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Capturing Desired Attributes of a Dynamic Airspace Design Method

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From 2007 to 2010, six airspace design methods were developed by NASA with the goal of dynamically changing sector boundaries to reduce imbalances between air traffic demand and control capacity. These airspace design methods were evaluated in either or both fast-time and human-in-the-loop air traffic simulations. Whereas all of the six airspace design methods share a common goal – to reduce demand and capacity imbalances by redrawing sector boundaries – each method uses a different approach to achieve this goal. The objective of this paper is to capture desired attributes of a dynamic airspace design method. That is, using the previous simulations' data, identify attributes from the six methods that increase air traffic system benefit and generate airspace designs that are acceptable to air traffic controllers. The intent of this paper is not to specify a particular airspace design method. Rather, the intent is to compile a list of desired attributes of a consolidated airspace design method that may be implemented in the future for further evaluation and development. Results show that the system benefit and the controller acceptance level of redrawn airspace boundaries increased most with attributes that enhanced the output sectors' alignment to the direction of traffic flow. They are clean-sheet followed by local-improvement redrawing approach, aircraft count and sector design cost function base, and modified topology from the input airspace. Another attribute, implicit output sector number specification, increased the system benefit when compared to explicit specification.

I. Introduction

NASA has been conducting research and development in future airspace that is flexible, dynamic, and adaptable based on air traffic demand. In the current U.S. national airspace system, imbalances between traffic demand and control capacity are mainly addressed by reducing demand, with use of traffic flow restrictions such as ground delay and rerouting. For the future airspace, adjusting the capacity portion of the imbalances by changing airspace is proposed.[1] As a part of this effort, six airspace design methods have been developed between 2007 to 2010, with the goal of dynamically changing airspace boundaries to decrease the demand-capacity imbalances.[2-14] With this decrease, reduction in traffic flow restrictions is expected.[15,16] To evaluate these design methods, a series of fast-time and human-in-the-loop air traffic simulations were performed. These studies include assessment of the benefits of redrawn sectors relative to the original ones,[17-20] and human factors issues such as the controllers' subjective acceptance level of the redrawn sectors,[21,22] operational feasibility,[23] and the effect of sector boundary changes on the controllers' subjective workload ratings.[24,25]

Whereas all six dynamic airspace design methods share a common goal – to reduce demand and capacity imbalances by changing airspace boundaries – each method uses a different approach to achieve this goal. For example, the inner boundaries of input airspace are either modified or discarded and replaced with a new clean-sheet design. The objective of this paper is to capture desired attributes of a dynamic airspace design method. That is, to identify from among the attributes of the six methods that increase both the air traffic system benefit and the controller acceptance level of redrawn airspace boundaries. First, attributes of the six airspace design methods are cataloged according to a taxonomy developed for this purpose. Next, air traffic system benefits and controller acceptance levels of dynamic airspace are compiled from previous studies that investigated the relative performance of the six methods. Finally, the compiled benefits and acceptance levels are converted into a relative scale, which is

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used to identify desired attributes. The intent of this paper is not to specify a particular airspace design method. Rather, the intent is to compile a list of desired attributes of a consolidated airspace design method that may be implemented in the future for further evaluation and development.

The paper is organized as follows. Section II briefly describes the six airspace design methods, shows how an attribute catalog was developed, and presents this catalog. Section III describes fast-time and human-in-the-loop air traffic simulations in brief, and shows a compilation of air traffic system benefits and controller acceptance levels of dynamic airspace. Section IV describes steps taken to identify desired attributes, and presents the results. The paper is concluded in Section V.

II. Dynamic Airspace Design Method Attribute Catalog

In this section, the six airspace design methods are briefly described in the first subsection. The following subsection shows a process used to develop an attribute catalog, and presents this catalog.

A. Dynamic Airspace Design Methods

A dynamic airspace design method uses an algorithm to change input airspace boundaries to accommodate input traffic demand. Six airspace design methods have been developed by NASA and its research partners. These methods are identified as CellGeoSect, FlightLevel, Graph-based, SectorFlow, Voronoi, and Dynamic Airspace Unit (DAU), using the same naming convention as in Ref. 19. Algorithms in these methods all apply a cost function and constraints to generate output airspace that reduces imbalances between the input air traffic demand and control capacity.

CellGeoSect combines two methodologies into one; Cell[2,3] and GeoSect.[4-6] The Cell part of this method tessellates input airspace with hexagons, then groups them to generate output airspace. The GeoSect part refines this resulting airspace locally. FlightLevel[7] vertically partitions input airspace. Graph-based method[8,9] partitions a graph of traffic routes within input airspace to generate output airspace. SectorFlow method[10,11] clusters flight track points in input airspace to generate interim output airspace, then refines this locally. Voronoi[12,13] partitions input airspace by using Voronoi diagrams. DAU[14] moves the inner boundaries of input airspace in predefined increments to generate output airspace.

B. Attribute Catalog

Attributes of the six dynamic airspace design methods are organized into four groups: redrawing approach, cost function base, output sector number specification, and output airspace topology. These groups are discussed below. Because some methods are being developed beyond their final delivery to NASA, and each method can be configured in multiple ways to redraw sectors, this cataloguing effort is limited to the version and the configuration of each method that was used to redraw high-altitude sectors for five air traffic simulations. These simulations are described in the following section. With this limitation, Table 1 shows an attribute catalog of the six airspace design methods.

1. Redrawing Approach

The Redrawing Approach has three categories: clean-sheet, local-improvement, and clean-sheet followed by local-improvement. Clean-sheet indicates a method is using only the outer boundary of input airspace to generate output airspace, disregarding any inner boundaries. Local-improvement indicates a method is locally modifying the inner boundaries of input airspace to generate output airspace. Clean-sheet followed by local-improvement indicates a method is using both approaches sequentially.

2. Cost Function Base

The Cost Function Base has two categories: aircraft count, and aircraft count and sector design. Aircraft count indicates a method is using aircraft counts and count-related metrics, such as the number of aircraft moved from one region of airspace to another over a period, to assemble a cost. Aircraft count and sector design indicates a method is using geometric design features,[26] such as a sector's elongation and alignment with respect to the direction of traffic flows, in addition to aircraft count to assemble a cost.

3. Output Sector Number Specification

The number of sectors in output airspace is specified in two categories: explicit and implicit. Explicit specification indicates a method can determine the number of output sectors before the method runs. Implicit specification indicates that this number is not determined before a method runs, typically involving iterations to generate a specific number of output sectors.

4. Output Airspace Topology

The Topology of output airspace has two categories: preserved and modified. Preserved indicates the spatial relationships among the output sectors are the same as the input ones. For example, if three-sector input airspace were arranged as west, center, and east sectors, the same relationships exist in the output airspace. Modified indicates these spatial relationships are not the same as the input.

Table 1. Dynamic airspace method attribute catalog

Airspace Design Method	Redrawing Approach	Cost Function Base	Output Sector Number Specification	Output Airspace Topology
CellGeoSect	CL	AS	E	M
Dynamic Airspace Unit	L	A	E	P
FlightLevel	C	A	E	M
Graph-based	C	A	I	M
SectorFlow	CL	AS	E	M
Vornoi	C	AS	I	M

C: Clean-sheet
L: Local-improvement
CL: Clean-sheet and local-improvement

A: Aircraft count
AS: Aircraft count and sector design

E: Explicit
I: Implicit

M: Modified from the input airspace
P: Preserved as the input airspace

III. Air Traffic Simulations and Previous Airspace Design Method Evaluations

This section describes fast-time and human-in-the-loop air traffic simulations, along with associated benefits and controller acceptance levels, in three subsections. The first subsection describes three fast-time simulations and the second subsection describes two human-in-the-loop (HITL) simulations. The third subsection shows a compilation of the system benefits and the controller acceptance levels from these simulations.

A. Fast-time Air Traffic Simulation

The three fast-time simulations were performed using the Airspace Concept Evaluation System.[27] The scope of the first simulation was the high-altitude airspace of the continental United States, 24,000 feet and above. This airspace was reconfigured twice using three dynamic airspace design methods, CellGeoSect, SectorFlow, and Voronoi, to accommodate two different 24 hour traffic demands. A nominal traffic demand from year 2005, and 1.5 times of this demand were used.[20]

The scope of the second simulation was the airspace above 24,000 ft in the Kansas City Air Route Traffic Control Center (ZKC). This airspace was reconfigured to accommodate 24 hour traffic demand using all six methods.[19] Two-times year 2007 nominal traffic demand was used. The first and the second simulations assumed good weather condition.

In the third simulation, the same airspace as the second simulation was tested. Four methods, CellGeoSect, DAU, SectorFlow, and Voronoi, were used to reconfigure this airspace to accommodate two hour weather rerouted traffic demand.[17] Nominal traffic demand from year 2007 was increased by 15 percent, then rerouted to avoid regions of airspace with severe weather from a different day.

B. HITL Air Traffic Simulation

The two HITL simulations were performed in the Airspace Operations Laboratory at NASA Ames Research Center. The scope of the first simulation was four sectors in ZKC that include airspace at 29,000ft and above. This airspace was reconfigured using three dynamic airspace design methods, CellGeoSect, DAU, and SectorFlow, to accommodate artificial traffic demands.[23] Traffic demand was designed to have two 10 to 20 minutes peaks above the control capacity of input airspace.

The second simulation used four and seven sectors in ZKC, above 34,000 ft, in two tests. This airspace was reconfigured using four methods, CellGeoSect, DAU, SectorFlow, and Voronoi, to accommodate weather rerouted traffic.[21] Input from subject matter experts was used to reroute nominal traffic to avoid simulated convective weather cells in both tests. In both HITL simulations, controllers' subjective acceptance levels of the redrawn sectors were surveyed.

C. Summary of Airspace Design Method Evaluation

Table 2 shows a compilation of air traffic system benefits and controller acceptance levels from the fast-time and HITL air traffic simulations of participating methods, with data from Refs. 17 and 19-21. In this table, these references' nomenclatures are used where available. Also, underlined values indicate the best performance within a column, and blank cells indicate non-participation in the simulation. Columns 1-13 of Table 2 are metrics used to assess air traffic system benefits. In particular, columns 1, 5-7, and 10-11 assessed decrease in the average flight delay. Column 2 assessed increase in the average throughput, which is defined as a ratio between the numbers of actual landings and planned ones over a period. Columns 3, 8-9, 12-13 assessed increase in control resource utilization. This utilization is defined as a ratio between traffic demand and capacity, with the maximum value of 1 or 100%. Column 4 assessed an efficiency in the use of control resource. That is, for a given traffic demand, smaller number of sectors were considered as more efficient use of the control resource. Columns 14 and 15, with grey background, are controller acceptance levels. Data from the first HITL simulation are excluded from this table and also from the study. This is due to a significant difference in developmental states of the participating methods to the rest of simulations.

Table 2. Air traffic system benefits and controller acceptance levels. *For Fast-time 3, c indicates case. For HITL 2, s indicates number of sectors.*

	Fast-Time1				**Fast-Time 2**	**Fast-Time3**				**HITL 2**					
Airspace Design Method	R_t (%)	R_ε (%)	$\sigma_{\rho d}$	n_s	d	F c1	F c2	U c1 (%)	U c1 (%)	F s4	F s7	U s4 (%)	U s7 (%)	Z s4	Z s7
CellGeoSect	31	33	0.18	593	68	50	43	66	66	70	125	76	86	3.5	4.1
DAU					23	84	92	62	62	70	163	75	83	2.5	2.6
FlightLevel					25										
Graph-based					18										
SectorFlow	55	59	0.16	1031	30	44	44	65	66	63	115	74	86	3.3	4.6
Vornoi	50	63	0.17	565	58	67	54	63	64	57	160	75	76	4.3	2.4

R_t : Recovered average total delay
R_ε : Recovered average throughput
$\sigma_{\rho d}$: STD of flight count/capacity
n_s : Total number of sectors
d : Average total flight delay
F : Number of delayed/rerouted flights
U : Control resource utilization
Z : Controller acceptance level

IV. Desired Attributes of a Dynamic Airspace Design Method

In this section, the steps taken to identify desired attributes of a dynamic airspace design method are described, and the results are presented. The main idea is to transfer air traffic system benefits and acceptance levels of airspace design methods to attributes, on a relative scale. This transfer is performed in five steps: 1) conversion of the attribute catalog, represented in Table 1, into a method-attribute matrix, 2) conversion of values in system benefit metrics and acceptance levels, represented in Table 2 using a relative scale, 3) summation of the converted system benefits for methods, and the same for the converted acceptance levels, 4) transfer of the summed system benefits to attributes via matrix multiplication, and the same for the summed acceptance levels, and 5) normalization of the resulting two matrixes of the last step for number of times each attribute was evaluated for system benefits, and for acceptance levels, respectively. Each step is described in details below.

In the first step, the attribute catalog of the six airspace design methods, shown in Table 1, is converted to a six-by-nine method-attribute matrix α, Eq. (1). In α, rows correspond to airspace design methods, columns to attributes, and 1 indicates that the column attribute is in the method.

In the second step, benefits and acceptance levels in Table 2 are converted using a relative scale. This is done by mapping values in each column of Table 2 to three classes, high, medium, and low, according to their performance. For columns with four participating methods, medium is mapped twice. For example, the sixth column is converted to medium, low, high, and medium, from the top. The fifth column, with six participating methods, is converted to high, low, medium, low, medium, and high, from the top. When a column contains the same values, additional information, such as standard deviation of these values, are used in the mapping. Two exceptions are in columns 10 and 13. Due to lack of additional information to distinguish the two same values in these columns, column 10 is mapped to low, low, medium, and high, and column 13 to high, medium, high, and low. Once this classification is completed, relative scale values of 1.5, 1.0, and 0.5 are assigned to high, medium, and low, respectively, to facilitate numerical operations. The result of this conversion, β, is shown in Eq. (2). The blank cells in Table 2, which indicated non-participation, are replaced with 0s in β.

In the third step, air traffic system benefits, now converted to the relative scale values in columns 1 to 13 of β, are summed for methods then transposed to a one-by-six matrix $\left(\sum \beta_b\right)^T$, Eq. (3). Controller acceptance levels,

$$\alpha := \left.\overbrace{\begin{bmatrix} 0 & 0 & 1 & 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \end{bmatrix}}^{\text{C, L, CL, A, AS, E, I, M, P}}\right\} \begin{matrix} \text{CellGeoSect} \\ \text{DAU} \\ \text{FlightLevel} \\ \text{Graph-based} \\ \text{SectorFlow} \\ \text{Vornoi} \end{matrix} \qquad (1)$$

$$\beta := \left.\overbrace{\left[\underbrace{\begin{matrix} 0.5 & 0.5 & 0.5 & 1 & 1.5 & 1 & 1.5 & 1.5 & 1 & 0.5 & 1 & 1.5 & 1.5 \\ 0 & 0 & 0 & 0 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1.5 & 1 & 1.5 & 0.5 & 1 & 1.5 & 1 & 1 & 1.5 & 1 & 1.5 & 0.5 & 1.5 \\ 1 & 1.5 & 1 & 1.5 & 1.5 & 1 & 1 & 1 & 1 & 1.5 & 1 & 1 & 0.5 \end{matrix}}_{\beta_b} \; \underbrace{\begin{matrix} 1 & 1 \\ 0.5 & 1 \\ 0 & 0 \\ 0 & 0 \\ 1 & 1.5 \\ 1.5 & 0.5 \end{matrix}}_{\beta_z}\right]}^{R_t,\, R_\varepsilon,\, \sigma_{\rho d},\, n_s,\, d,\, F,\, F,\, U,\, U,\, F,\, F,\, U,\, U,\, Z,\, Z}\right\} \begin{matrix} \text{CellGeoSect} \\ \text{DAU} \\ \text{FlightLevel} \\ \text{Graph-based} \\ \text{SectorFlow} \\ \text{Vornoi} \end{matrix} \qquad (2)$$

converted to the relative scale values in columns 14 and 15 of β, are summed then transposed to another one-by-six matrix $\left(\sum \beta_z\right)^T$, Eq. (4).

In the fourth step, the summed air traffic system benefits are transferred to attribute by multiplying $\left(\sum \beta_b\right)^T$ with α, resulting in a one-by-nine matrix γ_b, Eq. (5). The summed controllers' acceptance levels of airspace design methods are transferred to attributes by multiplying $\left(\sum \beta_z\right)^T$ with α, resulting in another one-by-nine matrix, γ_z, Eq. (6).

$$\left(\sum_{column=1}^{13} \beta_b\right)^T = \underbrace{\begin{bmatrix} 13.5 & 5.5 & 1 & 0.5 & 15 & 14.5 \end{bmatrix}}_{} \tag{3}$$

CellGeoSect, DAU, FlightLevel, Graph-based, SectorFlow, Voronoi

$$\left(\sum_{column=14}^{15} \beta_z\right)^T = \overbrace{\begin{bmatrix} 2 & 1.5 & 0 & 0 & 2.5 & 2 \end{bmatrix}}^{} \tag{4}$$

$$\gamma_b = \left(\sum_{column=1}^{13} \beta_b\right)^T \times \alpha \tag{5}$$

$$\gamma_z = \left(\sum_{column=14}^{15} \beta z\right)^T \times \alpha \tag{6}$$

In the fifth and the final step, relative air traffic system benefits of the nine attributes, *C, L, CL, A, AS, E, I, M, P*, are normalized by dividing each value in γ_b by the number of times a corresponding attribute was evaluated for system benefits. For example, the clean-sheet redrawing approach attribute, *C*, is in FlightLevel, Graph-based, and Voronoi. The FlightLevel was evaluated for air traffic system benefits once, as indicated in column five of Table 2. The Graph-based was evaluated once, in the same column. The Voronoi was evaluated 13 times, as shown in columns 1 to 13 of Table 2. Therefore, a normalization factor of *C* for system benefits is 15 (1+1+13). Relative controllers' acceptance levels of the attributes, γ_z, are normalized with a similar process. Table 3 shows the number of times each attribute was evaluated for system benefits and acceptance levels.

Table 3. Attribute normalization factors

	Redrawing Approach			**Cost Function Base**		**Output Sector Number Specification**		**Output Airspace Topology**	
	C	**L**	**CL**	**A**	**AS**	**E**	**I**	**M**	**P**
Times included in System Benefit Evaluations	15	9	26	11	39	36	14	41	9
Times included in Acceptance Level Evaluations	2	2	4	2	6	6	2	6	2

C: Clean-sheet
L: Local-improvement
CL: Clean-sheet and local-improvement
A: Aircraft count
AS: Aircraft count and sector design
E: Explicit
I: Implicit
M: Modified from the input airspace
P: Preserved as the input airspace

The results of steps one to five are two one-by-nine matrixes: normalized relative air traffic system benefits of the nine attributes, $\overline{\gamma_b}$, and normalized relative controller acceptance levels of the attributes, $\overline{\gamma_z}$. Larger values in these matrixes indicate more benefit and better acceptance level, with the maximum possible value of 1.5. These transfer steps include two limitations. First, the relative scaling in the step two does not reflect differences of performance magnitudes within a system benefit metric. For example, if 100 , 99, and 98 were mapped to high, medium, and low, so were 100, 2, and 1. Second, the summation in the step three assumes that the benefit metrics in Table 2 have equal importance.

To identify desired attributes of a dynamic airspace design method that increase both the air traffic system benefit and the controller acceptance level of redrawn airspace boundaries the most, the normalized relative system benefit and acceptance level of the nine attributes, $\overline{\gamma_b}$ versus $\overline{\gamma_z}$, are plotted in Fig. 1. This figure indicates that *CL* in the Redrawing Approach group, *AS* in the Cost Function Base group, *I* in the Output Sector Number Specification group, and *M* in the Output Airspace Topology group are identified as most desired. Since two airspace design methods, FlightLevel and Graph-based, were evaluated only once for the system benefit and none for the controller acceptance level, these methods had limited impact on identification of the desired attributes.

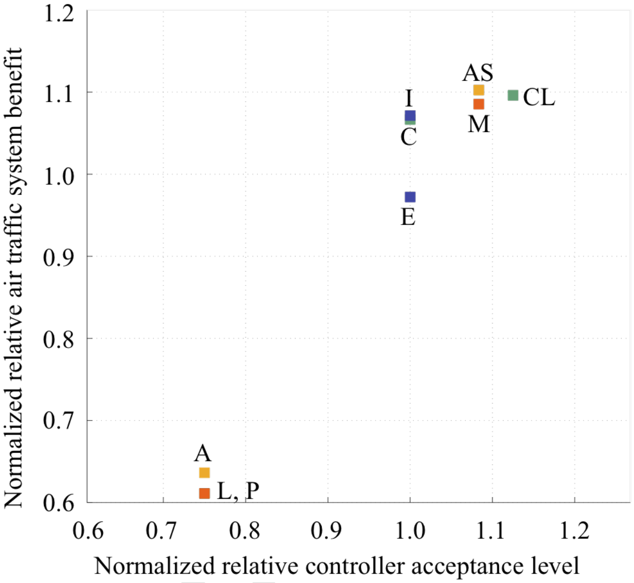

Figure 1. $\overline{\gamma_b}$ vs. $\overline{\gamma_z}$ *. L and P share the same location, and I is above C. Attributes in Redrawing Approach group are shown in green, Cost Function Base in Orange, Output Sector Number Specification in blue, and Output Airspace Topology in red.*

Based on the above results, the following observations are made. First is the performance difference between output airspace topology attributes *M*, modified from the input airspace, and *P*, preserved as the input airspace. Intuitively, if the spatial relationships among the output sectors were the same as the input ones, this output airspace would be familiar to the controllers. Therefore, higher acceptance level was expected for *P* over *M*. However, all acceptance levels came from the second HITL air traffic simulation, where traffic flow direction changed from the nominal to avoid regions of airspace with severe weather. Therefore, higher acceptance level of *M* over *P* indicates that the output sectors' alignment to the direction of flow was more important to the controllers than preserving the topology of the input airspace. Next is the performance difference between cost function base attributes, *A*, aircraft count, and *AS*, aircraft count and sector design. By considering output sectors' geometric design features, such as their elongation and alignment to the direction of traffic flows, *AS* outperformed *A* by far, both in system benefit and acceptance level. The last is the performance difference between redrawing approach attributes *C*, clean-sheet, and *CL*, clean-sheet followed by local-improvement. By refining the clean-sheet output airspace with local modifications, *CL* modestly improved performance of *C* in both system benefit and acceptance level.

V. Conclusion

From 2007 to 2010, six dynamic airspace design methods have been developed. These airspace design methods were evaluated in fast-time and human-in-the-loop air traffic simulations. Whereas all of the six dynamic airspace design methods share a common goal – to reduce demand and capacity imbalances by changing airspace boundaries – each method uses a different approach to achieve this goal. The objective of this paper is to capture desired attributes of a dynamic airspace design method. That is, to identify attributes of the six methods that increase both air traffic system benefit and controller acceptance level of redrawn airspace boundaries most. To meet this objective, first, attributes of the six methods are cataloged using four groups: Redrawing Approach, Cost Function Base, Output Sector Number Specification, and Output Airspace Topology. Next, air traffic system benefits and controller acceptance levels of redrawn airspace are compiled from the earlier studies that investigated the relative performance of the six methods. Finally, the compiled benefits and acceptance levels are transferred to the attributes in a relative scale. From this, attributes that enhanced the output sectors' alignment to the direction of traffic flow are found to increase the system benefit and the acceptance level most. They are clean-sheet followed by local-improvement attribute in the Redrawing Approach group, aircraft count and sector design attribute in the Cost Function Base group, and modified from the input airspace attribute in the Output Airspace Topology group. Another one, implicit attribute in the Output Sector Number Specification group, increased the system benefit when compared to explicit specification. These four desired attributes are identified within the taxonomy and the relative scale developed for this study. Therefore, a consolidated airspace design method is expected to be implemented in the future for further evaluation and development.

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