keywords: UAS traffic management; airspace design; airspace structure; UAV

1. Introduction

The use of Unmanned Aerial Vehicles (UAVs) is increasing, with various demands in industrial activities such as package delivery, surveillance, information gathering, and precision agriculture [1]. A safe and efficient traffic control service needs to be provided as the number of UAV flights increases. Existing Air Traffic Management (ATM) systems are based on the flight characteristics of manned aircraft, manual monitoring and control, and voice communications, making them unfit to control UAVs and unable to handle the rapidly increasing flight demands. In addition, small UAV applications are more in demand in places with intensive human economic activity and are concentrated in low-altitude airspaces (e.g., Class G) where no ATM services are provided. Therefore, efforts are being made to develop and standardize Unmanned Traffic Management (UTM) in many countries: UTM in the USA [2], U-space in Europe [3], U-Cloud in China [3], JUTM in Japan [3,4], K-UTM in Korea [5], and UTM-UAS in Singapore [6].

The main goals of UTM are to develop UAV-oriented control services, flight rules, navigation systems, and airspace management, and to solve operational problems in low-altitude urban areas and existing ATM-controlled airspaces. A UTM system determines safe-assured paths and approves flight plans in response to flight requests from users. An approved flight path should be free from conflict with other flight plans, and sufficient separation is required to prevent collision with ground obstacles such as terrain, buildings, and trees, as well as other UAVs in flight. While operating the UTM with multiple flights simultaneously, significant communication and computational burdens arise in solving conflicts and processing approval. Although there may be diverse methods to operate a UTM considering the above factors, the most intuitive and straightforward concept is to determine whether to approve the desired flight path presented by the user upon a flight.
request, without using any pre-designed spatial or temporal structure of airspace [2,7,8]. However, in this case, the desired flight path of a user can frequently overlap in demanding areas or takeoff and landing facilities, and, thus, the airspace utilization quickly reaches its capacity. Accordingly, various concepts of airspace structures have been proposed for using limited airspace as efficiently and safely as possible.

While NASA proposed an operational concept of UTM which was based on unstructured flight management [2], there was also a study considering possible airspace structures [9]: it suggested four spatial and temporal airspace design options. Europe has been working on basic path structures such as Corridors, Free-Route, and Fixed-Route [3]. In Singapore, the TM–UAS team studied various airspace designs, named the Air-Matrix model, so that they might operate UAVs effectively in urban areas [10]. The proposed work in [10] analyzes and compares three different types of route networks: a grid-based discretized airspace concept suggested in previous studies [11,12] and two graph-type designs having nodes over buildings or roads. There have also been proposed basic structuring methods for airspace configuration: keep-in, keep-out geofences, as well as topological approaches [13–16].

Related studies on structuring airspace for UTM can be categorized into two cases: structured and unstructured, as summarized in Table 1. The first group constructs pre-designed structures for planning a flight path, and the other group does not have any definite airspace structure. Various airspace structure concepts were proposed in the first group. The concepts are classified into three models within this paper according to their spatial partition and forms: Air-Matrix, Air-Network, and Air-Tubes, which are described in the following section. Furthermore, the structured concepts in the literature are sub-categorized herein based on the methods of operating and assigning airspace to flights.

In this paper, the UTM airspace structures presented in the previous studies are classified and systematized according to the characteristics of their spatio-temporal structures and operational methods. Although a few surveys on UTM studies exist [17,18], there has never been an analysis focusing on the classification of airspace designs and operational methods in the literature. Therefore, this has practical value in building the basis for identifying and analyzing the characteristics of UTM airspace structures and unstructured operations that will be in operation in the near future. In addition, the combinations of possible airspace structures and operational methods, including those not yet presented in the literature, are presented, and the safety, efficiency, and computation/communication complexities of each combination are qualitatively analyzed. This enables an evaluation of the pros and cons of airspace structure and operational methods before a detailed high-cost analysis. In addition, this study can be used as preliminary data for quantitative analysis through simulations of UAV flights and UTM system models.

The rest of this paper is organized as follows. In Section 2, the concepts are presented for categorizing airspace structures and operational methods. The detailed reviews on the classified airspace structures and operational methods in the literature are given in Section 3, with the reviews for unstructured cases in a subsection therein. Section 4 provides a qualitative study of airspace structures, and Section 5 concludes the paper.

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Table 1. Classification of airspace designs and operational methods.
2. Airspace Structures and Operation Methods

2.1. Airspace Structure Models

This section presents three proposed models of airspace structure for the operation of low-altitude UAVs and mentions their general advantages and disadvantages. These models are categorized Air-Matrix, Air-Network, and Air-Tubes, and were developed by embracing various concepts presented in the literature. The existing UTM ideas for structured airspace operations can be classified into one of these three models.

2.1.1. Air-Matrix

Air-Matrix is the most intuitive way to discretize airspace (Figure 1a). In airspace allocated for UAVs, the space, except for places where obstacles limit flight, is divided into cubes using a grid of a certain size. The flight path of a UAV can be created by connecting the center points of the cubes, and a passage linking the consecutive cubes is assigned to the UAV flight. Another way to utilize the Air-Matrix structure is to create the flight path by connecting adjacent grid points. In this case, instead of explicit airspace allocation with the cubes, a recommended path is created along the grid, and the width and height of the cube are used to provide separation from other flight paths.

The former of the two methods is more common in the literature, so it is hereafter described based on the former method. The width, length, and height of the cubes, which
are units of discretized airspace allocation, can differ according to a given operating environment. With more granular unit cubes, the size of the allocated space can be flexible by assigning multiple cubes for each flight of a single UAV or a group of ones. It is efficient in terms of airspace utilization because it can vary the size of the allocation space depending on the aircraft characteristics (flight weight, sensor and flight accuracy, etc.) or operating environment, such as the weather. However, as the amount of discretized airspace increases, more calculations are required to search and confirm the overlap of allocated airspace between flights. Air-Matrix makes it easy to manage airspace by simply assigning a unique address to each cube. Data structures that process three-dimensional spatial information can quickly handle access and search queries between cubes. Hence, it provides a convenient way to check the UAV operators’ flight-plan overlap, suggest conflict-free routes, and secure flight paths between UAVs.

There are two main disadvantages of Air-Matrix. First, when the management space is extensively larger than the unit cube, the amount of data to be stored and managed by UTM increases considerably. The second is that the path of the aircraft, created along the shape of the cube of a square lattice, is only a series of straight lines connected at right angles. This can be slightly alleviated by dividing the cube into sub-structures, such as triangular prisms, but this can make the necessary calculations for traffic management more difficult. Therefore, Air-Matrix is more suitable for operating rotorcraft UAVs that can hover and fly vertically; for fixed-wing aircraft, it can lead to inefficient airspace utilization because a large number of peripheral cubes must be allocated around gentle turning curves or climbing paths for safety.

2.1.2. Air-Network

Air-Network is a method for constructing a transportation network in an airspace using a graph having nodes and edges (Figure 1b). A node is a chunk of space set up over takeoff and landing sites or at a major UAV traffic intersection, and an edge is a passage-type space connecting these nodes. The edges can be set around the shortest straight line connecting the nodes or bent to avoid intersecting with terrain, obstacles, and other edges. One or more UAV units can be assigned to fly within the edge. In the case of multiple flights in a single edge, a directive passage in the edge can be installed to reduce the autonomy requirement and the chance of mid-air collisions. Moreover, a safe separation should be provided for the multiple flights in an edge. Without any further segmented structures, UTM can monitor, command, and control UAV traffic, as in conventional ATMs, or the UAVs themselves can solve the separation problem with their own sensors and communication. However, a UTM system demands high cost requirements for surveillance infrastructure or flight autonomy. Instead, it is possible to divide each edge into several sections along its length and allocate each section to a UAV exclusively.

Since Air-Network is a graph-type airspace structure consisting of nodes and edges, it is possible to process allocation and management of airspace quickly by utilizing data structures for graphs. Therefore, it is straightforward to identify each UAV’s location and flight situation, and many existing graph search algorithms can be utilized for planning routes. However, congestion is likely to occur at nodes where flight flows are concentrated, and there may be problems in determining the order of multiple UAVs trying to pass the same node for takeoff and landing or transit purposes, just as there are traffic lights at intersections. Some previous studies proposed specific detailed structures and rules within nodes to deal with these problems. The congestion can be prevented by allowing every flight for only pre-planned time and space and by allocating each node/edge space to only one flight unit at a particular time, but this significantly reduces airspace utilization.

Air-Network airspace is convenient for UTM managers to understand the traffic situation and intuitively construct the structure according to the existing ground transportation network and UAV takeoff and landing sites. However, it is necessary to re-configure the network whenever a new takeoff and landing site is built, or traffic demands change.
Moreover, there are dead spaces where no nodes nor edges are installed, meaning that the given airspace for UTM is not fully utilized.

2.1.3. Air-Tubes

Air-Tubes are similar to the concept of edges in Air-Network: they are airspace structures that connect the origin and destination points directly, without any transit node (Figure 1c). This can be seen as a concept of an expressway for UAV flights. The airspace structures of the Air-Tubes category vary slightly within the literature, and a specific flight direction can be set within the tube. Although Air-Tubes are very efficient at connecting two high-traffic nodes because they directly connect the nodes, they may not be suitable for handling various flight plans. Therefore, this concept can be used as a supplementary structure for solving traffic congestion in the other ones, i.e., the Air-Matrix or Air-Network concepts.

2.2. Operational Methods: Partitioning, Plurality, Temporal Allocation

In order to allocate acceptable airspace and flight rights for safe low-altitude UAV operation, it is essential to consider allocation methods as well as to design the airspace structure. A UTM manager carries out the distribution of airspace, and structured spaces or unstructured flight areas of the airspace are allocated to operators who request flight approval by following certain priorities and procedures. Because the priority of airspace allocation and flight approval procedures may vary depending on the UTM system’s environment and the policies of aviation authority, this paper classifies and analyzes only the operational methods and forms in terms of the physical aspects of airspace distribution. The methods of distributing airspace can be divided in several ways, depending on how unit space is distributed over time, the number of flight units operated per unit space, and whether or not unit spaces such as nodes and edges are subdivided.

A unit space is a basic component that an airspace is divided into. Typically, a cube in Air-Matrix or a node/edge in Air-Network is a unit space. In the case where a node or an edge is partitioned into smaller portions using specific criteria, each portion is a unit space. A flight unit is an object or a group of flight vehicles that carries out a flight mission. In a package delivery mission, for example, a flight vehicle delivering a light parcel alone and a flight group cooperating for a heavy parcel are the cases of a single flight unit. UAVs with different operating purposes, destinations, and paths can be considered separate flight units.

As a UAV operator submits a flight plan to the UTM manager, the plan is reviewed, and the flight path is appropriately modified if there is a conflict with other plans. Then, the spaces around the flight path are assigned as the airspace allowed for the UAV. At this moment, the allocated airspace can be used for a certain period, and the operation method diverges according to how the time for each space is assigned. There are ways to allocate the entire airspace along the path from the starting time to the end of the flight plan and to divide the airspace into multiple parts with different time intervals allocated (Figure 2). When time is partially allocated in a structured airspace, each space on the path is a unit space of the structure. Allocating the entire time in the flight plan to UAV operations reduces the possibility of collisions with other UAVs and allows the UAV to freely adjust its flight speed or return to its origin, as needed or in an emergency (Figure 2a). However, the longer the flight path and the time allocated, the more restricted other UAV flights are, thus reducing the efficiency of airspace operations. On the other hand, if time is partially allocated, there are multiple possible options: the allocated space can be returned (Figure 2b), the space with enough time left to be reached can be allocated later (Figure 2c), or the allocated time window can be set for each unit space (Figure 2d). Therefore, more flights can be handled in limited airspace, enabling much more efficient operation. However, the requirements for communication, infrastructure, UAV sensors, and autonomy required for these dynamic operations should be stricter than the full allocation of time. If the airspace is not discretized, a dynamic geofence corresponding to
the separation distance can be set around the predicted UAV position in the flight plan, which moves continuously over time.

![Figure 2. Options for temporal allocation of airspace.](image)

An additional factor to consider when allocating unit spaces to UAVs is the exclusivity of airspace use. In other words, it is necessary to determine whether to limit the number of UAVs allocated simultaneously in a unit space to one (Figure 3a) or to allow plurality (Figure 3b). Suppose only one UAV is allocated in the unit space within a specified time. In that case, the possibility of a mid-air collision can be kept very low, given that there is no conflict with other plans and that all UAVs fly normally (i.e., as planned). In addition, UAVs’ sensing and communication requirements to secure separation or prepare for exceptional situations can be relaxed. On the other hand, in areas where traffic is concentrated, such as nodes in the network structure or takeoff and landing sites, other UAVs cannot utilize the space until the flight of an allocated UAV is completed, which may cause congestion. Multiple flight units can be allocated to a unit space to mitigate the congestion. In this case, the efficiency of airspace use may increase, but it is highly probable that mutual communication and sensing requirements are strengthened, accompanied by an increase in cost and weight because UAVs need to secure a separation distance by themselves.

![Figure 3. Plurality of flight operations in each airspace unit: (a) single operation; (b) multiple operations. A single UAV or a group of ones controlled by an operator for carrying a single flight operation forms a flight unit, enclosed by a circle.](image)

Along with the plurality of flight units, additional division of unit space is also considered in the operational methods shown in the literature. In particular, if a tubelike edge space is divided into several subspaces along the length in the Air-Network structure, UAVs can be allocated separately to the divided space. This means that the separation
within the edge can be controlled by the UTM system, not only by the UAVs themselves. In addition, because congestion is likely to occur in nodes where various traffic flows converge, there are ways to solve this problem by dividing nodes into multiple layers or installing auxiliary structures such as rotary intersections.

3. Review of Related Works

3.1. Air-Matrix

3.1.1. Single Operation per Unit Space

Full Allocation of Time

Skorup [19] suggested auctioning airspace, in which the federal government divides low-altitude and urban airspace into a number of small blocks and auctions off exclusive rights to use each block to operators who want to fly UAVs. An operator who purchases blocks can combine them and make free flight paths only for their own UAVs. The specific size of blocks was not suggested, but it was assumed to be the average size of UAVs. Since the blocks assigned to one flight are reserved for the entire operation time of the flight, there will be no conflicts with other UAVs. However, the utilization efficiency of airspace remains low because blocks already passed through by the assigned UAV are wasted.

Partial Allocation of Time

Researchers at Nanyang Technological University (NTU) proposed and analyzed multiple concepts of airspace structures, including Air-Matrix and Air-Network models. An earlier concept of Air-Matrix was presented by Salleh et al. [6]. The urban airspace is divided into small blocks, each of which can be occupied by a UAV, and flight paths are created by connecting the nodes of the Air-Matrix lattice. The size of the block is determined by evaluating the degree of risk during flight. Each operator may evaluate the suitability of the block for its UAV operation based on C3 (Command, Control, and Communication), GPS, and RF capabilities. The authors suggested both temporal assignment methods: single-operation and multiple-operation in unit airspace. In the single-operation method, the UTM system generates routes by granting or denying permissions to enter each block according to the occupancy state of the block over time. Due to operating blocks dynamically, UAVs can fly along conflict-free routes safely without time delay once the flight path is approved.

3.1.2. Multiple Operations per Unit Space

In the following studies by the NTU researchers [10,21], the structuring of the Air-Matrix concept was presented with deconfliction for accommodating multiple flights in the same flight routes. First, the airspace is divided into small blocks of a certain size and the centroid of each block is taken as a node. The nodes of neighboring blocks are connected by a link and the collection of the nodes and links for collision-free blocks from obstacles forms a network for building flight routes. The operator of each UAV submits a flight permission request, which contains the takeoff node, destination, preferred takeoff time, and maximum endurable delay time for takeoff. Path planning algorithms can be used to independently create flight routes in the network, and, thus, multiple flight operations may have the same nodes and edges in their routes. Then, the UTM system controls the delay time of each operation to resolve the conflict and secure the separation time between flights sharing the same paths. An algorithm for deconfliction based on a genetic algorithm has been proposed in [21].

3.2. Air-Network

3.2.1. Single Operation per Unit Space

Partial Allocation of Time

Sunil et al. suggested four airspace designs, including two Air-Network designs [22], namely, Tube and Zones. The Tube design accommodates single-flight operation per unit space, while Zones allows multiple operations. In the Tube concept, the airspace is divided into several layers by altitude. Each layer is set to have a differing network
density, depending on its altitude. The higher the altitude, the lower the number of nodes and edges, so the network allows UAVs to fly at high speed over a long distance. For example, given two layers, the UAVs flying short distances are operated on the first layer at low speed, since the layer has a high density of nodes and edges, whereas the UAVs carrying out long-distance travel can be operated at higher speeds on the second layer. This means the UTM system can reduce the time delay that occurs when operating the UAVs at different speeds simultaneously. When a UAV plans to pass a node, the system assigns the node for a prescribed time interval. During the time the UAV occupies the node, other UAVs cannot pass that node. A list of predicted occupancy is updated for each node in real time. This list is shared with all UAVs, and new routes are created along non-occupied nodes using the list. As the occupancy of a node is irrelevant to the flight direction, the edges allow two-way traffic.

Zhu and Wei proposed two different Air-Network designs [24,25]. The first one builds a network with locally connected nodes, whereas the nodes are fully connected in the second design. The first design has a simple network structure with a low degree (number of connected edges of a node) per node, but flight routes are zigzag. The flight paths in the fully connected network are straighter than in the first one, but conflicts of plans are more probable due to the maximized degree of every node. The path must avoid any no-fly zones and be built along one-directional edges. When the paths of a flight are defined as static geofences, they can be used for other UAVs only when the flight is completely finished. Therefore, a dynamic geofence is assigned around each UAV in flight to prevent a collision. The dynamic geofence is placed along the flight path, and its length is proportional to the speed of the UAV.

3.2.2. Multiple Operations per Unit Space

Partitioning only in Non-Node Unit Spaces

Salleh et al. also proposed two Air-Network designs: over-building and over-road methods [10]. In the over-building method, nodes are generated only at a specific height above buildings. A linking edge is configured between two nodes to pass over open spaces. In the over-road method, nodes are placed on each layer at a certain height above roads and are connected via links following the road contours. The collision avoidance systems in the two methods are the same as the Air-Matrix concept in Section 3.1.2.

The airspace design of Zones presented by [22,23] segments the airspace horizontally. It is composed of directed edges entering or exiting a city center and circular edges surrounding the city center in a clockwise or counterclockwise direction, as shown in Figure 4. Since there is no altitude limit at the edges, the flight altitude of each UAV is determined in its own flight planning. This method uses self-separation resolution, such as by velocity or altitudinal difference, to avoid conflicts between UAVs. However, adjusting the horizontal heading angle is not allowed in the flight along the edges.

![Figure 4. Airspace design of Zones. Redrawn from [22].](image)

Bae et al. used graph-based networks with similar operational concepts in the existing ATM system [27]. The entire space of an edge is a unit space that is one-way only, and if
a UAV approaches within the safe distance of the preceding UAV in the same edge, the follower needs to match its speed with the predecessor. Each UAV should be separated from others by a safe distance of 5 s. There are two types of nodes: confluence nodes and intersection nodes. A confluence node is a node in which two edges are merged into one edge. When two UAVs approach the confluence node, the faster one has the priority to go first. On an intersection node, a UAV that arrives first within a certain distance from the node takes priority, regardless of speed. Therefore, UAVs may be required to decelerate or hover for a moment when they approach a busy intersection.

Partitioning in All Unit Spaces

Labib et al. divided airspace into a few layers with regular intervals of altitude [28]. The interval of layers is determined by a containment limit of the largest UAV flying in the airspace, which is defined by the International Civil Aviation Organization (ICAO) as the volume with a 95% chance a mobile vehicle is within it for any time of its stated position. The containment limit is calculated from the error between the true position and the assigned flight path of a UAV. The airspace is discretized using the alpha shape method [39], then the UTM system builds up a network of structuring airspace, specifically, the static obstacle-free layers, based on a topological approach (illustrated in Figure 5). The topological method divides the original three-dimensional airspace into two-dimensional horizontal layers and samples the obstacle-free points in the layers so that they can be reconstructed in three dimensions by being connected with links [40]. In this network, edges are operated only with a set of rules, such as a speed limit, driving direction, and maximum traffic density. Information is exchanged through ad hoc communication between UAVs without direct communication with a UTM system. The cross-sectional area of edges is regulated by the UAV’s containment limit, as in Figure 6, in the same way for the interval of layers. The flight state of UAVs (e.g., hovering and cruising) can be changed in nodes, and the higher the layer is, the longer the created edges are, due to the topological properties. Therefore, a UAV takes a flight with higher velocity on the upper layers. Three methods were proposed to avoid collision between UAVs when the number of UAVs exceeds the maximum capacity of the edge. The first method is that a UAV simply hovers at the current node and waits its turn to enter a crowding edge. The second is a method of stochastically determining whether to stay on the same path or take an alternative new path. The third is to prevent, beforehand, other UAVs from selecting the same path through information exchange between UAVs, determining and modifying paths. It is argued that all the methods lessen the system load through communication between UAVs, and UAVs can satisfy the limited mission time because time delay can be reduced by local routing decisions through the airspace.

Figure 5. Representation of the topological approach in [40].
Devasia and Lee presented airspace structuring with the concept of UAV traffic network (UNET), which is a unit of large and wide airspace, and several sector-level UNETs (SNETs) separated into sectors at a regular size [29]. The nodes and edges are defined away from obstacles in each SNET. The SNET dynamically updates available route networks, and local commercial groups can develop or manage information on SNET. An operator can generate an optimal route in an actual flight using an internet application. When all UAVs fly at a constant speed, they have different departure times so that they do not collide within the same edge. If the speeds are different, the SNET searches for different routes for each operating speed, or a UAV following another one scheduled earlier can hover and wait in an edge. In addition, a structure for preventing collisions at a node has been proposed. As shown in Figure 7, each edge entering a node has a number, and a UAV entering the node through the edge moves to the layer of the level number that matches the edge number. The UAV traffic can pass a node without conflict with this three-dimensional roundabout.

In the airspace design proposed by Sacharny and Henderson, edges are set up on the road, and all UAVs take a flight at a constant speed [30]. The capacity and the flight direction are assigned to each edge. Edges of opposite directions are installed above the same road just as a multi-lane road on the ground. A node is composed of several small edges in the form of a roundabout, as illustrated in Figure 8, and multiple UAVs can enter there within the capacity of each node. As an operator suggests a flight plan with destination and preffered routes, a greedy scheduler algorithm determines the time to take off and a corrected route by considering the congestion level in the future. Since the greedy algorithm is employed in a fast and intuitive manner, it is possible to operate UAVs immediately upon request. However, the use of the entire airspace is less efficient than in the case that dedicated flight operation management is implemented.
3.3. Air-Tubes

Low et al. suggested an airspace concept with several two-way traffic lanes [31]. Safe separation distance exists between UAVs in the same lane and adjacent lanes in all directions for mid-air collision avoidance. The lanes are continually developed by bypassing densely populated areas or restricted airspace and using infrastructure facilities such as train tracks and traffic lights. Therefore, lanes can be installed along roads, tracks, etc., by connecting transit points with different altitudes along the side of a high building. The priority of lane usage is determined according to the purpose of UAVs.

There are exclusive tunnels for UAV flights in the airspace concept proposed by Pathiyil et al. [32]. The lanes are created along canals, reservoirs, or coastal areas flowing around low-populated areas or on existing infrastructure facilities, just as railroads in urban areas. The airspace structure can be dynamically designed according to UAV traffic volume and flight characteristics. In addition, the authors set a no-fly zone as a keep-out geofence, which prohibits any UAVs from entering the designated area. While takeoff and landing sites are utilized to exchange traffic information of UAVs in real time, UAV traffic management stations can be added to the UTM infrastructure by considering the required communication range, flight convenience, distance to the airport, etc.

Embraer-X, an aerospace corporation developing eVTOL, suggested several principles, including flexibility of airspace structures to design the Urban Air Traffic Management (UATM) system for Urban Air Mobility (UAM) flights [33]. The key concepts in the suggested airspace design are Skyports and Corridors: Skyports are the stops for air taxis, and a Corridor is a public transport path to accommodate a number of vehicles, similar to highways [41,42]. When a pilot submits a flight request, the Urban Airspace Service Provider (UASP) plans direct routes on the corridor based on the information presented in the request. Furthermore, the UASP optimizes the route so that only one designated air taxi flies on that route.

Peinecke et al. suggested a modified class G airspace, class G+, in order to resolve the problems of operating UAVs within class G, such as heavy payload requirements for sensor equipment and conflict with the existing ATM system [34]. Class G+ is the form of a corridor that connects airfields and is created above rarely developed areas such as deserts, rivers, and forests, so as to not pass the city center or inhabited areas as much as possible. A network for low-altitude air delivery service is configured by installing antennas throughout corridors so that all airspace users can access information, including the UAV’s location, altitude, and speed. Information on aircraft operating in other classes is also shared through the network, and, thus, if an aircraft intrudes into the corridor, UAVs can utilize the shared information to self-separate to avoid mid-air collisions.

Gharibi [35] separated airspace into several zones, and each zone was structured into a system similar to a road traffic network, as shown in Figure 9. The proposed unit spaces are similar to the node and edge concepts in this paper but are defined slightly differently. The ‘airway’ is a unit space of the road of UAV flights, and an ‘intersection’ is the place connected by at least two airways; there are flight restrictions, similar to traffic direction.
designations. Additionally, a specific area of interest, such as a national park, is defined as a ‘node’, and free flight is possible within the node. A system called Zone Service Provider (ZSP) is introduced more than once in each zone. It provides navigation information of unit spaces within its designated area and traffic control order of overall operations (e.g., hovering, forced landing) to the UAVs. When a UAV moves to another zone, the operation authority is transferred to the new ZSP of the corresponding zone. Inbound and outbound gates are boundary junctions of adjacent zones and are considered intersections. Moreover, there is an express airway between the gates where UAVs can fly across a zone at once, called ‘transit’. The airspace design in [35] is a mixture of the Air-Network and Air-Tube models. Each ZSP creates an optimized route for a UAV flight in real time with its controlled unit space elements. The space assigned to the UAV flight is exclusive to other flights, and, thus, this idea can be categorized in Section 3.2.1, whereas the transits bypassing zones are Air-Tube structures.

**Figure 9.** Airspace design. Redrawn from [35].

### 3.4. Unstructured or Layered Airspace

This section summarizes the cases in which airspace is not structured at all or is only partially structured, meaning layer division and path planning are not performed with pre-designed unit spaces. The NASA UTM system is typical of these cases, in which a flight route is created by the UAS Service Supplier (USS), once a given operator submits a flight approval request. The airspace can also be temporarily structured until the finish time of flight when the route is generated [36]. It is difficult to classify the studies in this section with the criteria in the previous sections because the definitions of unit spaces are unclear or ambiguous. Therefore, the unstructured concepts are classified into two cases: airspace designs controlled by centralized systems and others operated in distributed manners.

#### 3.4.1. Centralized System

NASA’s UTM research [2,7] states that a UAS operator needs to propose an operation plan for a four-dimensional volume of airspace with spatial and temporal data, including takeoff and landing sites, flight time, and stopover, based on the information provided by the USS, in order to receive airspace allocation. Then, the USS compares the plan of airspace volumes with the FAA’s UAS Facility Map to determine the authorization of the airspaces. The details of structuring airspace are not described, but the system is operated by planning a direct optimal flight path based on the given operation plan.

Sedov and Polishchuk [8] proposed layer-based airspace designs: a single-layer design in which all UAVs operate at the same altitude and a multi-layer design with several layers of an appropriate height using graph-coloring algorithms [43]. Each design of airspace is operated by a centralized system or a distributed operational method. The centralized system means the UTM system knows the past and current operation plans and the state of all UAVs and also generates/approves routes without any conflict of plans. In the centralized system, a ground delay strategy is used for the single-layer design, and a layer assignment strategy is operated in the multi-layer one. In the ground delay strategy, the UTM system examines a flight plan from an operator and delays departure for a certain amount of time when a collision is predicted. This strategy is completely free from collisions...
and is easy to control through system management, whereas it may induce inefficiency compared to other methods because the departure delay is unknown at the time a flight plan is submitted. With regards to the layer assignment method in the multi-layer design, it allocates UAVs to layers, each of which is conflict-free, so that UAVs whose flight plans overlap are not assigned to the same layer. There is no additional delay time other than the calculation for processing path generation.

Sarim et al. divided the airspace under 400 ft into several layers, based on the minimum diameter for safe operation [36]. It is similar to the concept in [8], but they have some differences in structuring airspace when planning paths. In [8], paths are immediately planned on the layers, but, in [36], each layer is temporarily divided into sections of the size that UAVs can traverse within an appropriate time. A route is generated using waypoints, each of which is the center of each path segment, by the A* algorithm according to an operator’s request. In line with the departure and arrival time intervals corresponding to each spatial division along the route, as shown in Figure 10, the UAV occupies the spaces only at the corresponding time intervals. Other UAVs are treated as moving obstacles, and the optimal path is then regenerated using a MILP algorithm. Consequently, the airspace is operated space-efficiently, since the space is divided and dynamically managed with time intervals.

![Figure 10. Space allocation of dynamic geofence. Redrawn from [36].](image)

McCarthy suggested an airspace composed of three sets of layers above the minimum altitude of 50 m [37]. Each layer set consists of deconfliction layers and travel layers. If the flight distance is short, a UAV is operated in the lowest layer, and the opposite occurs, it can fly in the upper layer. A total of three geofences are determined using geospatial data, namely, No-Fly Zone (NFZ), Prior Permissions Zone (PPZ), and Temporary Reserve Zone (TRZ). The UTM system assigns routes to UAVs using the A* algorithm, based on these geofences. If there is a point where a UAV meets NFZ and PPZ on its direct route from origin to destination, then the flight is detoured, and each detour point is defined as a ‘node’, which is different from the previous definition of this paper. A safety tube is set for every time point at least 15 s before and 60 s after the point where the UAV is expected to pass, similar to a dynamic geofence, and the space is regarded as NFZ to other UAVs. The UTM is alerted after 45 s from the specified time of the safety tube due to the slowdown of the UAV. When no other UAVs are scheduled to fly in the safety tube, it is regenerated based on the location. However, if there is an overlap with the existing path, the UAV moves to the deconfliction layer and returns, as shown in Figure 11. At this moment, if a UAV already exists in the deconfliction layer, it remains in the travel layer and bypasses the other UAV in a horizontal direction to avoid the collision. Similarly, Maciel also suggested an airspace design with two-way droneways consisting of three lanes [38], which are an emergency lane, a cruising lane, and a slow lane, following the transmission line pathways shown in Figure 12.
3.4.2. Distributed System

Among the operations proposed in [8], a hovering strategy in a single-layer design and an on-demand descent strategy in a multi-layer design are used as distributed methods. The distributed system operates with vehicle-to-vehicle communication (V2V) capabilities in UAVs. In the hovering method, when UAVs approach each other within a safety distance, the UAV with low priority moves down for a while and hovers until no possibility of collision is identified. Since this method has a high fuel consumption rate for hover and wait, the priority between UAVs can be re-evaluated by checking the fuel consumption state. In the case of on-demand descent, all flights start from the top layer, and, when mid-air collision is detected, the UAV with low priority descends to lower layers in order. In both methods, a UAV that has started initially has a higher priority, and a UAV with a lower priority should act first when a mid-air collision is predicted. For emergency missions, the system assigns a high priority that matches the urgency.

As is introduced in Section 3.2.1, Sunil et al. also proposed two less-structured designs, i.e., Full Mix and Layers, in addition to their two Air-Network types [22,23]. The Full Mix airspace is an unstructured airspace in which each path is planned as a highway connecting the origin and destination immediately. It is argued that structuring airspace reduces operational efficiency due to high fuel consumption and rising expenses. Layers is a form in which several layers are vertically stacked in the airspace, but differently from Sedov and Polishchuk’s multi-layer concept. A certain heading range is assigned in each layer, as shown in Figure 13. A UAV starts flying in a layer that matches the direction of travel. There are two sets of layers, upper and lower, and the lower group can be used for low-speed and the upper group for high-speed flights. While both methods avoid collisions through self-separation, the Layers concept does not take into account the altitude resolution except for takeoff and landing.
4. Qualitative Research of Airspace Designs

Most existing studies on airspace structures and operational methods have only presented concepts that have yet to have a systematic comparison with other ones. Even in studies comparing the efficiency of several structural designs with numerical simulation, it is difficult to perform a consistent evaluation due to different performance criteria. In addition, as classified and analyzed in Sections 2 and 3, various airspace structures and operational methods appear in the literature, and, thus, it is necessary to analyze these concepts systematically. In this paper, the structure partitioning is categorized, in order to investigate the concepts and possible combinations formed with the temporal allocation and plurality in unit space. A qualitative study is performed in this section for the combinations that include design evaluation criteria.

4.1. Qualitative Study

Qualitative studies are considered as steps before starting primary research, giving reasonable support in designing the primary research while also working as a powerful and universal tool that allows decision-making. It is thus called a 'broad umbrella term' for selecting research methodologies that can be applied to subsequent main studies [44]. Conducting a qualitative study enhances the quality of subsequent quantitative research by refining research questions, developing precise measurement tools, and providing a comprehensive contextual understanding. This sequential approach is particularly advantageous for investigating intricate or less-studied subjects. However, qualitative research has limitations, including inherent subjectivity and potential bias from researcher interpretation, challenges in replicating findings, interpretive complexity during data analysis, and potential bias introduced through purposive sampling. Appropriate quantitative studies may be required as follow-up based on the qualitative study results.

Designing suitable evaluation criteria is essential to build up a standard qualitative study. In designing evaluation criteria, numerical reasoning can be employed. This reasoning can be built upon existing theory, studies, researchers’ experience, and collected opinions with surveys [45]. Calculating scores based on the weights given to criteria is considered one of the most efficient methods to quantify qualitative data [46,47]. Therefore, a comparative analysis based on the scoring is proposed using the classification in the following subsection: airspace spatial partitioning and operation methods. The airspace design combinations composed with the classification are evaluated with four criteria from operational perspectives. Subsequently, the total scores for the design combinations are calculated with distinct weights that emphasize stability and efficiency.

4.2. Spatial Partitioning and Operation Methods

To compare and evaluate the design and operation methods of the airspace structure, it is necessary to classify feasible spatial and temporal airspace allocation concepts and construct their combinations. The spatial partitioning of the airspace can be categorized into eight cases, as shown in Figure 14, depending on how the unit spaces allocated to flight units are defined:
(a) No partition in edges/nodes: All space in each edge and node forms a unit space for a single flight unit;
(b) Partition in edges: Only edges are partitioned into multiple unit spaces with a certain time interval;
(c) Layers in nodes: Nodes are partitioned into multiple layers with differing altitudes;
(d) Partitioned edges and layered nodes: Edges and nodes are divided into sub-structures;
(e) Direct corridor: Each pathway from a starting point and destination is directly connected by a single corridor;
(f) Corridor shrinking over time: The direct corridor is established at the beginning and it shrinks as the planned position of the flight moves over time. The space that the flight has already passed is returned for other uses;
(g) Dynamic geofence tubelet: A tube-like safety buffer is installed around the planned UAV’s position and moves over time along the corridor;
(h) Blocks: Rectangular cuboids created by a lattice.

Figure 14. Spatial partitioning methods of airspace.

Table 2 summarizes the relationship between the spatial partitioning methods and the proposed airspace structure models in Section 2 and unstructured design. The blocks (h) fit only the Air-Matrix model, and the methods of edges and nodes (a–d) can be used in the Air-Network. The methods of non-partitioned nodes (a,b) are suitable for Air-Tube, and corridor-based methods (e–g) are the possible cases in an unstructured UTM system where airspace is allocated and fenced upon user request.

Table 2. Airspace structure designs and possible partitioning methods.

<table>
<thead>
<tr>
<th>Structure Designs</th>
<th>Partitioning Methods in Figure 14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air-Matrix</td>
<td>(h)</td>
</tr>
<tr>
<td>Air-Network</td>
<td>(a), (b), (c), (d)</td>
</tr>
<tr>
<td>Air-Tubes</td>
<td>(a), (b)</td>
</tr>
<tr>
<td>Unstructured</td>
<td>(e), (f), (g)</td>
</tr>
</tbody>
</table>

The methods of operating airspace can be classified in terms of a temporal allocation strategy and the plurality of allocating flight units per unit airspace. Based on the analysis in Section 2, the following five types are presented:

(1) Temporal allocation—full: A flight dominates every unit space on its flight path during total time of operation;
(2) Temporal allocation—partial: Each unit space allocated to a flight is only usable for a period of time;
(3) Multiple operations at nodes: Multiple flight units can be assigned in nodes;
(4) Multiple operations at non-node spaces: Multiple flight units can be assigned in a unit space except nodes;
(5) Multiple operations at edges and nodes: Multiple flight units can be assigned in edges and nodes.

4.3. Score Setting

In order to perform quantitative analysis, criteria for evaluating the spatial partition and operation methods summarized in the previous section are devised. There are four criteria: airspace efficiency, computation load, communication load, and safety. First, efficiency indicates how efficiently the airspace can be used: the more flying units located in the same space, the higher the score. Computation load refers to the required computation of the UTM system to maintain the corresponding structure or operation method and resolve conflicts of plans. The score is high for a significant computational load. Communication load indicates the amount of communication between UTM–UAS and inter-UAS required for safe UTM operation. Safety refers to the robustness of the UTM against mid-air collisions and crashes that may occur due to disturbances or emergencies.

Table 3 shows the scores on every type of spatially partitioned airspace. The stability factor is not considered in this evaluation because it closely ties with temporal allocation and plurality options and, thus, is mainly used for evaluating them. The efficiency score of blocks (h) is set to be the same as one of the partitioned nodes and layered edges (d), since the level of segmentation is maximal in both partitions. The efficiency scores for the others are given by comparing the two methods. Computation load score varies with the real-time computation required in the methods: dynamic geofence (g) receives the highest and simple less-partitioned ones obtain low scores. Partitioned nodes and layered edges (d) and dynamic geofence (g) have high marks in computation load because they may require frequent communication for preventing collisions between successive flights in a congested area.

<table>
<thead>
<tr>
<th>Partitioning Methods</th>
<th>Efficiency</th>
<th>Computation Load</th>
<th>Communication Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) No partition in edges/nodes</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(b) Partition in edges</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>(c) Layers in nodes</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(d) Partitioned edges and layered nodes</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>(e) Direct corridor</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(f) Corridor shrinking over time</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>(g) Dynamic geofence tubelet</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>(h) Blocks</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 4 shows scores of the five temporal allocation and plurality options. Allocating the entire time is the safest, with minimal flight capacity among the options, and also requires a small amount of computation and communication load. As the plurality of operations increases, the stability score of airspace operation is set lower while the efficiency and required communication increase. Up to the third option, i.e., multiple operations at node spaces, the separation between flights can be controlled by the assignment of UTM with increasing computation load. However, it is conjectured that, in the rest of the options, the centralized UTM control would not be enough to separate the UAVs flying along the same edges at low altitude, which would instead cause an increase in communication burden.
Table 4. Scoring of temporal allocation methods and plurality in operation.

<table>
<thead>
<tr>
<th>Temporal Allocation and Plurality</th>
<th>Safety</th>
<th>Efficiency</th>
<th>Computation Load</th>
<th>Communication Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Temporal allocation—full</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>(2) Temporal allocation—partial</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>(3) Multiple operations at nodes</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>(4) Multiple operations at non-node spaces</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>(5) Multiple operations at edges and nodes</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>

4.4. Evaluation of Airspace Design Combinations

The derived airspace partitioning and operation methods are combined, and each combined airspace design is evaluated based on the scores of its component methods. Table 5 shows the possible combinations of spatial partitioning with temporal and plurality allocation. Because not all operational methods are feasible, depending on spatial partitioning, a total of 13 design combinations are feasible. For example, the structure from (a) or (b) does not offer multiple operations in a node, since no sub-structure is given in the node. Blocks (h) are only available in Air-Matrix, and no edges or nodes can be placed in the airspace structure. Thus, only temporal allocation methods are combined with block partitioning. On the other hand, the same combination can lead to designs of different complexity depending on the airspace structure model. No partitioning (a) combined with a ‘full’ temporal allocation method may have considerably different operation complexity in Air-Network and Air-Tubes.

Table 6 presents two sets of weights assigned with the four criteria, i.e., safety, efficiency, computation, and communication load, with distinct emphasis on stability and efficiency. The safety-focused weighting assigns greater importance to safety scores of the combinations compared to their efficiency scores, while the efficiency-focused weighting exhibits the opposite. Table 7 displays the scores for the 13 combinations based on the given criteria, along with their weighted sums using the focuses in Table 6. In the symbol representing each design combination in Table 7, the character in parentheses denotes the partitioning method, while the number after the dash signifies the operation method. This operation method is one of the temporal allocation strategies and plurality options within unit spaces. The scores for the combinations are primarily calculated by summing the scores of component methods, namely, partitioning and operation methods. Scores for the same combination applied in different structural models are adjusted while considering varying implementation aspects.

Upon reviewing the summation in Table 7, combinations with full temporal allocation ((a)–(1) in Air-Network and Air-Tubes) exhibit higher scores compared to others, particularly when safety is the primary weighting factor. Conversely, under a stronger emphasis on efficiency, ((a)–(1) in Air-Network) attains a higher score than ((a)–(1) in Air-Tubes), due to the inherently more space-efficient nature of the Air-Network design. The weighted sums of similar design combinations may differ greatly due to their elemental differences. For example, the design combinations ((a)–(1) in Air-Network) and ((a)–(2) in Air-Network) both have no partitions in space. However, ((a)–(1) in Air-Network) employs full temporal allocation, while ((a)–(2) in Air-Network) utilizes partial temporal allocation for each flight unit. With the safety-focused weighting, full temporal allocation reduces the likelihood of emergencies compared to partial temporal allocation. This results in a much higher total score for ((a)–(1) in Air-Network) than for ((a)–(2) in Air-Network). On the other hand, for the unstructured combinations, high scores are given when airspace is totally allocated to a flight unit shown in ((e)–(1)), which minimizes computation and communication loads. Table 7 indicates that unstructured designs receive lower scores than structured ones with multiple flight operations, especially when optimizing airspace efficiency is the primary consideration.
Table 5. Combinations of partitioning and operation methods.

<table>
<thead>
<tr>
<th>Spatial Partitioning</th>
<th>Temporal Allocation and Plurality Allocating</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
</tr>
<tr>
<td>(a) No partition in</td>
<td>No partition with full temporal allocation</td>
</tr>
<tr>
<td>edges/nodes</td>
<td></td>
</tr>
<tr>
<td>(b) Partition in edges</td>
<td>None</td>
</tr>
<tr>
<td>(c) Layers in nodes</td>
<td>None</td>
</tr>
<tr>
<td>(d) Partitioned edges and layered nodes</td>
<td>None</td>
</tr>
<tr>
<td>(e) Direct corridor</td>
<td>Full temporal allocation at direct corridor</td>
</tr>
<tr>
<td>(f) Corridor shrinking over time</td>
<td>None</td>
</tr>
<tr>
<td>(g) Dynamic geofence tubelet</td>
<td>None</td>
</tr>
<tr>
<td>(h) Blocks</td>
<td>Full temporal allocation at blocks</td>
</tr>
</tbody>
</table>
Table 6. Weights with distinct emphasis on stability and efficiency.

<table>
<thead>
<tr>
<th>Main Focus of Weights</th>
<th>Safety</th>
<th>Efficiency</th>
<th>Computation Load</th>
<th>Communication Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety focused</td>
<td>3</td>
<td>2</td>
<td>−2</td>
<td>−1</td>
</tr>
<tr>
<td>Efficiency focused</td>
<td>2</td>
<td>3</td>
<td>−2</td>
<td>−1</td>
</tr>
</tbody>
</table>

Table 7. Scoring of the combinations of airspace structure designs and operation methods.

<table>
<thead>
<tr>
<th>Design Combination</th>
<th>Safety</th>
<th>Efficiency</th>
<th>Computation Load</th>
<th>Communication Load</th>
<th>Summation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Safety Focused Efficiency Focused</td>
</tr>
<tr>
<td>(a)–(1) in Net.</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>(a)–(1) in Tub.</td>
<td>3</td>
<td>0</td>
<td>1 *</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>(a)–(2) in Net.</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>(a)–(4) in Net. or Tub.</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>(b)–(2) in Net. or Tub.</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>(c)–(3) in Net.</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>−1</td>
</tr>
<tr>
<td>(c)–(5) in Net.</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>(d)–(3) in Net.</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>−3</td>
</tr>
<tr>
<td>(e)–(1) in Un.</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>(f)–(2) in Un.</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>−1</td>
</tr>
<tr>
<td>(g)–(2) in Un.</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>4</td>
<td>−4</td>
</tr>
<tr>
<td>(h)–(1) in Mat.</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>(h)–(2) in Mat.</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>


5. Conclusions

For a UTM system to be successfully developed for low-altitude urban areas, it is essential to design efficient and safe airspace structures and operation methods. In our research, previous studies on operating airspaces in UTM systems were reviewed and classified with several features: structuring methods of airspace, methods of temporal assignment and operation plurality, substructure partitioning, and centrality of unstructured airspace management. The structured concepts in the literature were categorized by the airspace structure models proposed in this paper: Air-Matrix, Air-Network, and Air-Tubes. Based on this review, a qualitative study was undertaken to build a guideline for quantitative studies in the future. Evaluation criteria are designed for comparing design alternatives, which are formed by combining spatial partitioning, temporal allocation, and plurality options. Considering the rise in the need for UAS operations in low-altitude urban areas and current efforts to establish UTM systems in many countries, preliminary studies of building estimation and evaluation tools for safe and efficient UTM architecture are necessary. With the qualitative study presented in the paper, further deeper analysis with quantitative approaches and numerical simulations is required for future work.

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