# Benefits of Mid-Term Flexible Airspace Management in Presence of Weather

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**By examining the relative benefit of reconfigured airspace to the original airspace under the same traffic conditions, this paper assessed Flexible Airspace Management that reconfigures airspace boundaries. Using weather rerouted flight plans, four airspace design methods reconfigured the original airspace design in Kansas City Center. Air traffic simulations with estimated NextGen midterm (2018) airport capacities and traffic demand were performed for the original and each reconfigured airspace design. Analysis showed that within the simulated scenarios, reconfigured airspace demonstrated user benefit by decreasing 68% of the number of flights needing to be delayed or turned away from entering the airspace to maintain balance between traffic demand and capacity. Utilization of available air traffic control resources increased by 8%, demonstrating service provider benefit. Airspace design methods that applied more changes to the original airspace achieved more benefit. However, increased change from the original airspace configuration implied a possible increase in air traffic controller workload during the transition from the original to the reconfigured airspace.**

## Nomenclature

$a(i,k)$ = number of flights with short dwell time (less than three minutes) in sector $k$, airspace configuration $i$
$c$ = airspace reconfiguration threshold, in number of aircraft
$d(i,k)$ = average distance between traffic crossing points to boundary of sector $k$ in airspace configuration $i$
$D_i$ = similarity distance between sectors in airspace configuration $i$ to ones in the original configuration
$F_i$ = number of flights reduced to balance traffic demand and capacity in airspace configuration $i$
$h(k_i,O)$ = Hausdorff distance between sector $k$ in airspace configuration $i$ and a set of the original sectors $O$
$i$ = airspace configuration index
$k$ = sector index
$n(i,k)$ = average aircraft count in sector $k$ in airspace configuration $i$, with a maximum value of $c$
$O$ = a set of the original sectors
$S$ = number of sectors in the airspace
$T_i$ = average number of flights with short dwell time in airspace configuration $i$
$U_i$ = average control resource utilization of airspace configuration $i$
$X_i$ = average distance between traffic crossing points to boundary of sectors in airspace configuration $i$

## I. Introduction

AS the current National Airspace System evolves to meet the expected growth in traffic demand, the NextGen mid-term is defined as a timeframe (around 2018) when several key enabling technologies, including satellite-

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based surveillance, performance-based navigation, and data communication, are in place.[1] With the enabling technologies implemented, system-wide enhancements are expected, resulting in improved air traffic services.

Part of the improved services in the mid-term is expected to be delivered through Flexible Airspace Management, where airspace is reconfigured to reduce imbalances between traffic demand and air traffic control capacity.[2] These reduced imbalances are expected to benefit both user and service provider. Whereas a limited form of airspace reconfiguration is performed presently, such as sector combine and split operation, increased flexibility to reconfigure airspace is expected in the mid-term.[3]

The benefit of Flexible Airspace Management can be assessed by examining the relative benefit of reconfigured airspace to the original airspace under the same traffic conditions. In previous studies, the relative value of reconfigured airspace that attempted to reduce the demand and the capacity imbalance due to an increase in traffic volume were examined.[4,5] Clear-weather day flight plans and multiple airspace design methods were used in these studies. Another set of studies examined the relative value of reconfigured airspace to the current-day configuration in the presence of weather, with each study employing a single airspace design method.[6-8] In these studies, airspace was reconfigured to accommodate weather rerouted flight plans. Due to differences in the weather data and the airspace used among these studies, a comparative analysis of their results was not performed.

This paper assessed the benefit of Flexible Airspace Management in the mid-term, where four airspace design methods were applied to reconfigure the original airspace design in Kansas City Center for weather rerouted flight plans. Air traffic simulations with estimated mid-term airport capacities and traffic demand were performed for the original and each reconfigured airspace design. The relative benefit of each reconfiguration to the original airspace design was assessed with metrics, calculated from the air traffic simulation output.

The paper is organized as follows. Section II describes the method, including simulation setup and metrics. Section III describes results from the simulations, with analysis. The paper is concluded in Section IV.

## II.  Method

In this section, the method to assess the benefit of the mid-term Flexible Airspace Management is described in two subsections. The first subsection describes air traffic simulation setup. The second subsection describes metrics used to calculate the relative value of reconfigured airspace to the original airspace.

### A. Simulation Setup

Air traffic simulations of the continental U.S. in the estimated mid-term environment (2018) were conducted to study airspace in Kansas City air route traffic control center (ZKC) above 24,000 ft during two-hour peak traffic period. The simulations were constrained only by airport capacities.[9] That is, arrival and departure rates for each airport were enforced. Scheduled flights were cleared for departure accordingly, with a first-scheduled-first-served principle. Traffic demand and airspace capacity imbalance was allowed. This imbalance was used to count the number of flights needing to be delayed or turned away from entering the studied airspace to maintain balance between demand and capacity. Airspace Concept Evaluation System version 7.1 (ACES) was used to run these simulations.[10] Steps taken to set up the simulations are described in the following.

#### 1.  Airport Capacity and Traffic Demand

For 2018, the airport capacities were grown by an average 7% from the 2007 level, and the traffic demand was grown by approximately 15% from the 2007 level. The capacity and the demand data were taken from a NASA study.[11] In the study, individual airport capacity from Aviation System Performance Metric in May 3, 2007 was grown with a corresponding growth rate from Boeing Commercial Airplane research.[12] Also, a flight plan file corresponding to May 3, 2007 Aircraft Situation Display to Industry data was grown to represent a single day of clear-weather traffic demand in 2018. FAA data, including terminal area forecast and airport capacity benchmark, were used to determine these capacity growth rate and demand growth.[13-16]

#### 2.  Weather Rerouted Flight Plans

Clear-weather day flight plans were taken from the same NASA study used to set the airport capacities and the clear-weather traffic demand for 2018, then modified to avoid regions of airspace with severe weather from a different day. To select the severe weather day, flight delay statistics and corresponding weather data from Aviation System Performance Metric from June 1 to July 31, 2009 were reviewed. July 16 was selected as there was a high amount of flight delay, with convective weather activity in ZKC during the two-hour study period. The National Convective Weather Forecast hazard scale three and above, clustered in two-hour intervals, were used to indicate the

severe weather regions to avoid. A weather-reroute algorithm, developed at NASA Ames, was used to modify the flight plans.

### 3. Original Airspace Configuration

The operational configuration that handled the two peak-traffic hours on May 3, 2007 was selected as the original airspace configuration. In 2007, ZKC airspace above 24,000 ft contained 27 sectors in six Areas of Specialization (AOS). According to the FAA, an area of specialization is a group of contiguous sectors on which an air traffic controller is required to maintain currency. To meet changes in traffic demand, ZKC operated with some intra-AOS sectors combined when the demand was low, or split when the demand was high. This resulted in a number of operational airspace configurations.[17] The selected configuration contains 24 sectors, where among the original 27 sectors ZKC07 combined with ZKC21, ZKC33 with ZKC31, and ZKC47 with ZKC41. Figure 1 shows the 24 sectors, vertically grouped into 15 Lower Class A (LCA) sectors and nine Upper Class A (UCA) sectors, and color-coded AOS boundaries.

### 4. Airspace Reconfiguration Threshold

The average aircraft count in a sector over the two-hour study period, a value of 18, was selected as a threshold to initiate airspace reconfiguration. This threshold is selected to incorporate feedback from Subject Matter Experts that moving a sector boundary is not a solution for dealing with short-duration demand overload.

The selected threshold incorporated an increase in the number of aircraft an air traffic controller could handle due to an increased proportion of data communication capable aircraft in the traffic.[18,19] Initially, the threshold was set at 17, based on the average of high altitude sector Monitor Alert Parameter values from 364 sectors in the National Airspace System.[20,21] This value was then adjusted to 18 using a linear relationship from a MITRE study.[22] Forty percent of aircraft were assumed to be capable of data communication in 2018 to make this adjustment.
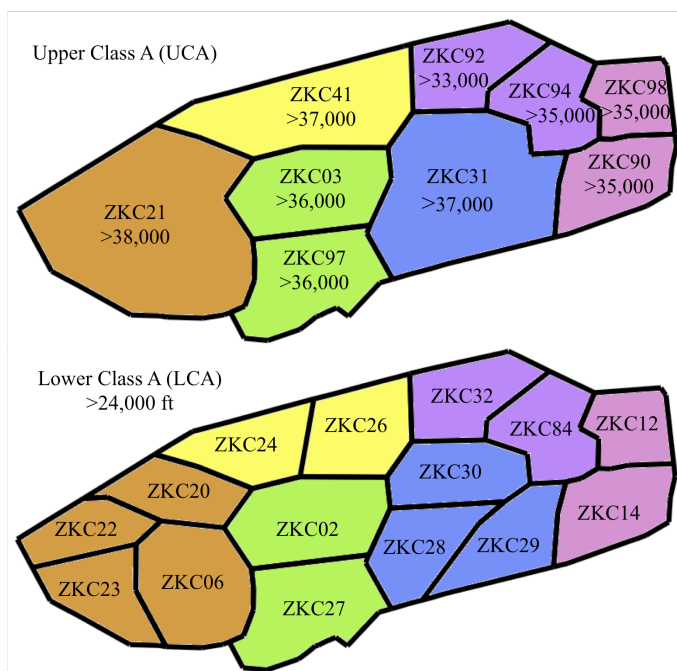


**Figure 1.** Original airspace configuration.

### 5. Airspace Design Method

Four airspace design methods were used in this study. They were Dynamic Airspace Unit (DAU),[23] Voronoi,[24] SectorFlow,[25] and CellGeoSect.[26,27] Given the original airspace configuration, the weather rerouted flight plans, and the airspace reconfiguration threshold, all methods attempted to reduce imbalance between traffic demand and airspace capacity. Whereas airspace capacity reduction due to severe weather was not explicitly input to these methods, weather rerouted flight plans implicitly represented such a reduction.

In a brief description, DAU effectively moves boundaries between sector pairs in discrete increments to balance aircraft count in airspace. Voronoi partitions airspace with Voronoi diagram, and uses a genetic algorithm to balance a cost. This cost includes aircraft count and airspace design parameters, such as number of flights with low dwell time in sectors and distance between traffic intersections and sector boundaries. SectorFlow balances aircraft count by partitioning airspace with clusters of flight track points, then adjusts these boundaries to refine the airspace design. CellGeoSect is a combination of two airspace design methods. A cell clustering method tessellates airspace with hexagonal cells. Aircraft count is balanced by partitioning airspace with clusters of these cells. An airspace splitting method, GeoSect, then refines the resulting boundaries between sector pairs. References 23 to 27 contain fuller descriptions of these methods.

### 6. Airspace Reconfiguration Cases

Two reconfiguration cases were developed to represent possible operational restrictions in 2018. In the first case (Case 1), when airspace was reconfigured the footprint between the ceilings of LCA sectors and the floors of

corresponding UCA sectors above must match. This restriction was placed to avoid a possible air traffic controller workload increase due to changes in vertical neighbors.[28,29] Airspace reconfiguration was also restricted to be within an AOS for Case 1. In the second case (Case 2), the footprint matching restriction was lifted. Furthermore, inter-AOS airspace reconfiguration was allowed among UCA sectors with a common floor altitude. Intra-AOS restriction for LCA sectors remained in Case 2. In both cases, the number of sectors within an AOS per vertical stratum was retained. For example, the number of LCA sectors in Ozark AOS was three for the original and the reconfigured airspace. Table 1 summarizes airspace reconfiguration conditions for Case 1 and Case 2.

All sectors in LCA and UCA were subjected to airspace reconfiguration except ZKC32 in LCA and its corresponding UCA sector, ZKC 92. The ceiling altitude of ZKC32 and the floor altitude of ZKC92 were different from that of its intra-AOS neighbor. Due to this difference, the sectors were excluded from reconfiguration to avoid creation of unusual sector shelving.

**Table 1.** Airspace reconfiguration conditions for Case 1 and Case 2

| Airspace Reconfiguration Condition | Case 1 | Case 2 |
|---|---|---|
| LCA airspace reconfiguration is restricted within AOS | Yes | Yes |
| Floor of UCA sector and ceiling of LCA sector below must match in shape and size | Yes | No |
| Inter-AOS airspace reconfiguration is possible in UCA among sectors with a common floor altitude | No | Yes |

## B. Metrics
Relative benefits of reconfigured airspaces to the original airspace were assessed with five metrics, calculated from the air traffic simulation output. The following describes each metric in detail.

### 1. Number of Reduced Flights
Weather reroutes effectively shift traffic demand in airspace, from severe weather regions to the remaining areas. If this shift created an imbalance between demand and capacity of the areas that traffic shifted into, the number of flights would be reduced, that is delayed or turned away from entering these areas, to reduce the imbalance.

Let $F_i$ be the number of flights reduced to balance demand and capacity in airspace configuration $i$. To calculate $F_i$, first, the sector with the highest average aircraft count during the two-hour study period is identified. Then, this sector's average aircraft count is compared to the airspace reconfiguration threshold that is used as the average sector capacity. If the average count is larger than the threshold, the flight that dwells longest in the identified sector is removed from the airspace configuration $i$ to reduce the demand, and $F_i$ is increased by one. Thereafter this process re-starts with the reduced demand. If the average count is the same or less then the threshold, calculation of $F_i$ is completed. $F_i$ is initially set to zero.

### 2. Air Traffic Control Resource Utilization
The ratio of an average sector aircraft count over the two-hour study period to the airspace reconfiguration threshold of 18 aircraft is used to estimate the average air traffic control resource utilization. For example, if the average sector aircraft count in the sector was nine, the average control resource utilization of the sector would be 50%.

The air traffic simulations were constrained only by the airport capacities, allowing sectors to have a larger average aircraft count than the average air traffic control resource. In these occurrences, the average aircraft count over the average control resource is assumed to be captured by $F_i$, and the maximum average control resource utilization is limited to 100%. Let $U_i$ be the average control resource utilization of airspace configuration $i$, given by

$$U_i = \frac{1}{S} \sum_{k=1}^{S} \frac{n(i,k)}{c}$$

(1)

*3. Airspace Similarity*

A previous study of airspace reconfiguration impact on air traffic controller workload indicated that a decrease in similarity between the original and reconfigured airspace was related to an increase in controller workload.[28] The similarity between airspace configuration $i$ and the original was calculated as a similarity distance, $D_i$, where larger distance indicates less similarity. Equation (12) from Ref. 30 was used to calculate $D_i$, given by

$$D_i = \sum_{k=1\ldots S} h(k_i, O) \tag{2}$$

*4. Number of Flights with Short Dwell Time*

Previous studies on airspace design indicated that increased number of flights with short dwell time in a sector was related to increased controller workload.[31,32] Let $T_i$ be the average number of flights with short dwell time in airspace configuration $i$, given by

$$T_i = \frac{1}{S}\sum_{k=1}^{S} a(i,k) \tag{3}$$

*5. Distance between Traffic Crossing Points and Airspace Boundary*

Studies also indicated that a decrease in the average distance between traffic crossing points and airspace boundary was related to an increase in air traffic controller workload.[31,32] Let $X_i$ be the average traffic crossing point's distance to airspace boundary in airspace configuration $i$, given by

$$X_i = \frac{1}{S}\sum_{k=1}^{S} d(i,k) \tag{4}$$

## III.  Results

In this section, results of the study are presented in four subsections. The first subsection presents the reconfigured airspace to accommodate the weather rerouted flight plans. The second subsection presents the assessed benefit of the reconfigured airspace. The third subsection presents a relation between the benefit of reconfigured airspace and magnitude of airspace design change. The fourth subsection presents reconfigured airspace design issues.

### A. Reconfigured Airspace

The original airspace, 24 sectors in ZKC above 24,000 ft, was reconfigured with four methods, DAU, Voronoi, SectorFlow, and CellGeoSect. After each reconfiguration, the reconfigured sectors were matched to the original sector identifications. To perform this matching, a pair of sectors between the original and the reconfigured airspace that shared the most amount of airspace was identified, and the original sector identification was transferred to the reconfigured sector. In case of multiple matching, the similarity distance from the airspace similarity metric was used to find a single match, where less distance indicated more similarity between the original and the reconfigured sector.

Each method was applied twice with different restrictions, Case 1 and Case 2. To enforce footprint matching between the ceilings of LCA sectors and the floors of corresponding UCA sectors in Case 1, the methods reconfigured vertically combined airspace within each AOS. For example, LCA and UCA sectors in an AOS were vertically combined, ZKC02 to ZKC03 and ZKC27 to ZKC97, then each algorithm reconfigured the AOS with the combined sectors. Once the reconfigurations were performed, the sectors were split back to LCA and UCA. When there was no matching between LCA and UCA sectors in AOS, such as Ozark, the methods separately reconfigured LCA and UCA sectors. Figure 2 shows reconfigured airspaces per algorithm and vertical stratum for Case 1.

For Case 2, inter-AOS reconfiguration was allowed in UCA sectors with a common floor, resulting boundary changes between ZKC41 and ZKC31, and also among ZKC94, ZKC98, and ZKC90. Figure 3 shows reconfigured airspaces per algorithm and vertical stratum for Case 2.
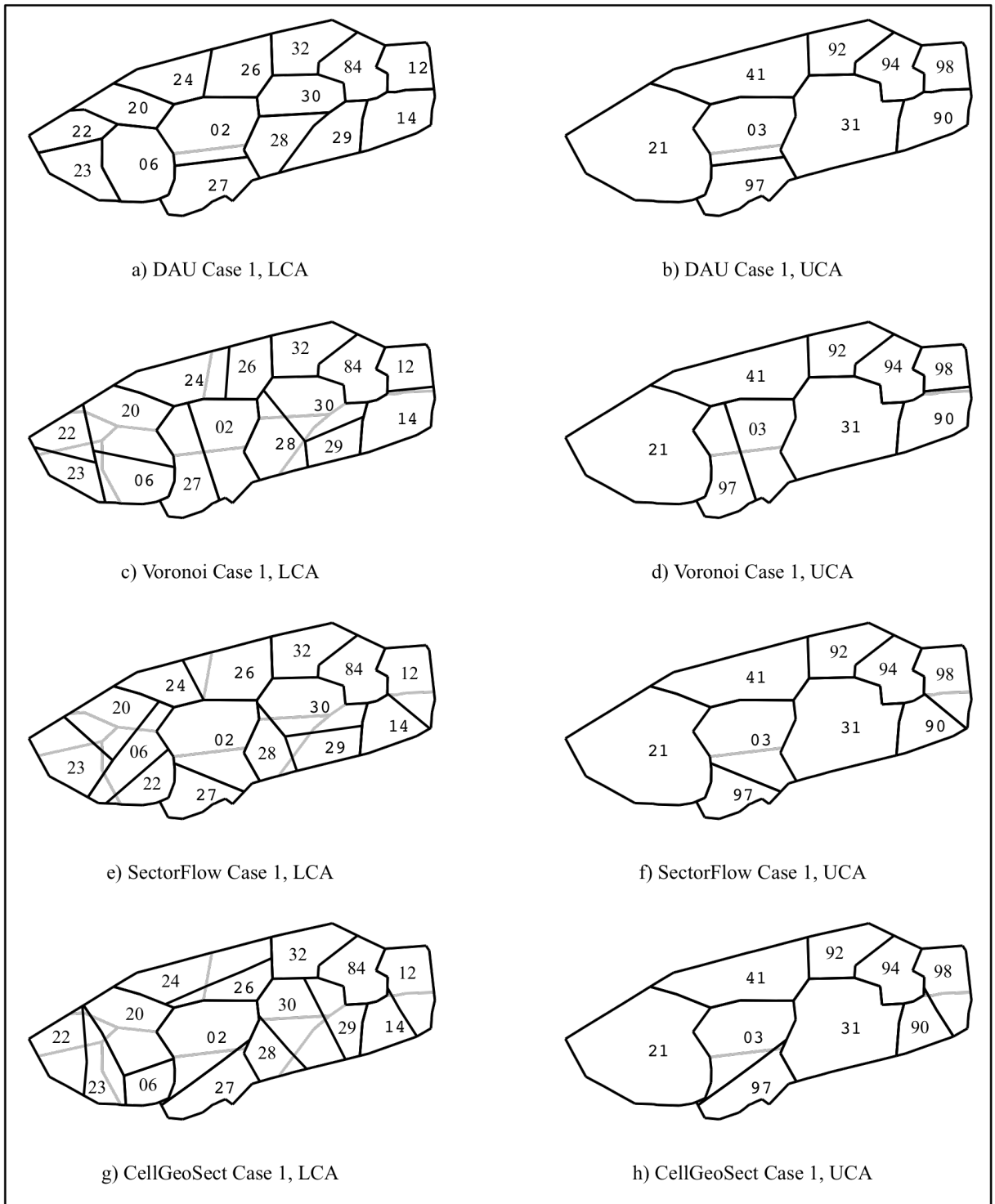
a) DAU Case 1, LCA

b) DAU Case 1, UCA

c) Voronoi Case 1, LCA

d) Voronoi Case 1, UCA

e) SectorFlow Case 1, LCA

f) SectorFlow Case 1, UCA

g) CellGeoSect Case 1, LCA

h) CellGeoSect Case 1, UCA

**Figure 2**. Reconfigured airspace, Case 1. *Lighter lines indicate the original boundary. Numbers indicate ZKC sector identification.*

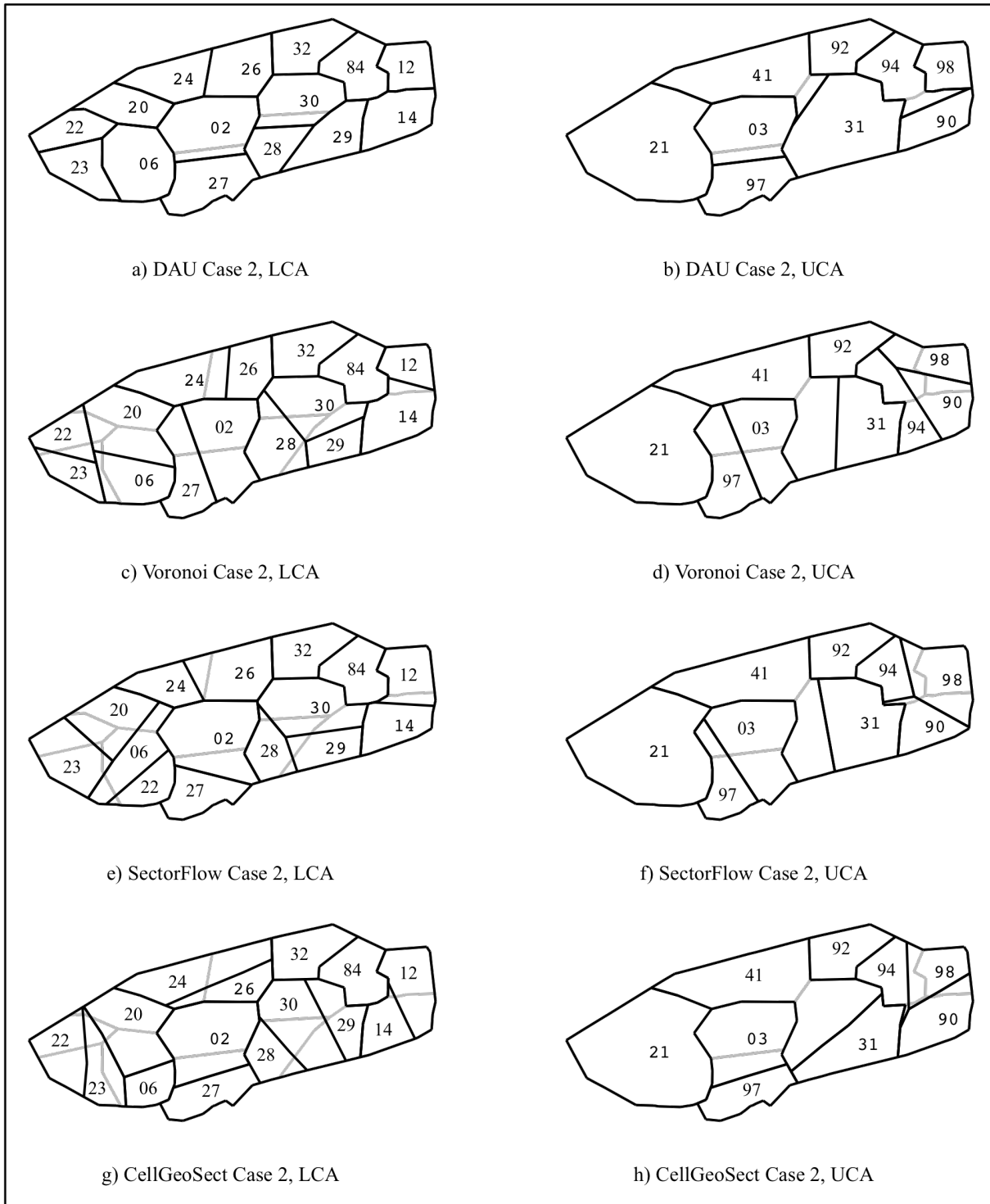American Institute of Aeronautics and Astronautics

a) DAU Case 2, LCA

b) DAU Case 2, UCA

c) Voronoi Case 2, LCA

d) Voronoi Case 2, UCA

e) SectorFlow Case 2, LCA

f) SectorFlow Case 2, UCA

g) CellGeoSect Case 2, LCA

h) CellGeoSect Case 2, UCA

**Figure 3**. Reconfigured airspace, Case 2. *Lighter lines indicate the original boundary. Numbers indicate ZKC sector identification.*

## B. Benefit of Reconfigured Airspace

The simulation results showed that weather rerouted flight plans caused the average aircraft count in the original sectors to change, on average, by 76 percent, compared to the clear-weather flight plans. Figure 2 shows the average aircraft count in each sector for the two-hour study period for both flight plans, with the average aircraft count from weather rerouted flight plan indicated by white bars with black edges.
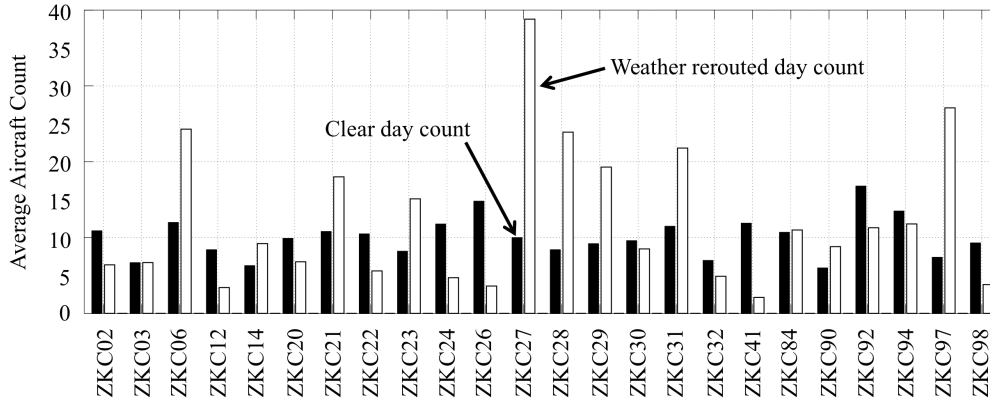


**Figure 4.** Average aircraft count in the original ZKC sectors.

The four airspace design methods attempted to reduce imbalance between traffic demand and airspace capacity. That is, under-used control capacity in the original airspace configuration would be applied to increased-demand regions of the airspace through airspace reconfiguration.

Figure 5 a) shows that when the original airspace was reconfigured, the number of reduced flights decreased. This decrease shows that reconfigured airspace provided benefit to the airspace users by allowing more scheduled flights to enter the airspace as planned.
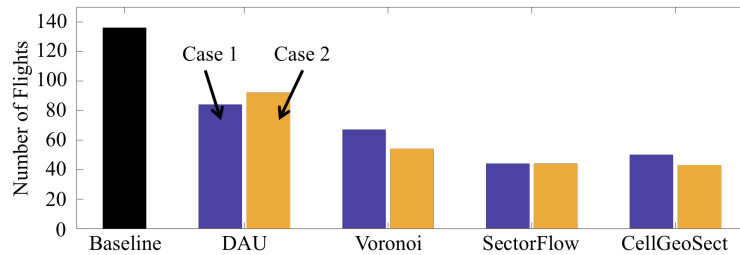


a) Number of Reduced Flights vs. Airspace Configuration
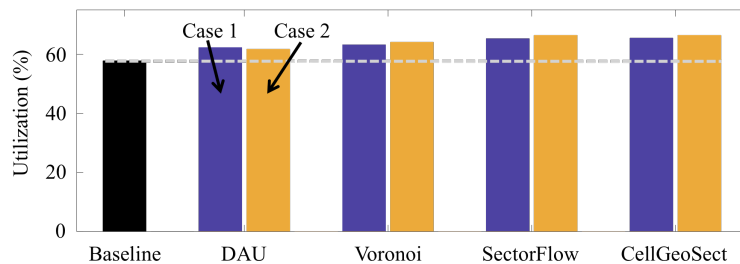


b) Control Resource Utilization vs. Airspace Configuration

**Figure 5.** Benefit metrics vs. airspace configuration

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Figure 5 b) shows that air traffic control resource utilization increased when the original airspace was reconfigured. This increase shows that reconfigured airspace provided benefit to the air traffic control service provider.

Airspace reconfiguration conditions, Case 1 and Case 2, were applied to represent possible operational restrictions in 2018. More restrictions were imposed in Case 1 than Case 2. A comparison between the cases in Fig. 5 a) and b) showed that these conditions did not significantly affect either benefits.

To assess the benefit of reconfigured airspace with a high confidence, accurate traffic demand estimation is necessary. Therefore, it is worthwhile investigating the impact of uncertainty in demand estimation on benefits in future studies.

## C. Reconfigured Airspace Design Parameter

From previous studies,[31,32] two airspace design parameters that can affect air traffic controller workload were identified. They were number of flights with short dwell time in the airspace, and distance between traffic crossing points and the airspace boundary.

An increase in the average number of flights with a short dwell time in the airspace was assumed to increase the workload of air traffic controllers. A short dwell time was defined as less than three minutes in a sector. Figure 6 a) shows that the average numbers of short dwell flights in Voronoi reconfigured airspace were less than the original airspace, indicating that it decreased controller workload. This suggests that Voronoi improved a design parameter of the original airspace with its reconfiguration. DAU, SectorFlow, and CellGeoSect had negative or no impact on this design parameter.

A decrease in the distance between traffic crossing points to the airspace boundary was assumed to increase workload of the air traffic controllers. Figure 6 b) shows that the average distances in Voronoi reconfigured airspace were more than the original airspace, indicating that it decreased controller workload. This suggests that Voronoi improved a design parameter of the original airspace with its reconfiguration. DAU, SectorFlow, and CellGeoSect had negative or no impact on this design parameter.
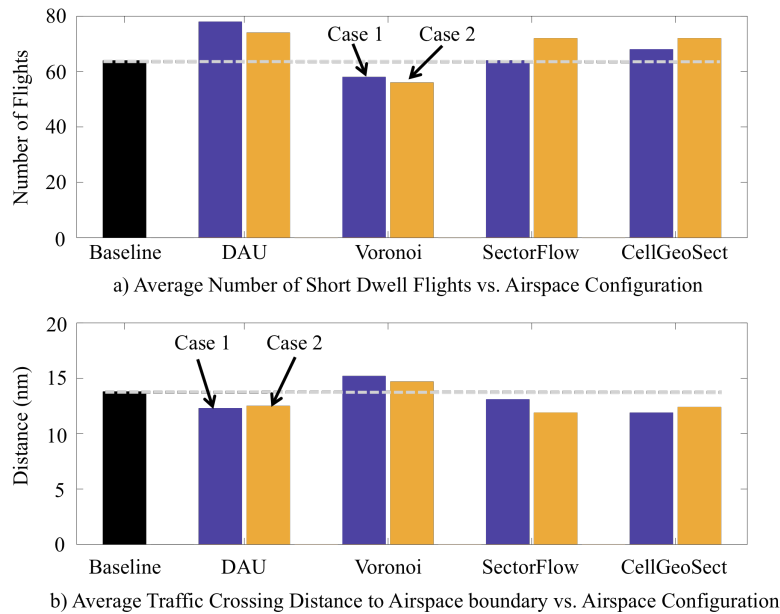


a) Average Number of Short Dwell Flights vs. Airspace Configuration

b) Average Traffic Crossing Distance to Airspace boundary vs. Airspace Configuration

**Figure 6.** Airspace design parameters vs. airspace configuration

Airspace reconfiguration conditions, Case 1 and Case 2, were applied to represent possible operational restrictions in 2018. More restrictions were imposed in Case 1 than Case 2. A comparison between the cases in Fig. 6 a) and b) showed that these conditions did not significantly affect the two design parameters.

## D. Benefit of Reconfigured Airspace and Magnitude of Airspace Design Change

When reconfigured airspace replaces the original airspace design, the air traffic controller would need to re-orient to the changed airspace design.[28] Calculating a similarity distance between the original and reconfigured

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airspace was one way to assess the magnitude of the airspace design change. Increased similarity distance represented increased magnitude of airspace design change, indicating increased re-orientation effort.

Figure 7 shows the similarity distance of each reconfigured airspace to the original airspace. When the similarity distance is compared with the benefit of the reconfigured airspace, it showed that an increase in similarity distance is related to an increase in the benefit. This indicated that airspace design methods that applied more changes to the original airspace achieved more benefit. For example, Fig. 8 shows the relation between number of reduced flights and similarity distance.
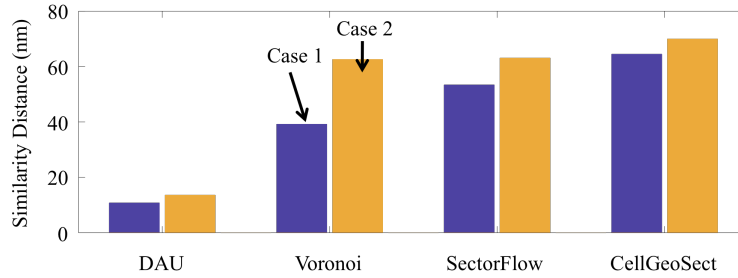


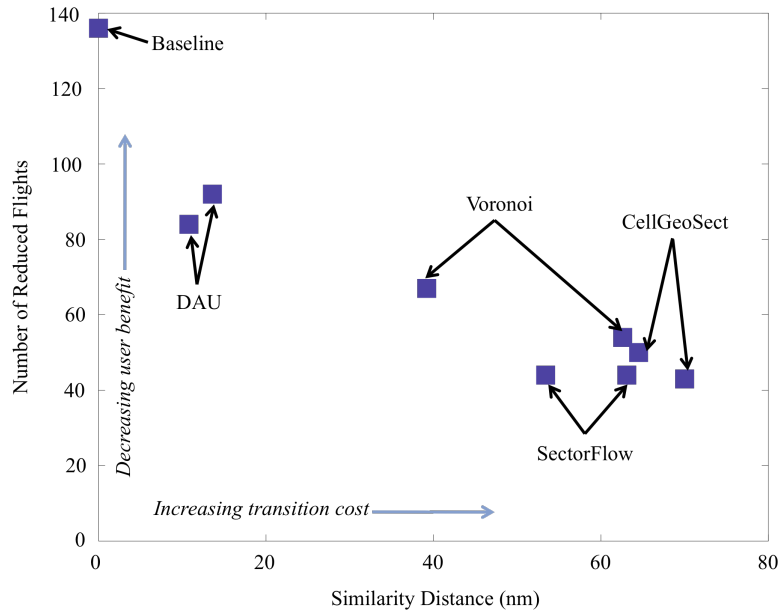**Figure 7.** Similarity distance of reconfigured airspace to the original airspace.



**Figure 8.** Number of reduced flights vs. similarity distance

## IV. Conclusion

This paper assessed Flexible Airspace Management that allows reconfiguration of airspace boundaries by examining the relative benefit of reconfigured airspace to the original airspace under the same traffic conditions. Four airspace design methods were used to reconfigure the original airspace design in Kansas City Center for weather rerouted flight plans. Air traffic simulations with estimated mid-term airport capacities and traffic demand were performed for the original and each reconfigured airspace design.

One airspace design method improved two design parameters of the original airspace with its reconfigurations by decreasing the average number of short dwell flights in the airspace and increasing the average traffic crossing distance to airspace boundary. The other methods had negative or no impact on these two factors.

With Flexible Airspace Management, all of the airspace reconfiguration approaches demonstrated user benefit by decreasing the number of flights needing to be reduced (i.e., delayed or turned away from entering the airspace) to

maintain balance between traffic demand and air traffic control capacity. Utilization of available air traffic control resources increased as well, demonstrating service provider benefit. Airspace design methods that applied more changes to the original airspace achieved more benefit. However, increased changes from the original airspace configuration implied a possible increase in air traffic controller workload during the transition from the original to the reconfigured airspace.

Accurate demand estimation is necessary to assess the benefit of Flexible Airspace Management with a high confidence. This suggests that it is worthwhile investigating the impact of uncertainty in traffic demand estimation on benefits in future studies.

## Acknowledgments

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