NEW PROCESS FOR "CLEAN SHEET" AIRSPACE DESIGN AND EVALUATION

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Abstract

The MITRE Corporation's Center for Advanced Aviation System Development (CAASD) has developed a semi-automated capability to conduct large-scale airspace design. The process is intended to replace traditional methods of developing alternative airspace designs with an approach that is not only more efficient, but also more objective, transparent, and repeatable. The approach outlined in this paper includes the use of automated design tools, fast-time simulation, and application of operational expertise applied in an objective framework. This approach makes efficient use of automated tools whenever possible, but preserves the benefits of operational ATC expertise while minimizing traditionally associated costs and subjectivity. The process has been applied to several real world airspace design projects in the United States (U.S.) with positive results and recently demonstrated its scalability by completing a theoretical resectorization of a significant portion of the U.S. National Airspace System (NAS). This paper will describe the motivation behind the development of the process, the functionality of its component tools, and a case study of its application.

Keywords: Network and Traffic Flow Optimization, Dynamic Airspace Management, Innovative ATM Concepts

Introduction

Airspace design is the process of creating operationally feasible sector boundaries and routes to support the safe and expeditious flow of aircraft within the technical and safety constraints of the National Airspace System (NAS) [1]. In the U.S., airspace has historically been redesigned by operational field personnel (i.e., air traffic controllers) when a problem is identified – e.g., a busy merge area with too much traffic to handle efficiently. Local airspace experts identify problems, discuss options, and propose solutions. In recent years, analysts have begun using quantitative techniques and experimentation to evaluate potential designs after they have been proposed. The entire process, problem identification through design evaluation, is repeated to refine proposed solutions [2]. This process is a mixture of art and science that has worked well in the past; however, it requires significant time and staffing resources as controller teams often must spend extended periods of time away from their facilities to participate in detailed airspace design activities. Also, due to the size, complexity, and interconnectedness of the national airspace system, controller solutions to local problems may have unintended ripple effects elsewhere in the system. To address these issues and the Federal Aviation Administration's (FAA) continued focus on cost and value, the MITRE Corporation's Center for Advanced Aviation System Development (CAASD) has developed a new, more efficient, process for airspace design and evaluation. This process replaces traditional techniques employed to generate alternative airspace design solutions in the FAA's Airspace Design Process as defined by the Airspace Management Handbook [2].

Unique to this new approach is the reversal of traditional design steps which used subject matter experts to develop initial design concepts early in the process and quantitative analyses to quantify benefits at the end. In the new approach, quantitative analyses are conducted first to objectively define the design concept, followed by the application of targeted subject matter expertise to ensure the operational feasibility. This subject matter expertise has been captured from air traffic controllers during previous design efforts and represents a set of best practices in sector design. As a result, the new process ensures objectivity and allows for the generation of "clean sheet" solutions by eliminating the potential for parochial influences that can restrict the set of solutions considered. Since the process relies on subject matter expertise only through the application of documented best practices, the process is repeatable by any qualified user and its results can be traced back to documented metrics and design principles. Using objective, repeatable, and transparent methods, the tools allow faster, less expensive, more efficient airspace redesigns.

Description of Clean Sheet Airspace Design and Evaluation Process

As shown in Figure 1, the process consists of four stages:

1. Traffic and Airspace Environment Definition
2. Airspace Partitioning
3. Workability Evaluation
4. Sector Design

The first stage produces aircraft trajectories that are to be served by the resultant airspace sector design. The second stage creates a map of spatially distributed traffic complexity (based on a specific set of metrics) in the geographic region to be designed. An automated airspace partitioning tool then divides the airspace volume into areas of equal complexity. The next stage in the process uses a fast-time, dynamic simulation model, called the *airspace*Analyzer to test these complexity regions (called partitions) for operational problems. The fourth stage uses the *sector*Evaluator tool, which applies a knowledge database of airspace design principles and best practices, to recommend solutions to the operational problems identified in the third stage. The following sections describe the process stages, particularly the tools used in them, in more detail.

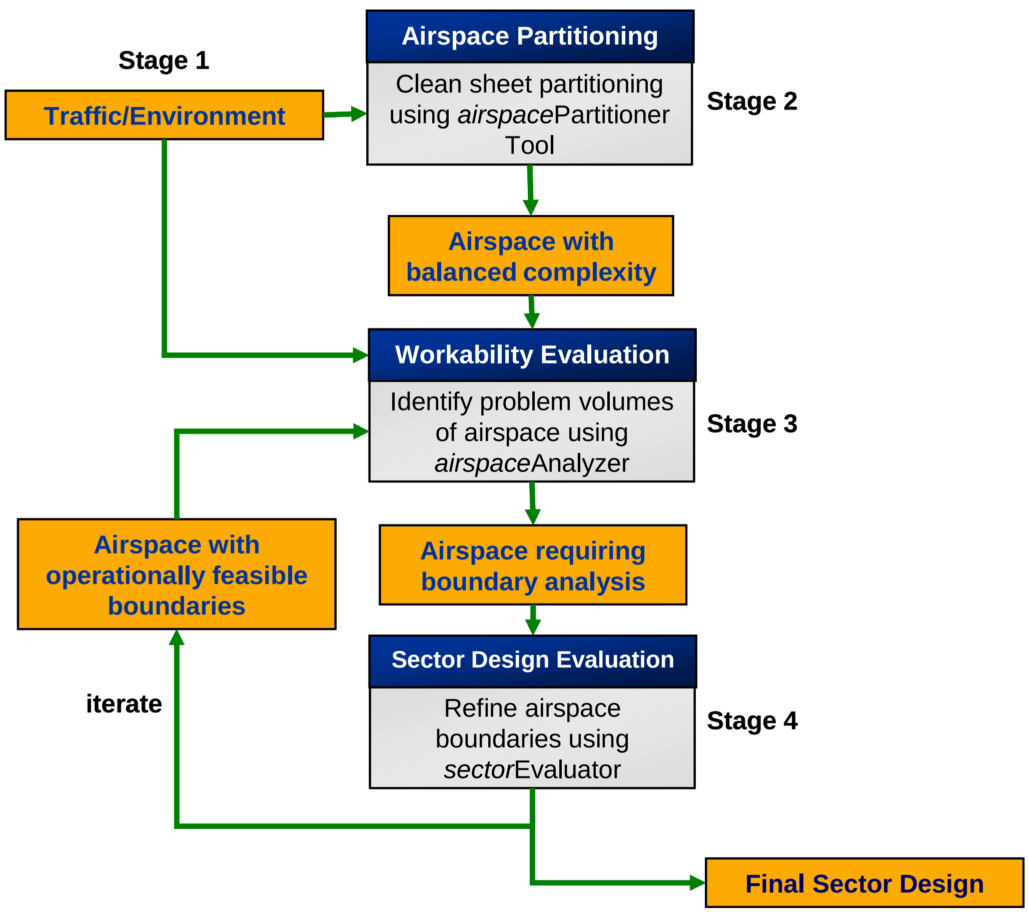

Figure 1. Airspace Design and Evaluation Process

Traffic and Airspace Environment Definition

Since the design process is driven by the services demanded by users of the airspace (as defined by the location, type, amount, and timing of traffic operating in the airspace), the first stage must define the traffic and airspace environment for which the sectors are designed. When redesigning airspace for current conditions, scheduled flight plans collected on representative days may be used as the basis of trajectory modeling to yield the required trajectories. Observed trajectories from radar sources should not be used as these tracks have already been de-conflicted by air traffic controllers and therefore exhibit less inherent complexity. When designing sectors to service new routes, future traffic levels, or other forecasted changes in the NAS, both flight planning and trajectory modeling are required to generate 4 dimensional tracks consistent with the desired assumptions. The sector design process is insensitive to the tools used to create the flight plans and trajectories; thus far, applications of the process have used the Future Air Traffic Timetable Estimator (FATE) [3] for future demand and prototype ETMS capabilities [4] for flight plan generation and trajectory modeling.

Stage 2: Airspace Partitioning

The traffic file generated in Stage 1 is the input for Stage 2 which begins by computing the spatial distribution of air traffic complexity for a given volume of airspace. Similar work has been done in the past to partition airspace based on distributed workload indicators [5], but this procedure seeks to expand the metric to account for as many factors contributing to complexity as possible. It also places partitioning in the context of a larger process where sector boundaries support the function of each sector. This “complexity density” metric is an aggregation of complexity indicators solely derived from the traffic, including the number of aircraft, aircraft-to-aircraft close proximity events, transitioning activity, and the number of aircraft that require spacing for major airports. Each of these indicators are identified from the traffic trajectories and located in 4 dimensional space. This task is performed by the *airspace*Partitioner tool which divides a given airspace volume into areas which all have equal target amounts of the complexity density metric [6]. The target amount of complexity for a partition is benchmarked against existing sectors and is adjustable to design one, two, or three person sectors as desired. Figure 2 shows an example of the output of *airspace*Partitioner.

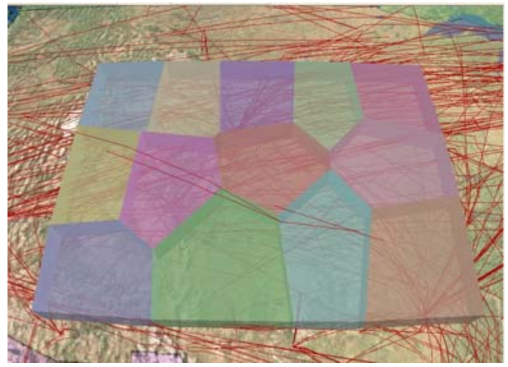

Figure 2. Example of *airspace*Partitioner Output

Partitioning Procedure

For a given set of traffic data, *airspace*Partitioner divides airspace into a grid of equally sized cells, calculates the complexity density metric within each cell, and then clusters the cells together so that the clusters, or partitions, all have complexity density values equal to the target complexity threshold. The complexity density value for a cluster of grid cells is the sum of the values of the cluster’s cells. The premise behind this process is that small regions (grid cells) can be measured, combined and recombined with other small regions to create larger, equal-valued clusters. Since the components of the complexity density metric are necessarily independent of sector boundaries, they may be added together in this fashion. However, restricting the metric to boundary insensitive factors requires that subsequent steps (Stage 3 and 4) address the operational issues associated with managing traffic within bounded sectors.

The processing within *airspace*Partitioner has three main phases:

- Creating compact clusters of grid cells, using an adapted k-means partitioning process
- Equalizing the complexity density weight of all clusters, by swapping grid cells from higher- to lower-valued clusters
- Straightening the cluster boundaries to remove the “serrated edge” effect created by the grid

Creating Compact Clusters of Grid Cells

To create compact initial clusters of grid cells, a well-known clustering algorithm frequently referred to as *k-means* [7] was modified and adopted. This clustering algorithm aggregates points into k clusters, where k is specified. Usually an attempt is made to minimize the sum of squared

Euclidean distances from all points to their cluster centroids. That approach will produce at least a local optimization, given a set of cluster centroids.

The *k-means* algorithm requires a starting set of centroids. A set of centroids could be arbitrarily chosen, but that would make the subsequent result just as arbitrary. A random set of centroids is less arbitrary but could (and will) yield radically different results depending on where the centroids were randomly placed. A better approach is to create a series of replications of the process where in each replication a different set of random centroids is used. At the end of the set of replications, the random set which produced the minimum sum of squared Euclidean distances will be considered the “best” one. During the *k-means* process, points will be reassigned to other clusters in an attempt to bring down the total sum of squared Euclidean distances. Each time a reassignment takes place, the centroids of the clusters affected by the reassignment must be recalculated. Thus the centroids will move during the process.

The *k-means* process tends to produce a clustering that is compact since it minimizes the sum of squared Euclidean distances. Therefore, long narrow clusters are unlikely to occur. However, the process will not produce clusters with equal amounts of complexity, unless the data were uniformly distributed.

Equalizing the Complexity Density Weight of all Clusters

The approach adopted by *airspace*Partitioner is to start with a k-means estimate after 30 replications and then attempt to “back away” from that initial clustering towards equal-weight clusters. In each subsequent step of moving toward equal-weight clusters, the cell that is reassigned will be that cell which adds the least to the overall sum of squared Euclidean distances. Each weight-equalizing iteration involves determining whether the cells on a cluster boundary should be reassigned to a contiguous cluster. This will occur if the current value of the receiving cluster is at least two below the donating cluster. This requirement ensures that the process will systematically reduce the size of large clusters while increasing the size of small clusters. The process continues until no further cells can be reassigned. At the end, the compact cluster structure created with the *k-means* initialization tends to be maintained.

Straightening the Cluster Boundaries

The result of the clustering process will be a set of almost equal clusters of square grid cells with sides exhibiting a ragged or serrated appearance. This is due to the artifact that the airspace is divided into grid squares. Cells of any shape could be used with the algorithm, but any system (e.g., squares, hexagons) must allow for complete coverage and will always result in a serrated edge which must be corrected. Since the purpose of the clustering is to create volumes of airspace that will eventually be sectors (which do not have jagged edges), a method was needed to create straight cluster borders.

A cluster border is a polygon consisting of edges and vertices. An edge is a straight line joining two vertices. Vertices can be of two types:

- Externally known (from the outer boundary of the clean sheet area)
- Calculated, or algorithmically determined breaks between clusters

Vertices need to be placed at the junction of three or more cluster, or at a junction of two or more clusters on the outer boundary. Thus two problems presented themselves.

- How to determine where three or more clusters adjoin
- How to determine where to locate a vertex on an outer boundary

In the first problem, cells may be contiguous to each other and contiguous to clusters. An algorithm was needed to determine when one cluster is contiguous to another cluster. A two-step approach was developed to determine first a series of proto-vertices and from them a series of full vertices. A *proto-vertex* is a cell which is *contiguous* to at least 3 clusters. A cell is contiguous to a cluster if it is contiguous to a cell within that cluster. A cell is also defined to be contiguous to its own cluster. Contiguity is measured in eight possible compass directions around a cell (represented by a square). After all proto-vertices are identified, *formal vertices* will be determined by establishing a formal vertex in the middle of a 2x2 square of 4 proto-vertices with the proviso that the 4 proto-vertices together must lie in at least 3 clusters. Each vertex will be linked with the clusters that contain its proto-vertices.

The second problem is addressed by then linking the externally known vertices representing the center boundary to the clusters. This is done by associating each externally known vertex with its nearest cluster. The vertices are then linked to form the smoothed polygon.

The Importance of Operational Evaluation

The partitions generated in Stage 2 are created by choosing a target level of complexity for each volume of airspace in the partition. The boundaries of each volume expand until a target level of complexity is achieved. Partition boundary placement occurs without knowledge of dominant traffic flows or key traffic flow interactions. Therefore, partition boundaries are likely to occur in locations that are inconsistent with the operational needs of an airspace sector. To illustrate this point, Figure 3 depicts how automated partitioning of airspace based on point data fails to produce sector boundaries that support the operational needs of air traffic control (ATC).

The dots depicted in Figure 3 represent the kind of limited complexity metrics available in a clean sheet partitioning process – complexity indicators that can be identified without regard to sector boundaries. The directional lines show underlying traffic patterns and interactions – the type of information not available in a point-based complexity density map but are critical to understanding the desirability of different sector boundary locations. The final stages of the process are designed to identify and adjust partition boundaries like the one depicted with the dashed lines where the sector is designed to support the required ATC functions in the sector. The *airspace*Analyzer is used to identify boundaries in need of refinement and the *sector*Evaluator aligns traffic flows and airspace boundaries.

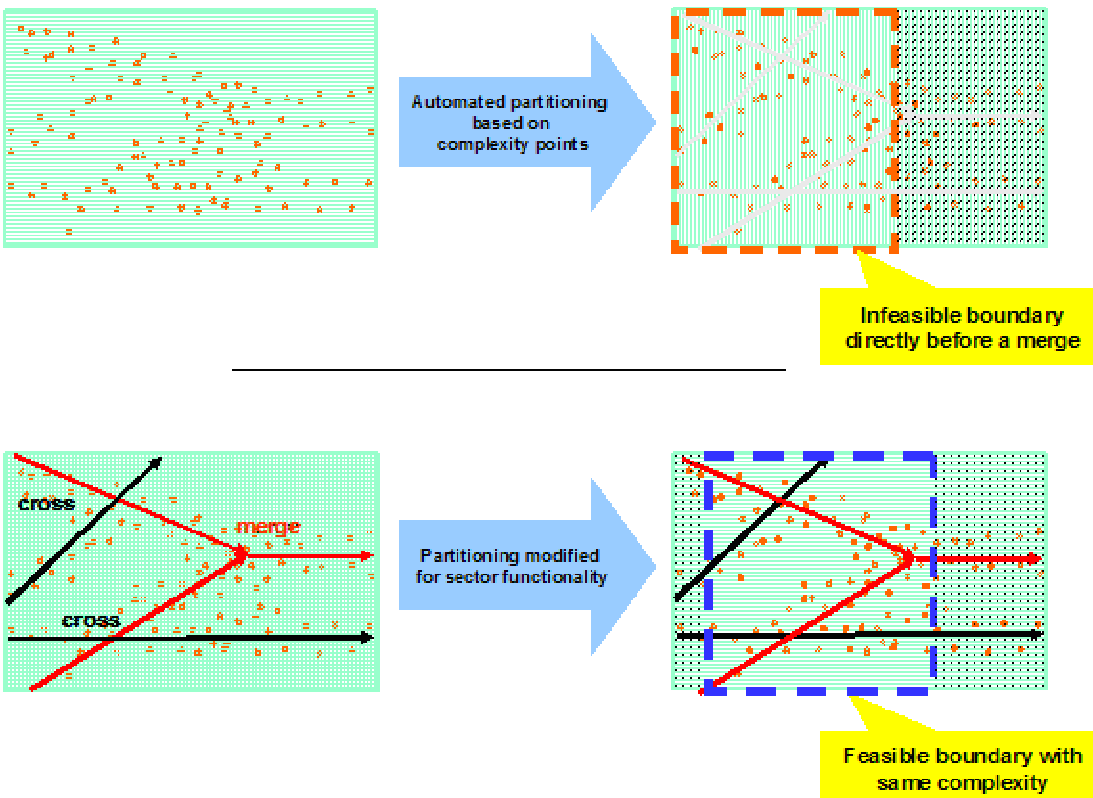

Figure 3. Need for Further Analyses of Partition Boundaries

Stage 3: Workability Evaluation with *airspace*Analyzer

In Stage 3 of the design and evaluation process, each volume of airspace in the partition generated in Stage 2 is tested with the traffic developed in Stage 1 using the dynamic workability evaluator, the *airspace*Analyzer. Using linear optimization techniques, *airspace*Analyzer simulates and solves the same types of Air Traffic Control situations a controller would. To accomplish this, *airspace*Analyzer mimics controller actions in the following by:

- Separating aircraft from airspace, weather and other aircraft
- Enforcing in-trail spacing
- Adhering to the aircraft flight plan to the extent possible

The *airspace*Analyzer's input includes aircraft flight plans, aircraft performance data, miles-in-trail restrictions, dynamic or static restricted airspace (e.g., thunderstorms or temporary flight restrictions), sector boundaries, and horizontal and vertical separation standards.

Many of the *airspace*Analyzer's capabilities are unique among airspace evaluation tools. Most of these tools measure how *hard a problem looks*. The *airspace*Analyzer computes *how hard the problem is to solve, and the degree to which it can be solved.* By "solve" we mean achieving many different ATC objectives, which have differing priorities and are not always compatible. These include separation requirements, miles-in-trail spacing, proper sector entry/exit, use of simple vs. complex maneuvers, and maximizing aircraft forward progress. The *airspace*Analyzer generates metrics that provide insight into the workability of the sector being analyzed, such as the amount and type of maneuvering in each volume of airspace and the amount of delay absorbed. These and other metrics are used to indicate which volumes of airspace have operational feasibility issues and require further analyses in Stage 4 of the process. Figure 4 is a screen capture of the *airspace*Analyzer simulation. In addition to providing a dynamic visualization of the traffic flows and the resolutions the *airspace*Analyzer generates to meet the given operational constraints, metrics are also provided in graphical and tabular formats.

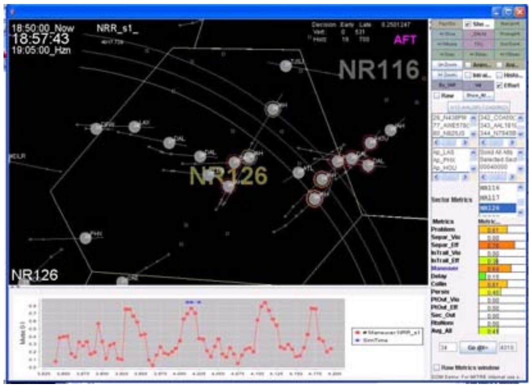

Figure 4. *airspace*Analyzer Simulation

Stage 4: Sector Design using the *sector*Evaluator Tool

In the final stage, the *sector*Evaluator is applied to assess the design quality of the volumes of airspace indicated to be infeasible by the *airspace*Analyzer in the previous stage. The *sector*Evaluator is a capability developed by CAASD to assess airspace based on boundary and flow geometry relative to best practices of sector design. Its audit report highlights the airspace design features that are most in need of refinement. With this guidance, qualified users can make the necessary design changes indicated by *sector*Evaluator to make a proposed sector operationally feasible. The *sector*Evaluator refined airspace is then ready for final review by ATC facility staff familiar with local issues prior to implementation. The *sector*Evaluator boundaries can also be re-evaluated in *airspace*Analyzer to understand the dynamic operation of the modified sector or to determine the impact of the refined airspace on neighboring sectors.

The *sector*Evaluator contains a knowledge database of fundamental airspace design principles and measures the proposed airspace design against this collection of preferred practices. Examples include keeping flows a minimum distance from sector boundaries, keeping flows a minimum distance from each other, and allowing adequate time/distance for different types of interactions in a sector.

The *sector*Evaluator is implemented as part of a Geographic Information System (GIS) which combines features of a database and a mapping capability. The *sector*Evaluator is able to exploit these capabilities for manipulating and displaying input, calculating geography-based airspace design metrics, and displaying output.

The GIS representation of the objects in the *sector*Evaluator allows for automatic derivation of the flow interactions, such as merge and crossing points, and the calculation of geography-based metrics. The GIS implementation also allows sector boundaries and traffic flows to be layered with other geographical data, such as in Figure 5 where flows and candidate sector boundaries are superimposed on measures of traffic density.

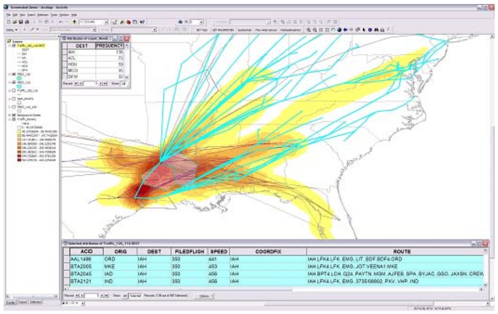

Figure 5. *sector*Evaluator Displaying Multiple Layers of Geographic Data

Application of Process to a Flow-Based Design Study

At the request of the FAA, CAASD applied its airspace design and evaluation capability to generate high altitude sector plans based on operational traffic flows – a demonstration of Flow-Based Design (FBD). For this particular FBD study, the traffic flows are not tied to ground-based navigation aids (NAVAIDS). Instead, the traffic flows exploit the flexibility of satellite-based and point-to-point navigation. Airspace sectors are then designed to provide services for these more efficient flows without regard to existing facility structures or ground-based navigation.

The demonstration of FBD presented here takes a clean sheet approach to realigning airspace above FL340, west of the Mississippi. CAASD's airspace design and evaluation capability was used to create traffic flows and the resultant airspace design.

Stage 1: Traffic and Airspace Environment Definition. The process began with the development of the air traffic trajectories for which the airspace was designed. For this study, a target year of 2010 was selected and flight plans for that year were developed according to the FAA's Terminal Area Forecast (TAF) projection – a 9.4 percent increase in traffic over that of 2005, and four different routing scenarios. The demand profiles are named according to the routing strategy:

- Current routing – traffic follows today's largely ground-based route system
- Non-restricted routing (NRR) – high altitude operations in the western U.S. fly point-to-point routes above FL340
- Great circle routing – flights follow great circle routes from origin to destination

Figure 6 is a visual representation of the traffic demand profiles considered. The demand profile charts reflect traffic densities – darker grey for the highest densities, lighter gray for the lowest. Traffic files with highly structured routes (like current or winter wind routing) show more areas of high density than traffic files with no structure (great circle routing) due to the higher density of traffic following structured routes. The NRR traffic density is similar to current routing in the eastern U.S. and to great circle routing in the western U.S.

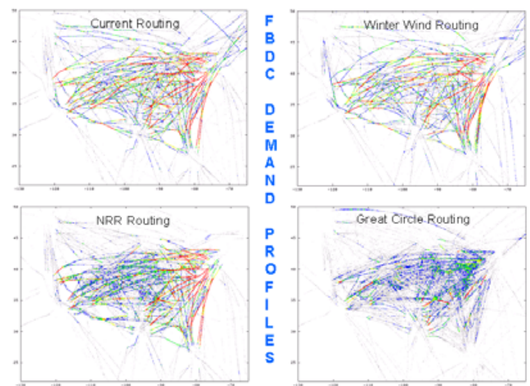

Figure 6. Traffic Demand Profile

Stage 2: Airspace Partitioning. Once the traffic files were generated, the *airspace*Partitioner was used to divide the airspace into equal units of a desired level of complexity. The target level of complexity for the FBD partitions was selected to be that of a typical super-high altitude sector in Indianapolis Air Route Traffic Control Center (ZID) staffed with both an R-side and D-side controller. The partitions generated for each of the traffic files are shown in Figure 7. This process results in discrete volumes of airspace of varying size; small where complexity is dense, large where sparse. As flight paths shift in the various demand profile scenarios (see Figure 6), corresponding shifts in the distribution of smaller partitions across the middle portion of the country reflect changes in the spatial distribution of the complexity metric.

Stage 3: Dynamic Workability Evaluation. Although partitions were generated for all of the traffic demand profiles, the tools in Stages 3 and 4 were applied only to the NRR case. To identify which volumes of airspace require further boundary refinement in the *sector*Evaluator, the NRR partitions and traffic were simulated in the *airspace*Analyzer. Figure 8 shows a thematic map of the *airspace*Analyzer's output indicating candidates for boundary refinement.

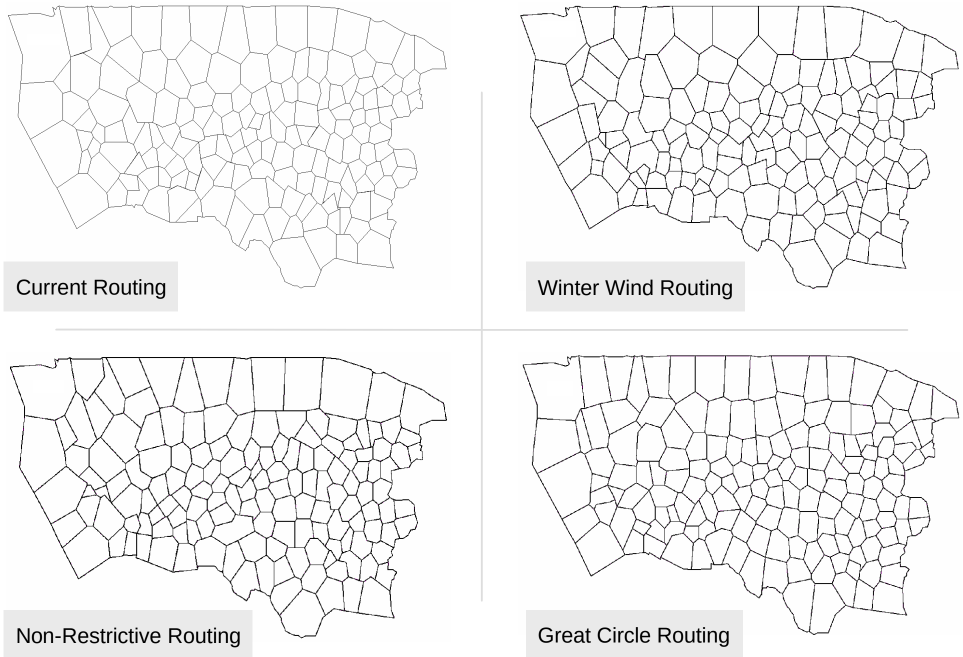

Figure 7. Partitions for Traffic Demand Profiles

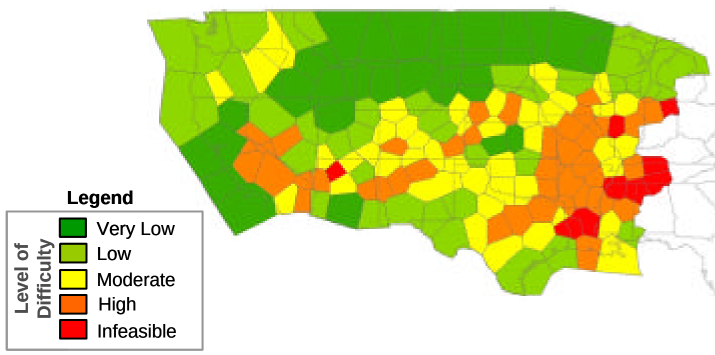

Figure 8. Thematic Map of *airspace*Analyzer Results

Stage 4: Sector Design Evaluation. The *sector*Evaluator was applied to all airspace partitions indicated to be infeasible by *airspace*Analyzer. As an example, Figure 9 illustrates how the *sector*Evaluator's audit report indicated improvements to one of the infeasible partitions (NRR sub-partition 126). The lines with directional arrows represent the flows extracted from the traffic through an automated process that identifies bundles of trajectories. The original boundaries for partition 126 are drawn with dashed lines; the adjusted boundaries are drawn with solid lines. The *sector*Evaluator's audit report suggested improvements to the airspace design. Two flows were found to be too close to the airspace boundary across the northern boundary and in the northwest corner of partition 126. The boundary flow in the northwest corner was removed by relocating the western boundary further east. The other boundary flow ceased to be a problem when the northern boundary was moved further north. Boundary expansions north and east provided more time and distance to manage crossing flows at three points (Flow 2 with Flows 1, 4 and 6). The adjusted partition 126 benefits from having its boundary runners eliminated and from having more distance and time to prepare for crossing flows.

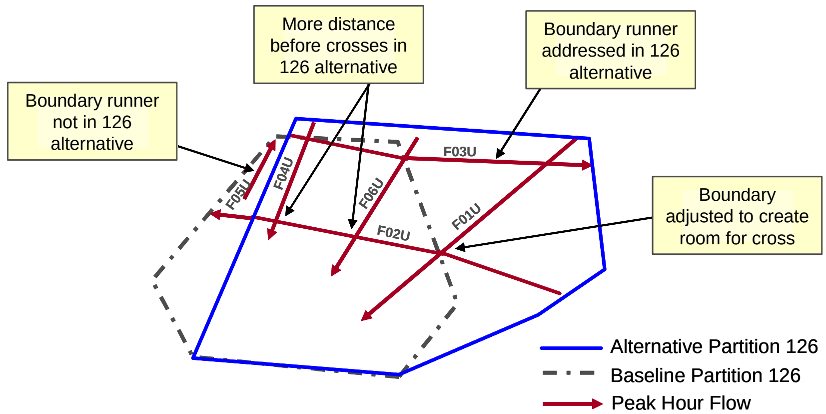

Figure 9. Sector Redesign using the *sector*Evaluator

Application Results

CAASD applied its clean sheet airspace design and evaluation process to consider airspace realignment activities for 2010 traffic levels. The application focused on high altitude airspace (FL340 and above) west of the Mississippi. This airspace is typically less congested and complex than that on the east coast, and it has been the testbed for new airspace and routing concepts. In applying the process, current sector and center boundaries were disregarded. Routing for this future scenario was modified to reflect the increased use of satellite navigation in the Non-Restricted Routing (NRR) program. All airspace above FL340 and west of the Mississippi was partitioned realigning the 173 sectors that currently comprise that airspace. Preliminary results indicate a significant reduction in the number of sectors is possible when sectors are designed to serve a consistent benchmark of traffic demand, and without regard to existing facility structures. The sector plan generated for this exercise was based on general assumptions that demonstrate the capability and scalability of the process, and the flexibility to develop sector designs for different implementations. This exercise demonstrated "clean sheet" design where results are not limited by typical airspace constraints. With the additional specification of desired constraints, one can use the same procedure to develop airspace designs that respect existing special use airspace boundaries, sector size limitations, or availability of communication or surveillance services. As a result, the process presented in this paper can define idealize airspace design goal as well as the transitional sector designs needed to evolve the airspace toward those goals.

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