Human-in-the-Loop Investigation of Airspace Design

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A part-task, human-in-the-loop study on Flexible Airspace Management (FAM) was conducted to explore the role of algorithm-generated airspace designs, human-centered design practices, and the potential benefits of FAM within these contexts. Participants were independently exposed to 4- and 7-sector traffic scenarios that involved sector load imbalances due to reroutes around convective weather. Peak sector loads were well above the imposed threshold of 22 aircraft and required active management in each of the following conditions: No Boundary Change (No BC) in which traffic load imbalances were addressed through reroutes alone, Manual BC in which participants modified the existing airspace boundaries to reduce and redistribute load imbalances followed by reroutes for the remaining excess, and Algorithm + Manual BC in which sets of algorithm-generated boundary configurations were available for selection and further modification followed by reroutes to reduce remaining excess traffic load. Overall, results showed that FAM operations in the Manual and Algorithm + Manual BC conditions required fewer reroutes and managed peak sector loads better than the No BC condition. Furthermore, algorithm-generated airspace designs and the support they provided in the Algorithm + Manual BC condition resulted in consistent benefits in terms of fewer reroutes and better peak management than in the Manual BC condition. Feedback from participants also highlighted the beneficial role of airspace optimization algorithms in FAM by providing a means of developing more acceptable and effective airspace designs and overall solutions to the problems presented.

Nomenclature

ANSP = Air Navigation Service Provider
AOL = Airspace Operations Laboratory
DAU = Dynamic Airspace Units
DD = Dynamic Density
DSR = Display System Replacement
FAA = Federal Aviation Administration
FAM = Flexible Airspace Management
FLM = Front Line Manager
HITL = Human-in-the-Loop
MACS = Multi Aircraft Control System
MIP = Mixed Integer Programming
NAS = National Airspace System
NASA = National Aeronautics and Space Administration
NextGen = Next Generation Air Transportation System
RNP = Required Navigation Performance
TMC = Traffic Management Coordinator

I. Introduction

IN the National Airspace System (NAS) the balance between user demand and airspace capacity is managed by a distributed team of Air Navigation Service providers (ANSPs) from facilities across the United States. To strike this balance, the ANSPs work together to assess the current and anticipated airspace capacity and formulate plans to

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accommodate the demand accordingly. However, perturbations to the system (e.g., convective weather) can throw this balance off. Whenever traffic demand exceeds airspace capacity for a sustained length of time, the demand must be reduced by restricting the flow of traffic. This is done through methods such as miles-in-trail, playbook routes, ground delay programs, or ground stops. While effective at reducing demand, such methods can potentially introduce unnecessary delays and costs to the airspace users with ripple effects that extend well past the impacted area.

The introduction and continued transition from the current system to the Next Generation Air Transportation System (NextGen) [1] is intended, in part, to address such issues through improved flight management and system efficiency. One proposed approach toward this realization is the Flexible Airspace Management (FAM) concept. As part of the Federal Aviation Administration's (FAA) NextGen implementation plan, the FAM concept was initially proposed as a component of the High Altitude Airspace (HAA) concept[2-4]. The environment previously envisioned in the earlier concept is comparatively advanced in that aircraft are expected to be fully equipped with air-ground Data Communication (Data Comm) capabilities and able to perform user-preferred Trajectory Based Operations (TBO) with greater precision in the form of lower Required Navigation Performance (RNP) values. Such an environment would allow for greater trajectory certainty, which would potentially allow higher traffic density and greater operational efficiency. Even in such an environment, however, operations would be susceptible to the adverse effects of weather or other traffic disturbances. The FAM concept seeks to mitigate such effects through the reconfiguration of airspace. FAM in this context is expected to better utilize the airspace, be more responsive to imbalances between demand and capacity, and provide ANSPs with a means of strategically managing the overall airspace in a manner that has less negative impact on the users and operators relative to operations today.

The design and reconfiguration of airspace is by no means a simple task, however. Depending on the situation, the traditional means of designing airspace can be a laborious and very complex undertaking. In recognition of that fact, a focused research effort has been directed toward developing and applying airspace optimization algorithms to aid in the process. A substantial body of work has been developed in this area, but how the algorithms might be integrated to complement human decision-making has not been explored. This paper will describe and report on a part-task, human-in-the-loop (HITL) study that set out to examine both the benefits and acceptability of combining algorithm-generated airspace designs with those created by ANSPs and the potential role that the algorithms might play within the FAM concept.

A. Prior Research

The ideas underpinning FAM are not necessarily new. Today, sectors are regularly split and combined in response to demand, environmental, and staffing considerations Special configurations and procedures also exist to accommodate anticipated traffic situations related to certain events. Using these existing components as a starting point, research has been conducted with the aim of being able to expand upon such capabilities and adapt them for more dynamic and flexible use. Earlier research into this area focused on the feasibility and benefits of being able to dynamically resectorize airspace in a less limited manner than what is possible today[5-8]. Results showed that such operations were feasible and that benefits could be realized in the form of more aircraft being able to maintain their user-preferred trajectory. However, a number of human factors issues were cited that warranted further investigation. The benefits and human factors issues of resectorization provided researchers with multiple avenues in which to explore and develop the FAM concept further. The development of airspace optimization algorithms and HITL simulations are two such avenues that have been used in this exploration.

The reconfiguring of airspace today is based on existing structures and procedures and may not always result in the most optimal or adaptive solution to a system problem. In an effort to further examine the benefits of FAM while providing a means of developing optimal airspace designs from a mathematical perspective, a number of different approaches have been taken in the development of algorithms. At the heart of these algorithms lies the common goal of distributing traffic and workload in the most effective way that provides maximal utility of the airspace through the design of the airspace's boundaries. This goal can be achieved in a variety of ways, which has consequently given rise to a number of different approaches. Some of the approaches are geared toward FAM in the mid-term timeframe (approximately 2018), which incorporate current day methods and structures of airspace design such as sector combining/splitting and Fix Posting Areas into a more dynamic and flexible process[9, 10]. Other approaches focus on the possibilities of a farther-term timeframe that are less constrained by the current infrastructure, which expands the design space and provides further flexibility and possibilities for the final configurations[11-17].

In 2009, a HITL simulation was conducted in the Airspace Operations Laboratory (AOL) at the NASA Ames Research Center[18-21] that leveraged existing work on algorithm development by using airspace boundary configurations generated by three separate algorithms. The different approaches of these algorithms resulted in three very different sets of airspace designs that were progressively more aggressive in terms of volume and orientation change. Using these design sets allowed for the testing of FAM operations along a spectrum of difficulty that ranged from simple to extreme. The goal of this study was to explore the feasibility of airspace reconfiguration under a variety of situations and to better understand the interplay of factors related to system benefits and impact on the human operator. An additional goal was to examine the airspace design considerations that surfaced through the different algorithm solutions with the intent of providing useful information that could be integrated back into the algorithms for refinement.

To address the goals of the 2009 study, controller participants operated in an environment in which three boundary changes were scripted to take place within a one-hour simulation run at varying times in relation to the traffic situation as well as in relation to the other boundary changes. As a comparative case, participants also controlled the same traffic in a baseline condition in which there were no boundary changes. In the ensuing analysis, operations with boundary changes were compared to those without and results showed that, as before, reconfiguring the airspace provided benefits in terms of minimizing reroutes (i.e., keeping aircraft on their user-preferred trajectories) and balancing the traffic load within the test airspace more effectively. These benefits were also shown to increase as the magnitude and aggressiveness of airspace change increased. Although the participants reported that they were able to handle most of the boundary changes effectively, results showed that as the magnitude of change increased the reported workload increased as well. There was also a corresponding decrease in the acceptability of the airspace configuration. Boundary change factors found to most negatively affect workload and acceptability were those that resulted in large changes in aircraft ownership, short sector transit times, and large volume changes that altered the orientation of the sector and the relationship to its neighbors[19, 21]. Such changes were reported by participants to result in a loss of situation awareness of the sector and traffic. Other factors that impacted situation awareness and performance were the inheritance of new traffic streams following a boundary change, changes in the relative locations of traffic merge points, and new boundary configurations that required scope range adjustments. Some specific sector design considerations offered by the participants to avoid were thin or narrow sectors that left controllers with little room to maneuver, sector characteristics such as jagged edges that resulted in unusable airspace, and designs in which multiple sectors adjoin at or near a common point.

B. 2010 FAM Simulation

In the mid-term NextGen timeframe, airspace configurations are expected to be developed in an offline process similar to today. However, with the advent of the En Route Automation Modernization (ERAM) program and the additional capabilities it is expected to provide, a greater number of pre-configured airspace designs will potentially be available for implementation. This will allow for greater flexibility in the airspace design and reconfiguration process. While the 2009 study examined the issues related to airspace reconfiguration from a human-systems integration perspective and incorporated airspace optimization algorithms through which valuable design considerations were learned, it did not address the role of the algorithms in the design process. To explore this aspect of FAM, a HITL study was conducted in 2010 in the AOL at the NASA Ames Research Center. This study investigated the potential role of airspace optimization algorithms in the airspace design process in terms of how well algorithm support would benefit airspace designers in developing optimal solutions relative to manual airspace design without such support. The effectiveness of the resulting designs was also of interest both in the comparison between manual and algorithm-supported designs as well as to operations without the option to reconfigure the airspace. What follows is a description of the study followed by a report of the findings and a discussion that relates those findings to the goals of the study.

II. Method

A. Participants

Four participants from the FAA took part in this simulation. Each had Traffic Management Coordinator (TMC) and/or Front Line Manager (FLM) experience. Two of the participants were active FLMs from Houston (ZHU) and Atlanta (ZTL) centers respectively. Another was an active FLM with recent TMC experience from Washington Center (ZDC). The final participant was a Supervisor TMC (STMC), who retired from Oakland Center (ZOA) in 2008.

B. Airspace

To be able to test airspace design with simple and complex configurations, four and seven en route sectors within Kansas City Center (ZKC) were selected and adapted for use as the test airspace. In accordance with the HAA concept, the floor of the airspace was raised to flight level 340 and was uniform for all sectors. Figure 1 shows the specific sectors that were used. For the four sector base configuration, the sectors used were ZKC 28, 29, 30, and 92. For the seven sector base configuration, sectors ZKC 3, 28, 29, 30, 47, 92, and 94 were used.

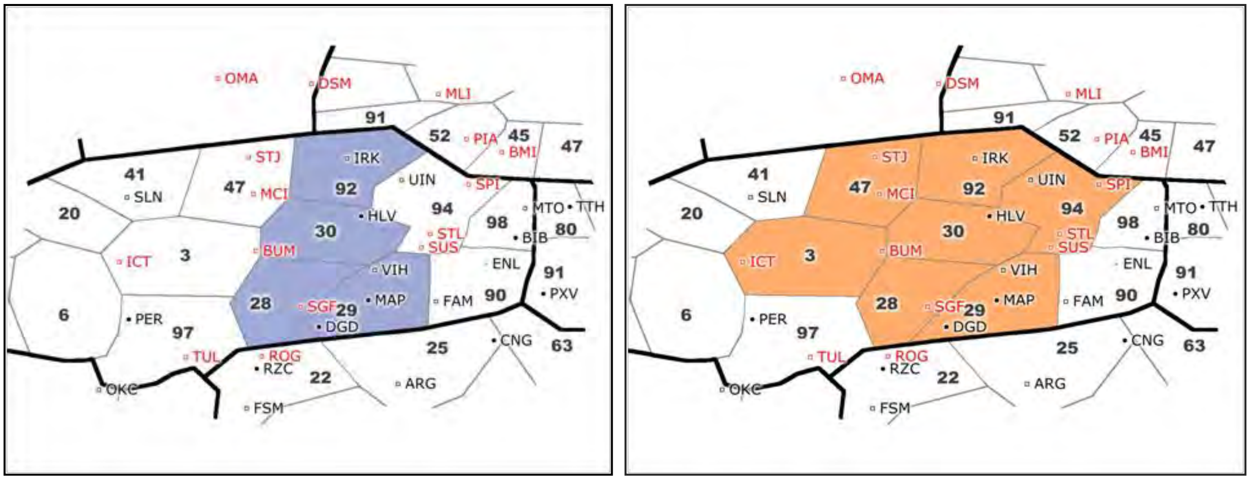


Figure 1. The four (left) and seven (right) sectors in ZKC that comprised the test airspace.

C. Traffic Scenarios

Three sets of base traffic scenarios were developed for the 4-sector and 7-sector airspace problems. These scenarios were generated using the scenario editor function of the Multi-Aircraft Control System (MACS)[22] software platform. The traffic that was developed consisted predominantly of a West-East flow (approximately 50%), and the remaining East-West, North-South, and South-North traffic flows contributed roughly equally to the other 50%. Of the traffic within these flows, most were at cruise altitude and level flight due to the airspace being FL340 and above. There was, however, a small contingent of transitioning aircraft to and from area airports that were included as well.

Sets of convective weather patterns were developed and integrated with the traffic scenarios. The visual representation of the weather was based on images of actual weather that were then adapted and modified for use through the weather editing function in MACS. The patterns were designed to traverse the airspace in and around the test area while morphing and changing with each six-minute update cycle. The final weather products were strategically positioned in and around the airspace in such a way that weather avoidance reroutes would create traffic load imbalances between the sectors in the test airspace. These weather-induced imbalances later served as the basis for what the human and algorithm generated airspace designs would work to rebalance.

The traffic scenarios were developed by taking nominal flight plans and rerouting them around the weather by scenario developers using the MACS scenario editor function. To make the reroutes look realistic, local subject matter experts were brought in to guide the process by providing advice on the most appropriate and logical reroutes to perform for avoiding the weather. This was done for all scenarios after which final adjustments were made in order to ensure that the imbalances and peaks adequately reflected the intended designs of the problems and that they would be sufficiently challenging for both the participants and the algorithms to deal with. For the design of the 4- and 7-sector problems, the final scenarios began with relatively low levels of traffic within the test airspace and proceeded to build such that a peak in traffic (nearly 40 aircraft in some sectors) with associated imbalances was present between 45 and 75 minutes into the problem. The 7-sector problem had an additional peak built in that occurred approximately two hours into the scenario.

With the scenarios complete, the track data from each was collected and sent to participating algorithm development teams. The data served as input for the algorithms, from which airspace designs could be generated according to the different algorithmic approaches in response to the traffic imbalances that were created. A brief description of the different algorithms used in this effort follows.

D. Airspace Optimization Algorithms

To begin exploring the potential role of airspace optimization algorithms in active FAM operations, four algorithms were selected based upon their different approaches to airspace design: Dynamic Airspace Unit (DAU) Slices, Mixed Integer Programming + Binary Space Partition (MIP/BSP), Flight Clustering (FC), and Modified Voronoi (MV). Including different algorithms not only allowed for an examination of their role at a high level, but also provided an opportunity to better understand the specific design factors and approaches that are the most effective both objectively and subjectively. Figure 2 presents an example of the differences in the designs that resulted from the application of each of the algorithms.

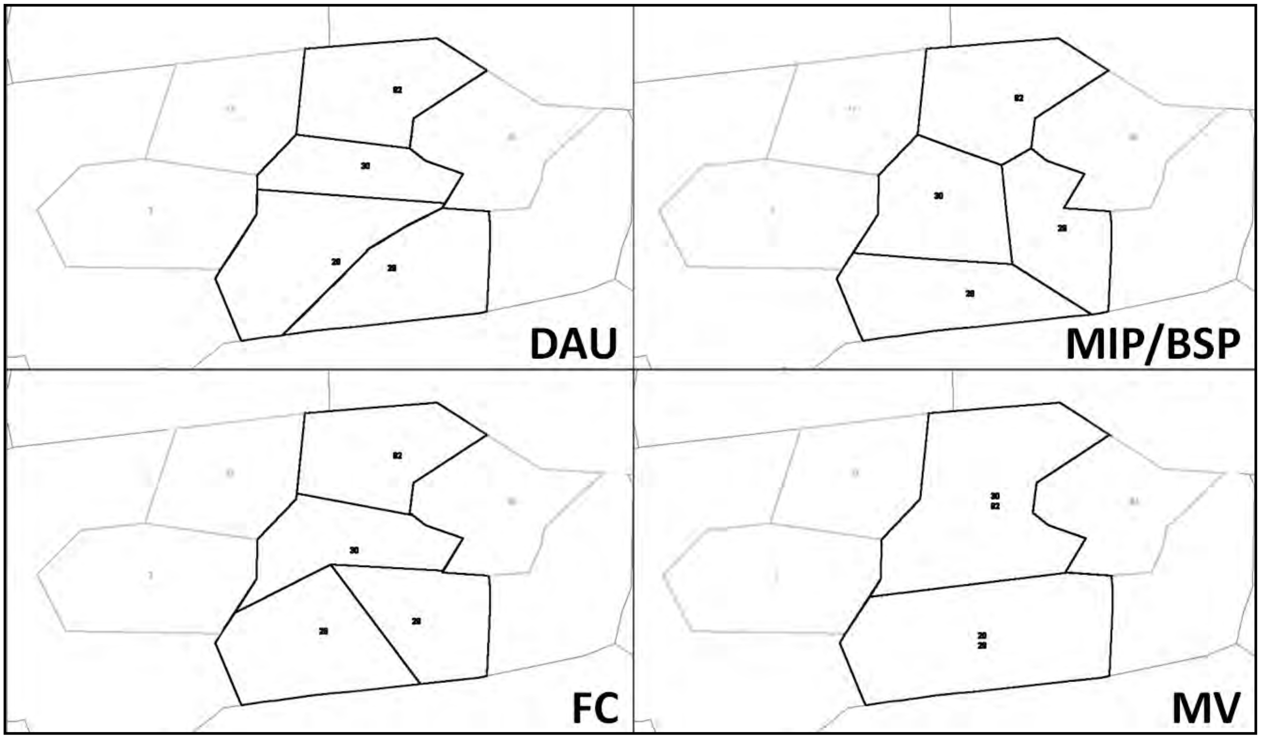


Figure 2. Example of 4-sector airspace designs generated from the four different algorithms (note the vertical partitioning in the Modified Voronoi design).

1. *DAU Slices*

This approach initially partitions the defined test airspace into a series of slices referred to as Dynamic Airspace Units[9]. The slices originate from a common boundary between neighboring sectors and propagate outward incrementally. Based on changes in the traffic demand, a redesign of the airspace is performed to accommodate and evenly distribute the demand by selectively assigning the slices to the most appropriate sector(s). As the demand changes over time, new designs can be produced in the same fashion at defined intervals in order to utilize the airspace most optimally.

2. *Mixed Integer Programming + Binary Space Partition (MIP/BSP)*

Two separate algorithms are used in this approach. Mixed Integer Programming (MIP)[11,23] is first used to balance a number of metrics between the defined test sectors (e.g., dwell time, aircraft count). The airspace is then divided into a network of small hexagonal cells, after which adjacent cells sharing common flows of traffic are systematically combined while respecting the balance of metrics achieved earlier. A Binary Space Partition (BSP)[17] algorithm is then applied to the resultant airspace design, which adjusts the configuration according to operational constraints (e.g., flow intersection points and sector geometries).

3. *Flight Clustering (FC)*

In this approach, time-sampled data for aircraft positions are first clustered together according to a set of criteria that define a flow through a given area of airspace[12]. Region growing methods are then used to further refine the clusters and assign any remaining aircraft positions to the most appropriate cluster. Computational geometry techniques are then applied to create an initial design that most optimally encapsulates the defined clusters for a given period of time. The resulting design is adjusted to balance Dynamic Density (DD)[24] factors while respecting the established traffic flows.

4. *Modified Voronoi (MV)*

This approach uses a combination of Voronoi diagrams[25,26] and genetic algorithms in generating an airspace design. The airspace is first partitioned using Voronoi diagrams into sectors that are convex-shaped with an associated set of "generating points." These points are then configured using genetic algorithms to optimize a predefined set of cost metrics (e.g., number of sector boundary crossings, aircraft count, flight dwell time, etc.). An iterative deepening method was further applied to provide a means of partitioning the airspace vertically as well as laterally.

E. Simulation Environment

The environment used to test airspace design in the FAM concept was developed and presented through the MACS software platform. This Java based software is capable of emulating current day operations and is scalable to prototype operations envisioned as part of NextGen.

For this study, the operational environment was assumed to be one in which all aircraft were conducting TBO and were equipped with Data Comm and ADS-B capabilities for trajectory changes and accurate position and intent information. Based on these capabilities and information, the airspace designer participants' duties were to assess the predicted traffic situation for the 4- or 7-sector airspace and, depending upon the condition, first modify airspace configurations to reduce peak aircraft count and distribute the loads most equitably or strategically between the test sectors. If peaks and imbalances remained, traffic reroutes were performed. To accomplish these tasks, the airspace designer workstation was configured to provide access to new and existing functionalities within MACS to facilitate each phase of the airspace design process. A brief description follows.

1. *Traffic Assessment*

The tools provided for the assessment and management of traffic were previously developed as part of the Multi-Sector Planner (MSP)[27,28] concept. Both the FAM and MSP concepts require an awareness of the current and predicted traffic situations from which to base decisions on. To enable this awareness, the airspace designer participants were provided with interactive load tables and graphs that were used to monitor peak values for aircraft counts in the test sectors (see Fig. 3). The tables and graphs presented current and predicted sector counts at different levels of granularity and in different formats. For the traffic load tables (upper right of Fig. 3), each row of the table corresponded to a test sector or sector of interest, and each cell in the row represented a 15-minute interval that contained the predicted peak sector count value for that period. The load graphs (lower portion of Fig. 3) provided a graphical representation of the same information contained in the load tables, but at one-minute intervals and plotted on an x- and y-axis (time and sector count respectively). For both the tables and graphs, color was used as a reference for a given value's relationship to the sector's capacity threshold, which was set at 22 aircraft. Values in green meant that the peak count was below the threshold, yellow was at threshold, and red meant that the count exceeded the threshold. The behavior and presentation of data in the tables and graphs were controlled through the Load Display Control Window.

In addition to the traffic load tables and graphs providing current and predicted peak sector count values, they were also interactive with the Display System Replacement (DSR) display's filtering mechanism. This allowed the participant to select a cell in the table or time slice in the graph, which highlighted the specific aircraft on the DSR that corresponded to the selected peak value. This provided a higher level of understanding and awareness to the participant by revealing the characteristics of the traffic and flows that contributed to the observed sector count values. The information provided by the predicted peak counts and their underlying composition were used as the basis for the airspace design and traffic management decisions that followed.

2. *Airspace Design*

New tools and functionalities for the airspace design process were developed for this study that allowed participants to modify the existing sector boundary configuration or select, review, and modify predefined configurations generated by the algorithms described earlier. In the Manual Boundary Change (Manual BC) condition, participants did not have access to pre-defined airspace solutions. Instead, they relied on their knowledge, expertise, and understanding of effective airspace designs to solve the problems presented in this condition. Airspace design in this condition first involved making a working copy of the existing boundary configuration. Working from a copy enabled the participant to discard their trial modifications and revert to the original configuration if and when needed. It also allowed them to safely modify sector boundaries, in isolation, without resultant changes to the existing environment.

Cell values
○ TOTAL ● PEAK ○ AVERAGE ○ PEAK/TOTAL

Categories
● ALL ○ CNFLT_CNT ○ CNFLT_AC ○ TRANS
○ FILTR ○ UNEQP ○ WETHR ○ CMPLX
● Show Category only ○ Show Category and ALL

Selection logic
○ Single cell ● In any cell
● Multi cell ○ In all cells
Deselect all

Display
Table font size: 2

Sector						
ZKC_29	[illegible]	21	20	22	19	17
ZKC_98	21	21	16	15	8	3
ZKC_90	23	20	[illegible]	[illegible]	[illegible]	20
ZKC_94	[illegible]	23	22	[illegible]	20	10
ZKC_92	[illegible]	24	13	9	10	9
ZKC_30	[illegible]	23	20	17	17	13
ZKC_28	23	19	18	15	10	8

1915 1930 1945 2000 2015 2030 2045

Figure 3. Traffic assessment tools used for gaining awareness and understanding of current and predicted traffic situations.

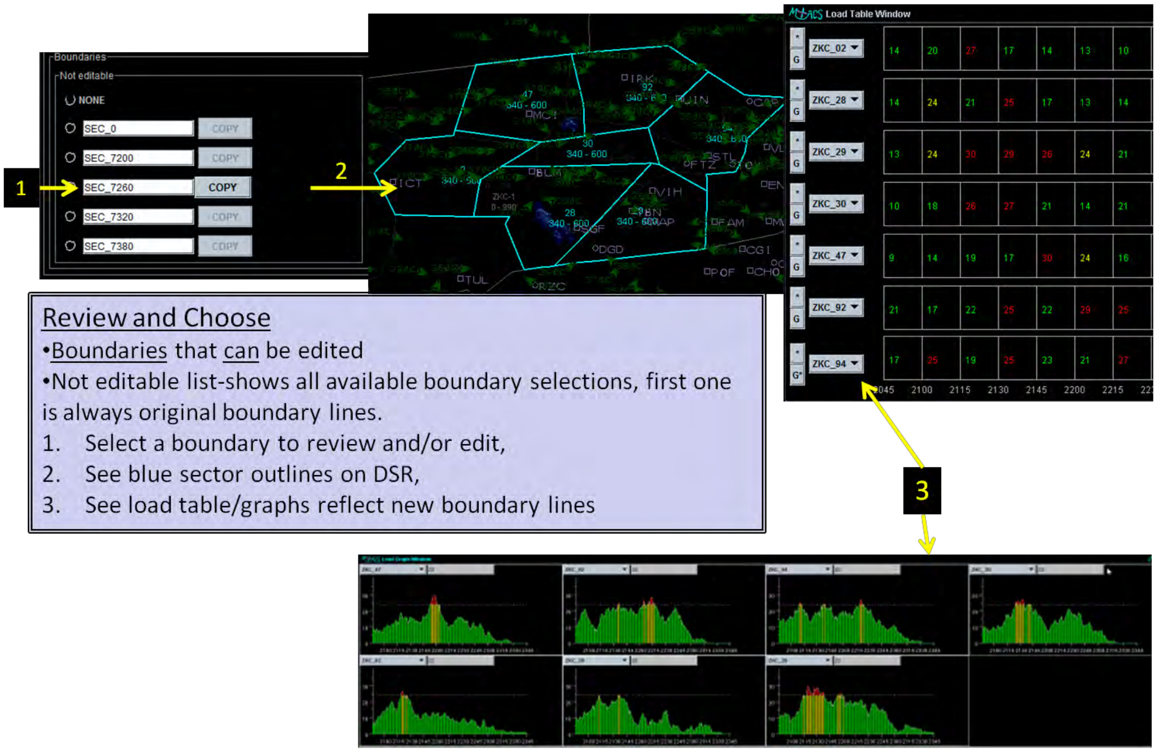
When a participant entered the editing mode and selected the working copy of the sector boundary configuration, an overlay of the current sectors was highlighted on the DSR display and made available for modification. Participants could modify the airspace laterally, vertically, or both in combination. The only constraints placed upon the process were that the outer boundaries of the test sectors could not be modified and the floor of the test airspace could not be violated. To make lateral changes, a number of pre-positioned points were highlighted at various intersections on the overlay. These points could be dragged laterally anywhere within the test area to create the desired sector geometries. Points could also be added anywhere along the inner sector boundary lines for greater design control. Points could be removed as well by right-clicking on them, after which the line snapped to connect the next two points nearest the deletion.

Depending on the traffic situation, splitting and stacking sectors vertically at a particular altitude stratum was the most effective or preferred approach. In this case, two adjacent sectors were selected and temporarily merged into a single sector. Following this step, the participant selected a particular altitude at which to split the sector, thus creating two sectors stacked vertically. The processes of splitting and stacking sectors vertically and making lateral modifications could be combined such that an airspace design would have elements of both evident in its final configuration.

Regardless of the method used in the design of airspace, as changes were being made to the configuration, real-time feedback was provided to the participant in terms of the proposed modification's impact on the predicted traffic load. This feedback was presented through the load tables and graphs in which the table's numbers and the graph's form would change dynamically to reflect the loads predicted for each of the test sectors resulting from the proposed design. In addition to the participants' understanding of airspace structure and design, the interaction between airspace modification and feedback regarding its impact on the traffic guided the entire process and served as the foundation for the overall strategy used in resolving the problems presented.

In the Algorithm+Manual BC condition, rather than the existing airspace structure serving as the initial state to design from, participants had access to a set of pre-defined configurations generated by each of the airspace optimization algorithms (as shown in Fig. 4). A different set of configurations was available for each run in this condition, which were tailored for the particular flows of traffic in the problem according to the specific approach of the algorithm. Prior to the start of modifications, participants cycled through the set of configurations while making initial assessments of their effectiveness. This assessment was based on the relative changes of the predicted traffic loads as reflected in the load tables and graphs as each configuration was selected. Based on this feedback, the most desirable configuration was selected, after which a working copy was made and then further modified in accordance with the designer's airspace and traffic management strategies. Modifications of the selected configuration were performed in the same manner as described for the Manual BC condition.

In both the Manual BC and Algorithm+Manual BC condition, once the desired modifications were made and a final configuration was derived, a boundary change was scheduled and activated at a time specified by the participant. If excessive peaks remained following this step, route modifications were performed to further reduce those values using the provided traffic management tools.



Review and Choose

- Boundaries that can be edited
- Not editable list-shows all available boundary selections, first one is always original boundary lines.

1. Select a boundary to review and/or edit,
2. See blue sector outlines on DSR,
3. See load table/graphs reflect new boundary lines

	2045	2100	2115	2130	2145	2200	2215
ZKC_02	14	20	27	17	14	13	10
ZKC_28	14	24	21	25	17	13	14
ZKC_29	13	24	30	29	26	24	21
ZKC_30	10	18	26	27	21	14	21
ZKC_47	9	14	19	17	30	24	16
ZKC_92	21	17	22	25	22	29	25
ZKC_94	17	25	19	25	23	21	27

Figure 4. Algorithm-generated configurations available for modification. Traffic load tables and graphs updated with each selection to reflect its impact on the traffic load values for each test sector.

3. *Traffic Management*

Although rerouting traffic is not part of the airspace design process, it was included in this study as a means of reducing the levels of excess traffic that the reconfiguration of airspace could not. A number of tools were available for this task, which included the selection, planning, and rerouting of aircraft. Traffic load tables and graph displays were interactive, which allowed the participants to select specific or multiple time steps of the traffic load predictions. This, in turn, highlighted the aircraft relevant to the selected peak values on the DSR. Having identified the desired traffic, trial plans of the associated trajectories were performed (Fig. 5). The trial plans could be moved laterally for heading changes, modified for altitude changes, or combined to enact a dual horizontal-vertical maneuver. Once an acceptable proposal was developed, the active trial plans were uplinked directly to the aircraft in the selection. The process of selecting aircraft, trail planning, and executing trajectory changes was performed iteratively until the excess sector count values were sufficiently reduced.

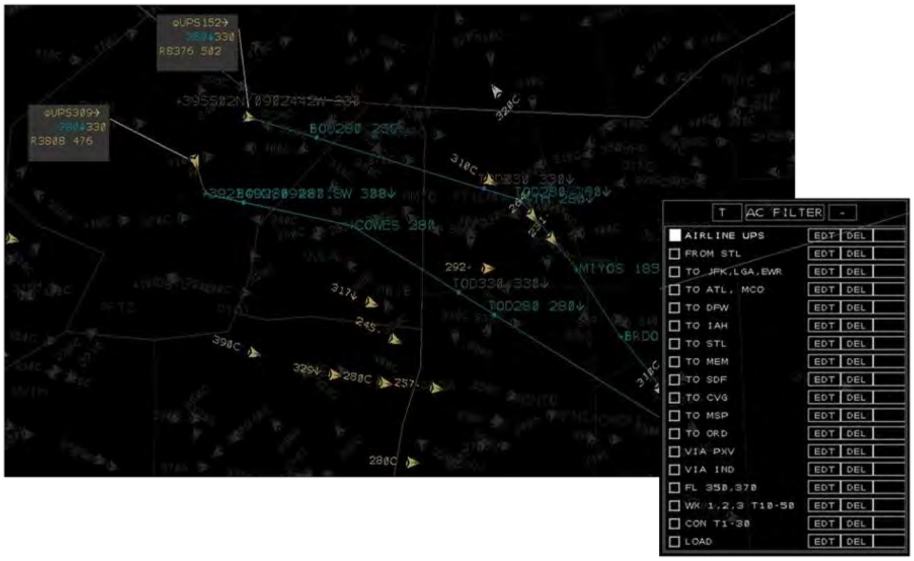


Figure 5. Traffic management tools for filtering, selecting, and trial planning trajectory changes.

F. Experiment Design

This study was a 3x2 within-subjects design. The two independent variables were ***Boundary Change*** (BC) with three levels (No BC, Manual BC, and Algorithm + Manual BC) and ***Number of Sectors*** with two levels (4-sector and 7-sector). These variables were manipulated to test the benefits and potential role of algorithm-generated airspace designs relative to FAM operations without algorithm support, as well as to non-FAM operations involving a traditional, static airspace. Comparisons between the BC levels were also designed to be made between simple (4-sector) and more complex (7-sector) operating environments in order to assess the nature and applicability of any potential benefits. A description of the BC variable's levels follows.

1. No BC

This condition served as a baseline in which airspace reconfiguration was not an option. The airspace was static and the only means to address the predicted peak values was through the removal of aircraft from their user-preferred routes. The number of reroutes performed in the No BC condition was a point of comparison with the other BC conditions in determining the overall benefits of FAM.

2. Manual BC

In this condition, the existing airspace configuration that was present in the No BC condition was available for modification through the use of the airspace design tools. Sector boundaries were modified to design the most optimal configuration that reduced and distributed the peak sector counts within the test area. Excesses and imbalances that remained after the boundary change were resolved through traffic reroutes as in the No BC condition.

3. Algorithm + Manual BC

This condition provided the airspace design participants with a set of pre-defined, algorithm-generated airspace configurations. These configurations were cycled through to determine the most effective initial solution to the peak load and traffic imbalance problem. The subsequently selected configuration was further modified manually as in the Manual BC condition to fit the designer's overall strategy and approach to the situation. Following the initiation of the boundary change, remaining peaks and imbalances were handled through reroutes as in the No BC condition.

Consideration was given to including an algorithm only condition in which algorithm-generated airspace designs would be available for selection and implementation but not modification. However, the goal of this study was not to test whether algorithm-based designs were better than human-based designs but to examine the potential for interaction between the two approaches. While algorithm-based designs often lack or simply cannot fully account for the specialized knowledge applied by subject matter experts to airspace design, they do have a computational advantage. Such an advantage allows for algorithm-based designs to be informed by a greater number of considerations and constraints than those designed solely by humans, which could ultimately produce more optimal airspace solutions. Based on this problem space, the final design of the experiment as outlined was constructed to answer the following questions: 1) can algorithm- and human-based airspace solutions be combined effectively, 2) is there a benefit to a combined approach, and 3) how acceptable are the algorithm-generated designs to the subject matter experts?

G. Procedure

This study was conducted over the course of four days in August of 2010. The first two days were devoted to training in which the participants were first introduced to the FAM concept and the process of airspace design that was the study's focus. Hands-on training was then provided on the decision support tools that were to be used as well as the procedures to be followed in the designing of airspace and management of traffic. Familiarity with the airspace and traffic was also gained through the presentation of sample 4- and 7-sector scenarios that increased the levels of traffic in stages to allow the participants the opportunity to gradually gain proficiency in the use of the tools. Following the conclusion of the final training run, a debrief discussion was held that provided an open forum for the participants to discuss and clarify their understanding of the tools, procedures, and concept prior to the start of data collection.

The order of runs for the two days of data collection were blocked according to BC condition such that the No BC condition block was presented first, followed by the Manual BC condition, and finally the Algorithm + Manual BC condition block (see Table 1). This particular order was designed with particular interest in having the Manual BC runs precede the Algorithm + Manual BC runs in order to prevent the participants from being influenced by the algorithm-generated airspace designs. The presentation order of the 4- and 7-sector problems were also alternated for each run in order to prevent the participants from becoming overly familiar with either set.

Prior to the start of each condition's block of runs, a practice run was conducted to prepare the participants for that condition's operational procedures. The data collection runs that followed were each 30 minutes in length. The four participants worked individually, in parallel at assigned workstations within an isolated network in separate rooms. The actions of each participant were not observable by the other participants nor did they have any impact on the environment of any of the other participants. AOL staff observers were assigned to each of the participants to both observe and assist with any technical issues that arose during the course of a run and ensure that the proper procedures were being followed.

Table 1. Data collection run schedule.

Day	Run	Condition	Sector
3	Practice	No BC	7-sector
3	1	No BC	4-sector
3	2	No BC	7-sector
3	3	No BC	4-sector
3	4	No BC	7-sector
3	Practice	Manual BC	7-sector
3	5	Manual BC	4-sector
3	6	Manual BC	7-sector
4	7	Manual BC	4-sector
4	8	Manual BC	7-sector
4	Practice	Algorithm + Manual BC	7-sector
4	9	Algorithm + Manual BC	4-sector
4	10	Algorithm + Manual BC	7-sector
4	11	Algorithm + Manual BC	4-sector
4	12	Algorithm + Manual BC	7-sector

For each of the data collection runs, the goal of the participants was to reduce the predicted peak values of traffic load to the threshold of 22 aircraft or less. In the No BC condition, the sole means of doing so was through manual reroutes using the traffic assessment and management tools described earlier. The constraints placed on the rerouting of traffic were that aircraft should be kept within the test airspace to the greatest extent possible before rerouting outside, reroutes should not place aircraft in weather, and the use of altitude to lower aircraft below the FL340 floor was restricted to aircraft landing at local area airports. In the Manual BC condition, participants were not allowed to begin rerouting aircraft until after the existing boundary configuration was modified and a boundary change was made. Participants were asked to spend no more than the first 10 minutes of the run designing the airspace before enacting a boundary change and moving on to the rerouting of aircraft (the actual durations for the design stage of the run were often much less than 10 minutes). In the Algorithm + Manual BC condition, participants were asked to cycle through the entire set of algorithm-generated configurations before making a selection and proceeding to make modifications. While modifications were not enforced, the participants overwhelmingly chose to further modify the algorithm-generated designs to address in their pursuit of developing an optimal configuration. The same constraints on the design duration and reroutes were in effect as described for the No BC and Manual BC conditions' runs.

At the conclusion of each run, participants were presented with an online questionnaire. In the Algorithm + Manual BC condition, participants were presented with an additional paper questionnaire that solicited feedback on the algorithm-generated designs that they had available to them in the completed run. Following the completion of the final run and its associated post-run questionnaires, an online post-simulation questionnaire was presented. This was followed by a debrief discussion in which any issues that surfaced during the training or data collection (e.g., the FAM concept, equipment, software, airspace design process/procedures, etc.) were openly discussed.

III. Results

This study investigated the potential role that airspace optimization algorithms can play in FAM operations. Of interest was how well algorithm support benefited the airspace designers in developing optimal solutions relative to airspace design without such support. The effectiveness of the resulting designs was also of interest both in the comparison between operations with manual and algorithm-supported airspace reconfiguration as well as to operations without. To first assess the potential benefits of algorithm-supported airspace design and FAM operations as a whole, analyses were performed on the relative effectiveness of managing the capacity overload problems in each of the experimental conditions. Further analyses were performed on the actual airspace configurations created in the Manual BC and Algorithm + Manual BC conditions and the processes involved in developing them.

A. Peak Traffic Management

The focus of initial analyses was on how well the algorithm-generated designs addressed the traffic problem relative to manually generated designs. This was measured by the number of required aircraft reroutes that followed a boundary change in the two BC conditions in addition to how effective those reroutes were in managing the predicted peak overloads within the test airspace.

1. Predicted Peak Reduction

In the Manual BC and Algorithm + Manual BC conditions, the airspace design process was guided in part by the participants' assessment of how effective the modifications and final configuration would be in reducing the predicted peak aircraft counts below the threshold of 22 aircraft per sector. It was hypothesized that in this regard, the computational power provided by the algorithms coupled with the participants' knowledge and expertise would enable the design of airspace configurations that were more effective at reducing the peaks than designs without such support. To test this hypothesis, the predicted peak aircraft counts that remained immediately following the implementation of the airspace configurations (and prior to any reroutes) were compared between the two BC conditions.

Figure 6 presents the mean predicted peak sector counts, over time, for the designs generated in the Manual BC and Algorithm + Manual BC conditions in the 4- and 7-sector problems. The original predicted peaks are included in the plots as well to illustrate what the participants were basing their design decisions on and to characterize the traffic situation as it would exist without any intervention. From Fig. 6, the results for the 4-sector problem show that the designs from both BC conditions did well to reduce the predicted peaks relative to the original predictions. This in itself is important because the spread between the peak counts in the original and BC cases is an indication of the number of reroutes that would be required in the No BC and other BC conditions to bring the peaks in line with the threshold. Based on this initial result, the reconfiguring of airspace as part of FAM shows a potential benefit. However, when comparing the impact of the configurations in the Manual BC and Algorithm + Manual BC conditions, there is essentially no difference. This is likely the case because the 4-sector problem was more tractable and easier to solve than the 7-sector problem. Therefore, the designs in the different conditions were equally effective.

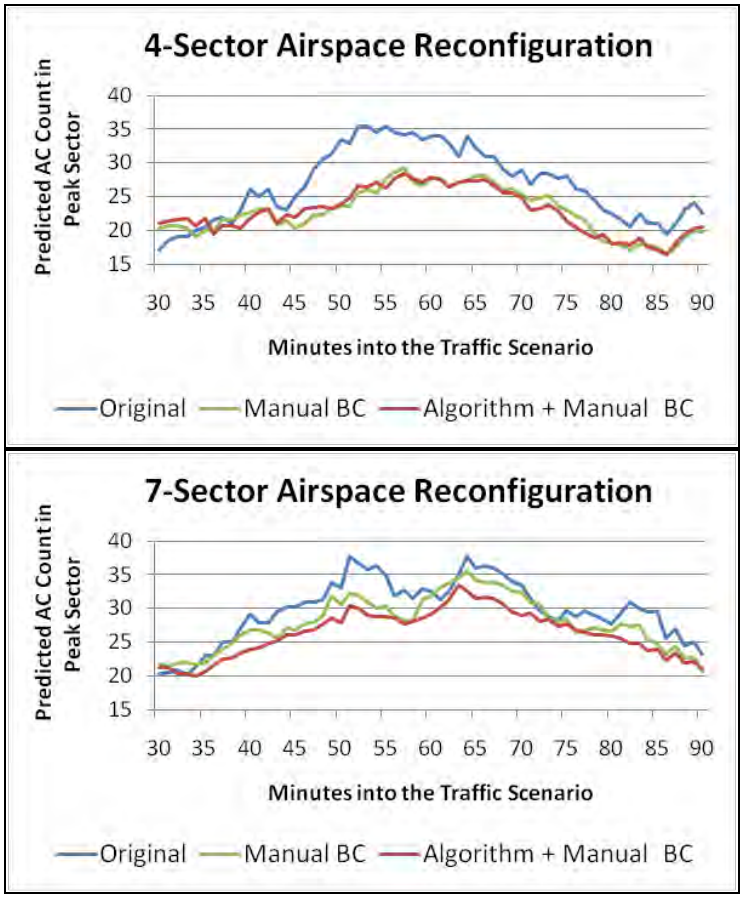


Figure 6. Comparison of mean predicted peak aircraft count in the 4- and 7-sector problems resulting from the designs in the Manual and Algorithm + Manual BC conditions. The "Original" plot represents the peak counts that exist as part of the base traffic problem.

Results for the 7-sector problem begin to show differences, however, as shown in the lower portion of Fig. 6. There it can be seen that over time, the designs from the Algorithm + Manual BC condition consistently resulted in lower peak aircraft counts relative to the Manual BC designs. Compared with the 4-sector problem, the traffic situation in the 7-sector problem was much more difficult with more information to process and considerations to account for. This highlights the possible advantage that algorithms provide in that much of difficulty and overhead involved with the traffic problem can be handled by the algorithm, leaving the designer with a simpler problem to resolve.

2. *Aircraft Reroutes*

The traffic problems developed for this study were challenging and could not be resolved through airspace configuration alone. Following a boundary change, participants were further required to reroute aircraft in order to manage the predicted peak overloads within the test area to at or below the sector capacity threshold of 22. Taking an aircraft off of its user-preferred route imposes a penalty on that aircraft and the airline, resulting in delay and fuel costs. One proposed benefit of using algorithm-generated airspace designs is the ability to allow more aircraft to remain on their original trajectories. This is also a key hypothesis of FAM overall[29]. To test whether this benefit was realized, comparisons were made between the numbers of rerouted aircraft in each of the three BC conditions. Results from the comparison between the Manual BC and Algorithm + Manual BC condition relate to benefits in terms of algorithm support in FAM. Comparison results for reroutes between these two BC conditions and the No BC condition speak to the overall benefits of FAM.

Figure 7 presents the mean number of reroutes performed in each of the three BC conditions where it can be seen that the No BC condition resulted in the highest number of reroutes (M = 74.75, SD = 13.77), followed by the Manual BC condition (M = 50.94, SD = 15.39), and the Algorithm + Manual BC condition resulted in the fewest number of reroutes (M = 39.19, SD = 12.56). Although these results appear to support the hypothesized benefit of algorithm support and FAM overall, there could have been alternative reasons for the observed reduction in reroutes. For example, one possible reason is that participants simply did not have enough time to perform the necessary reroutes to reduce the predicted peak overloads (i.e., the run ended before they could finish solving the problem).

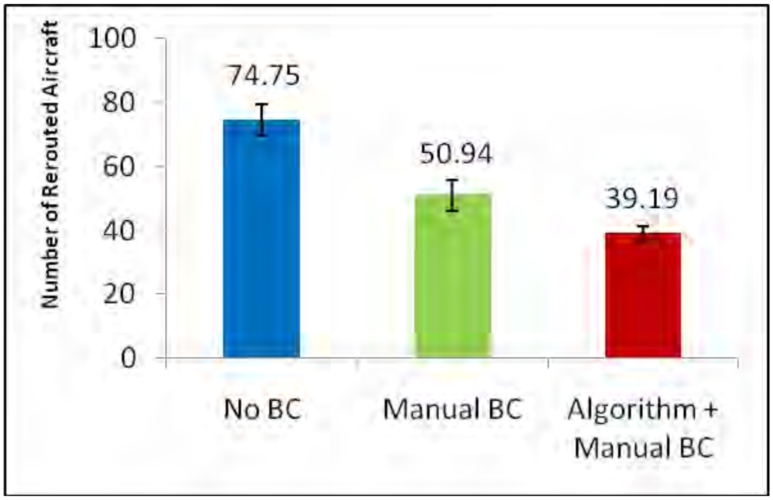


Figure 7. Mean number of aircraft rerouted per BC condition.

This would especially be the case in the Manual BC and Algorithm + Manual BC conditions since less time was available for reroutes due to the airspace design and implementation process.

If the issue of time were the case, the number of minutes above the threshold of 22 aircraft per sector in each of the conditions would be greater for the conditions that had fewer reroutes. To test this possibility, the mean number of minutes above sector threshold were compared where it was found that the No BC condition had the highest number of minutes (M = 47.69), the Algorithm + Manual BC condition had slightly fewer (M = 43.31), and the Manual BC condition resulted in the fewest number of minutes above peak threshold (M = 29.00). The fact that the No BC condition resulted in the greatest number of minutes above the threshold despite also having the highest number of reroutes removes the doubt that the reduction in reroutes for the other two BC conditions was due to insufficient time. However, when comparing the results for the Manual BC and Algorithm + Manual BC conditions, it appears that time may have been a factor that resulted in fewer reroutes in the Algorithm + Manual BC condition because of the greater number of minutes above threshold observed. Upon further investigation of this issue, it was found that one participant in particular was largely responsible for this unexpected result. Removing this individual's data produced results that followed the same trends observed in the reroute data where the No BC condition had the greatest number of minutes above peak threshold (M = 54.17), followed by the Manual BC condition (M = 31.08), and the Algorithm + Manual BC condition had the fewest number of minutes above threshold (M = 27.83). Based on these results, the stated hypotheses were supported in that there was a reduction in the number of required reroutes provided by FAM and the greatest reduction was provided through algorithm support.

B. Manual vs. Algorithm Supported Airspace Designs

Results for peak traffic management showed that the support provided by algorithm-generated designs in the Algorithm + Manual BC condition was beneficial and effective at reducing and redistributing traffic. However, such results alone fail to capture an assessment of the algorithms and their support from a user's perspective. To gain insight into this important aspect of the study, post-simulation questionnaires asked participants to provide ratings on the "goodness" of the final airspace configuration that was implemented during the run, the difficulty involved in selecting and/or creating that configuration, and the overall acceptability of the airspace configuration process. Table 2 presents the mean ratings to these questions for the Manual BC and Algorithm + Manual BC conditions.

"Goodness" of the final airspace configuration was an overall subjective assessment of how well the final design assisted in solving the problem that was presented and how well it corresponded to a realistic and workable configuration. The ratings for this question were on a scale from 1 (Very poor) to 6 (Very good). Results show that although both were high, the mean response ratings for the Manual BC condition were lower than in the Algorithm + Manual BC condition, suggesting that the algorithms may have enabled the participants to develop configurations that were better than ones in which they developed independently. This difference, however, was not significant (paired $t(3) = 1.73, p > 0.18$).

Participants were also asked to rate the difficulty involved in selecting and creating the final airspace configuration. Ratings were on a scale from 1 (Very easy) to 6 (Very difficult) and it can be seen from the mean response ratings that participants felt creating the final configuration in the Manual BC condition was marginally more difficult than in the Algorithm + Manual BC condition (paired $t(3) = 2.63, p < 0.08$). This again suggests that algorithm support may have provided some benefit by making the design process easier. Responses from the participants were somewhat mixed however when asked to explain their ratings. For the difficulties involved in the Manual BC condition, some participants mentioned that it was difficult to effectively distribute the traffic load, particularly in the 7-sector problem where boundary modifications simply resulted in the traffic loads "hop-scotching" around. In the Algorithm + Manual BC condition, participants remarked that difficulties arose when none of the algorithm options provided an adequate solution to the problem nor did they differ enough so that one configuration was a "clear standout."

Dynamically designing and reconfiguring airspace is not a process that is performed today. To gauge the overall acceptability of that process as presented in this study, participants were asked to rate the acceptability on a scale from 1 (Not at all acceptable) to 6 (Completely acceptable). The mean ratings were high for both BC conditions, although in this case the process in the Manual BC condition was rated as more acceptable than in the Algorithm + Manual BC condition. This difference was not significant, however (paired $t(3) = 0.58$, $p > 0.60$). Significant differences were found when comparing the acceptability ratings between the 4- and 7-sector problems (without respect to the BC conditions). Through this analysis, it was found that the process was significantly more acceptable in the 4-sector problem (M = 5.31, SD = 0.52) than in the 7-sector problem (M = 4.56, SD = 0.31) ($t(6) = 2.48$, $p < 0.05$). This is likely due to the fact that the 7-sector problems were inherently more difficult and complex than the 4-sector problems given the greater number of sectors involved and the amount of work and consideration required.

Table 2. Mean post-run ratings to questionnaire items on the "goodness" of the final airspace configuration, the difficulty involved in selecting and/or creating the final configuration, and the acceptability of the overall process. Standard deviations are in parentheses.

	Manual BC	Algorithm + Manual BC
"Goodness" of the final airspace configuration (1 = Very poor; 6 = Very good)	**4.63** **(1.01)**	**5.00** **(0.65)**
Difficulty of deciding upon and creating the final airspace configuration (1 = Very easy; 6 = Very difficult)	**3.25** **(1.02)**	**2.69** **(0.72)**
Acceptability of the airspace reconfiguration process (1 = not at all acceptable; 6 = completely acceptable)	**5.00** **(0.54)**	**4.88** **(0.66)**

C. Algorithm Supported Airspace Design

One of the main objectives of this study was to explore the potential role of algorithms and algorithm-generated airspace designs in FAM. This was partially addressed through the comparisons of the designs and processes involved in the Manual BC and Algorithm + Manual BC conditions. To gain a more detailed understanding of the algorithm-generated airspace designs, the support they provided, and some of the issues present in their use, further analyses were performed.

1. *Selection and Modification of Algorithm-Generated Airspace Designs*

As part of the post-run questionnaire presented to participants in the Algorithm + Manual BC condition, a number of questions were asked concerning the difficulties involved in the selection and modification of an algorithm-generated design as well as the "goodness" of its initial and final states. Table 3 presents the overall mean response ratings to these questions in addition to a breakdown of the results between the 4- and 7-sector problems.

In each run of the Algorithm + Manual BC condition, participants had access to a set of four algorithm-generated airspace designs to choose from. With these options in mind, one area of interest was the difficulty involved in the selection and subsequent modifications of the designs. For both related questions, participants were asked to rate the difficulty on a scale from 1 (Very easy) to 6 (Very difficult). For the difficulty experienced in the selection process, participants provided a mean overall difficulty rating of 2.75, which was between the categories of "Somewhat easy" and "Moderate to easy." Results differed somewhat when compared between the 4- and 7-sector problems in that selecting an airspace configuration was rated as more difficult in the 7- than the 4-sector problem.

Table 3. Mean post-run ratings to questionnaire items on the difficulty in selecting and modifying the airspace configuration and the "goodness" of the initial and final airspace designs in the Algorithm + Manual BC condition. Standard deviations are in parentheses.

	4-sector	**7-sector**	Overall Mean
Difficulty of selecting the initial algorithm-generated airspace configuration (1 = Very easy; 6 = Very difficult)	**2.25** **(1.06)**	**3.25** **(0.35)**	2.75 (0.87)
Difficulty of deciding how best to manually adjust airspace configuration (1 = Very easy; 6 = Very difficult)	**1.67** **(0.71)**	**2.83** **(0.24)**	2.50 (0.58)
"Goodness" of the initially selected algorithm-generated airspace configuration (1 = Very poor; 6 = Very good)	**4.83** **(0.24)**	**4.17** **(0.24)**	4.50 (0.43)
"Goodness" of the final airspace configuration (1 = Very poor; 6 = Very good)	**5.67** **(0.47)**	**4.50** **(0.24)**	5.08 (0.74)

To be presented with the question on the difficulty in deciding how to best to modify the selected airspace design, participants first needed to answer "yes" to a preliminary gateway question that asked if they had indeed made modifications. One of the participants replied "no" in three of the four runs and, as a result, was not presented with this follow-on question. The mean difficulty response rating of 2.50 from the remaining three participants showed that, overall, they felt that the decisions on how best to modify the algorithm-generated airspace design were between "Somewhat easy" and "Moderate to easy." The earlier trend also continued in the results between the 4- and 7-sector problems in that participants provided higher difficulty ratings for the 7-sector problems.

To better understand the participants' impressions of the algorithm-generated designs, they were asked to rate the "goodness" of the initial design that was selected for modification and implementation. Ratings of "goodness" were on a scale from 1 (Very poor) to 6 (Very good), and the results from Table 3 show that the participants' mean rating was 4.50. This rating translated to one between "Somewhat good" and "Moderate to Good." Similar to previous results, "goodness" ratings for the initial designs were lower for the 7-sector than the 4-sector problems.

Following from the question on the "goodness" of the initial algorithm-generated design, participants were asked to rate the "goodness" of the final design that was implemented after the modifications were performed. The overall mean response rating to this question was rather high at 5.08, "Somewhat good." "Goodness" ratings were again lower for the final configurations in the 7-sector problem than the 4-sector problem.

The results from the questions on the "goodness" of the initial and final airspace designs provided an opportunity to indirectly estimate the participants' contentment with their modifications. For this estimation, the mean "goodness" ratings for the initial and final designs were compared for the 4- and 7-sector problems. Figure 8 presents a comparison of the mean ratings where it can be seen that the final designs are uniformly higher for the final than the initial configuration. To further investigate these differences, a 2x2 mixed ANOVA was performed, using the initial/final component as the within-subjects variable and the 4- and 7-sector conditions as the between-subjects variable. The results from this analysis showed that the "goodness" of the final configuration was rated significantly higher than the initial configuration ($F(1,10) = 6.62$, $p < 0.03$). The differences between the 4- and 7-sector conditions only proved to be marginally significant ($F(1,10) = 3.76$, $p < 0.09$). A test for an interaction did not yield significance ($F(1,10) = 1.22$, $p > 0.2$).

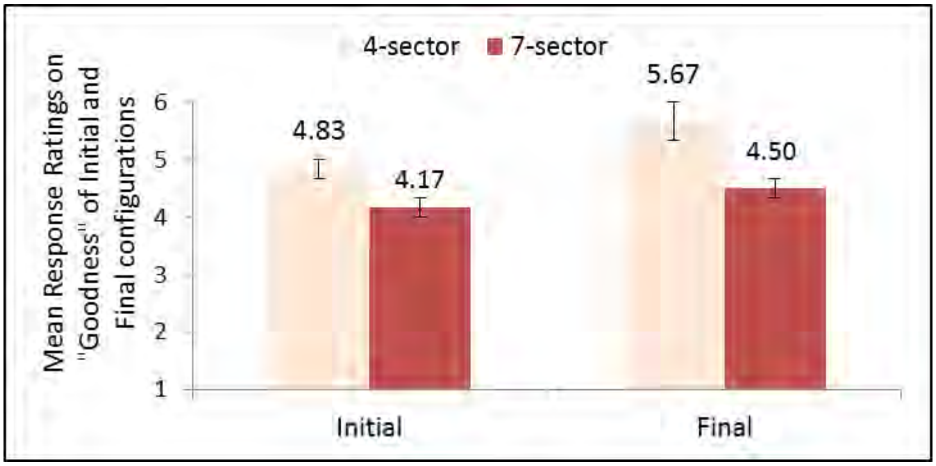


Figure 8. Comparison of mean initial and final "goodness" of algorithm-generated airspace design per sector problem.

2. *Airspace Volume Change*

In the Manual BC condition, participants first attempted to resolve the peak capacity overload problem through manual boundary modifications to the existing configuration. In the Algorithm + Manual BC condition, participants had access to a set of algorithm-generated airspace designs from which the most desirable design was chosen and further modified. The comparison of volume changes between the two conditions provided a means of assessing one aspect of the potential benefits provided by algorithm support in FAM in that less volume changed (i.e., fewer required modifications) would be an indication that the use of such support facilitates the airspace design process by enabling the designers to start from an advanced and viable initial state. This would, as a result, reduce the required effort in developing an optimal design solution.

To calculate the amount of volume change, the final configurations in both conditions were compared to the configuration on which the final design was based. In the Manual BC condition, this meant the original existing configuration. In the Algorithm + Manual BC condition the comparison was made in relation to the configuration that was selected as the starting point. In accordance with this approach, differences in volume were first calculated on a per-sector basis by comparing the final configuration to the corresponding original. The mean volume change was then computed to show the mean amount of change that resulted from the modifications. Units of measure were in cubic nautical miles due to the airspace changes occurring in three-dimensional space.

Figure 9 presents the results from this analysis where it is shown that the amount of airspace volume that changed was greater in the Manual BC condition (M = 1836.30 nmi^3, SD = 706.54) than in the Algorithm + Manual BC condition (M = 542.35 nmi^3, SD = 421.00). This difference was significant (paired $t(15) = 6.17$, $p < .001$),

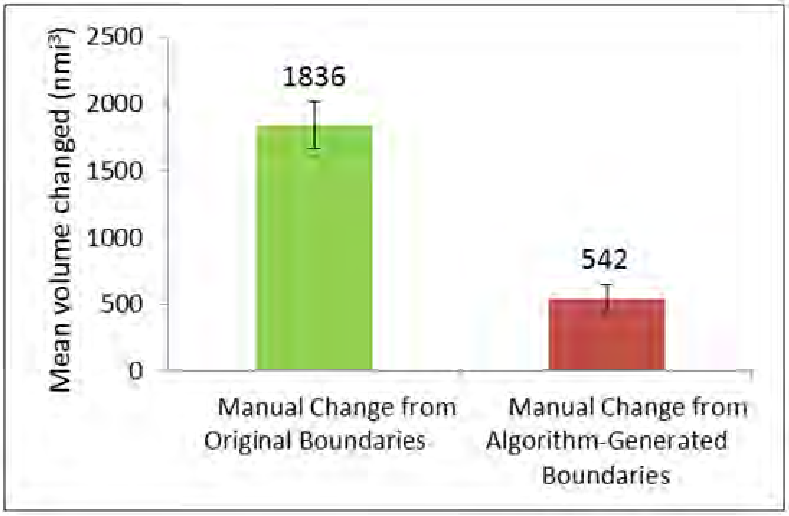


Figure 9. Mean volume change between two BC conditions

supporting the hypothesis that algorithm support can provide benefits by reducing the effort required by the airspace designers in developing viable airspace design solutions.

The difference in volume changes between the Manual BC and Algorithm + Manual BC conditions are not surprising given that the relative starting points are different. However, the moderately small amount of mean volume change in the Algorithm + Manual BC condition suggests that, overall, participants did not feel the need to adjust boundaries a great deal in order to arrive at an acceptable configuration. Figure 10 provides an example of this in which the algorithm-generated solution on the left was selected and modified by the participant. The final result on the right shows that the participant left much of the original design unchanged with only minor adjustments to the southern sectors in an effort to simplify their geometries. For similar examples, a full catalog of final algorithm, Manual BC, and Algorithm + Manual BC airspace designs can be found in the Appendix.

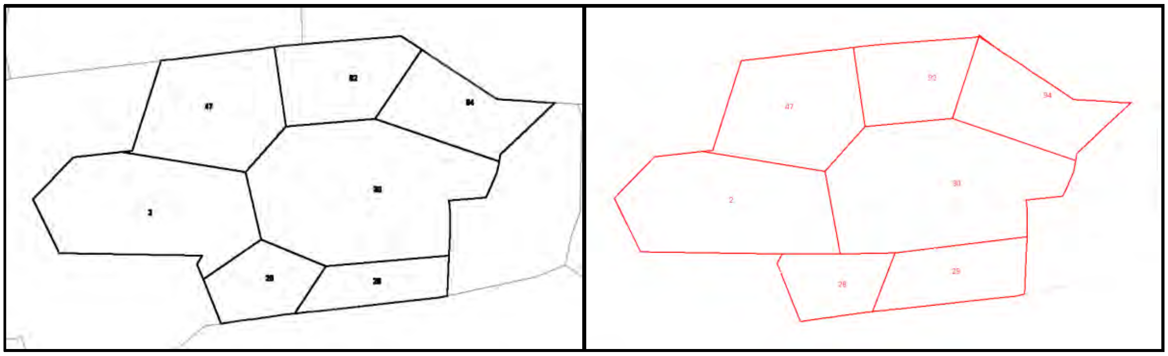


Figure 10. Example comparison of algorithm-generated solution and modifications made by participant.

D. Subjective Feedback

Many of the items in the post-run and post-simulation questionnaires provided participants with the opportunity to explain their responses or comment on particular aspects of the previous run's condition or overall concept. Based on the results presented thus far, this section will present and discuss some of the participants' feedback concerning the pros and cons of manual and algorithm supported airspace design, as well as feedback on the "goodness" of airspace designs that resulted from the two different approaches.

1. Pros and Cons of the Manual and Algorithm Supported Airspace Design Process

The results obtained from the comparison of manual and algorithm supported airspace design as they were presented in the Manual BC and Algorithm + Manual BC conditions respectively suggested that having access to algorithm-generated configurations to use as a starting point was beneficial: the process of reconfiguring the airspace was easier and the final configurations were better. Feedback from the participants on these regards expanded upon their response ratings and supported these results. For example, one participant remarked that, although "sometimes [the algorithm-generated configurations] didn't provide an efficacious solution, quickly toggling through options and then [building] on the best design" was one of its advantages. With respect to the ease of airspace design provided by the algorithm support, one participant commented that, "workload seems easier when choosing from the list and then manipulating the boundaries to one's liking. This was not overly difficult since most of the changes seemed to be fairly reasonable."

However, supportive comments like these often related to 4-sector problems. A slightly different picture began to emerge in the 7-sector problems where participants sometimes felt that the intended support of the algorithms became an impediment. For example, one participant commented that, "I analyzed the algorithm models for a long time thus negating my strategic reroute capabilities." Another remarked that by using a pre-defined design, one "could easily be pigeon-holed into the options as being the only solutions to [sector overload] problems." Such comments suggest that there is also value in approaching a particular problem with a clean slate as was done in the Manual BC condition. One potential advantage of a clean slate approach as with manual airspace design is that the designer is afforded a great deal of flexibility in how to approach a problem. Support for this idea was provided by comments such as: In the Manual BC condition, users were "forced to examine more aspects of the situation [where they] did not feel [that they] had to rely on a solution." Apparently, some participants felt that having a pre-defined solution to a problem degraded their ability to understand that problem fully, which may have negatively influenced their decision making process.

Despite the greater flexibility and awareness facilitated by manual airspace design, the process did have its own set of drawbacks as well. In relation to what was experienced with algorithm support, some participants felt that the process of manually designing an "acceptable boundary configuration" was more difficult and time consuming. For example, one participant remarked that they needed to, "…take a couple of minutes to process all of the available information before committing to [the] boundary change. If you just try to „beat down' the graphs without looking at flows, weather, etc., you will be working harder after you make the changes."

2. "Goodness" and Acceptability of Airspace Designs

In addition to response ratings for the "goodness" and acceptability of airspace designs, participants were asked to explain what design characteristics affected their assessments. Perhaps the most commonly cited considerations for the "goodness" and acceptability of airspace designs had to do with how the traffic volume was distributed and the configuration's relationship to the convective weather.

In terms of the traffic, "good" design approaches and resultant configurations were cited as those that most evenly distributed the traffic volume and expected workload between the test sectors. The most desirable designs, however, were those that took into account the location and impact of the weather. In explaining their design decisions, one participant remarked that, "I tried to first surround the weather with a sector-this proved to be a very effective solution. [I] manipulated the boundaries after that to adjust for flow volume. This process seemed to work very well." While some chose to surround the weather with their airspace design, others used a different strategy by "splitting" the weather in half. Where surrounding the weather results in one large sector with usable airspace on all sides for flows and reroutes, splitting the weather provides two sectors with area to work with, which is a viable approach to take in distributing workload. The approaches to design with respect to weather were consistent for both the Manual BC and the Algorithm + Manual conditions. It was a necessary strategy to use in the Algorithm + Manual condition because the algorithms used to generate the designs used aircraft track data as their input and not weather location. Therefore, the final designs from the algorithms were only implicitly aware of the weather from the reroutes made during the scenario development process. Further action by the participants was required as a result.

Sector geometry was another consideration cited as a factor affecting the "goodness" or acceptability of a design. Some sector geometry characteristics that were considered in the designs and their assessments were those that are unconventional as well as those that negatively impact taskload. One participant provided concrete examples of this when they stated that, "I didn't like the sectors with jagged edges that produced small angular sections in the sector." Aspects of a sector's design such as jagged edges, panhandles, or "nooks and crannies" were some specific characteristics that were considered by the participants in selecting and designing airspace with an eye toward removing them from the design in order to reduce the potential numbers of point-outs and handoffs that would be required if not addressed. Geometries that resulted in narrow sectors are another example of an undesirable or unacceptable design. This is because narrow sectors limit the degrees of freedom or the usable airspace available to the sector controller for controlling the traffic. Additionally, for certain flows, a narrow sector reduces the transit time of aircraft, which also reduces the flexibility of the controller in being able to use those aircraft in developing a solution to a possible problem.

An interesting design consideration offered by some participants expanded the definition of an optimal design from one that balanced load and volume to one that could also give the designers and traffic managers an "out" in dealing with traffic. Since the problems always required the rerouting of traffic to further manage the peak volumes, some participants would design airspace configurations that might be considered less than optimal at first glance. Designing an "out," however, was part of a process in which the airspace's suboptimal design was part of an overall strategy that was optimal at a higher level.

A final consideration for the "goodness" and acceptability of designs was splitting the airspace vertically at a defined altitude stratum. Participants felt this approach was acceptable, particularly in the 4-sector problems where they consistently performed vertical splits in the Manual BC condition or selected designs in the Algorithm + Manual BC condition that contained a vertical split component. For the algorithm-generated designs, however, participants felt that the altitude selected by the algorithm for splitting the sectors was often not the most effective. This often resulted in the participants manually re-splitting the airspace at an altitude that was better suited to the given traffic situation.

IV. Discussion

This study explored the potential role that algorithm supported airspace design can play in the Flexible Airspace Management (FAM) concept. In this exploration, participants were presented with challenging 4- and 7-sector traffic scenarios that incorporated peak airspace capacity overloads in the presence of convective weather. Their task was to reduce the peaks through three different methods and conditions: rerouting aircraft only (No BC); manually designing airspace then rerouting aircraft (Manual BC); and selecting a pre-defined algorithm generated configuration, making further modifications, and rerouting aircraft (Algorithm + Manual BC). The objective of this design was to understand the potential benefits, if any, provided by algorithm support in the design of airspace and management of traffic, and what design aspects and mechanisms facilitated such benefits. A more general objective was also to confirm the benefits of reconfiguring airspace as part of the FAM concept.

A. Benefits of Algorithm Support in Traffic Management

While it is important to understand the benefits and impact of algorithm support in the design process, it is equally important to understand the potential system benefits that could be realized by the airspace users. The first approach to promoting this understanding was taken through the analysis of how well the designs produced manually and with algorithm support reduced the existing peak capacity overloads. In this regard, little difference was observed in the 4-sector problem, but algorithm support in the Algorithm + Manual BC condition resulted in better peak reduction in the 7-sector problem relative to the Manual BC condition. This begins to highlight the contexts in which algorithm support might provide real benefits in that the 7-sector problems were more difficult and complex than the 4-sector problems, which is a situation ideally suited to leveraging the mathematical approach and computational benefits provided by algorithms.

The reduction in peak sector count values resulting from the implementation of airspace designs had associated implications on the number of additional reroutes required following the boundary change. The number of reroutes performed to reduce the peak counts is a direct measure where system and airspace user benefits of both algorithm support and FAM overall can be assessed. In this case, the fewest number of reroutes can be interpreted as the greatest benefit since more aircraft are able to maintain their user-preferred trajectory, which results in less delay and cost to the user. Based on this approach, the results showed that the No BC condition required the greatest number of reroutes, followed by the Manual BC condition, and the Algorithm + Manual BC condition required the fewest number of reroutes. These results were consistent with the hypothesis that reconfiguring airspace as part of FAM produces user benefits as observed in the two BC conditions relative to the No BC condition. The hypothesis that algorithm support would also provide user benefits was supported through the reduced number of reroutes that resulted.

Related to the reduction in peaks and number of required reroutes, participants were asked to rate their level of acceptability for the overall approach and solution to the peak capacity problem in each of the BC conditions. Interestingly, participants rated the Manual BC condition as least acceptable in this regard, followed by the No BC condition, and the Algorithm + Manual BC condition was rated as the most acceptable in terms of the final solution. However, similar to the results observed for peak reduction, a difference was observed for the acceptability of final solutions and approaches between the 4- and 7-sector problems: the solutions to the 7-sector problems were rated as significantly less acceptable than those for the 4-sector problem. This again highlights the potential area that algorithm support could provide its greatest benefit through the application of its advantages in more complex environments that pose difficulties for individuals to process and address independently.

B. Benefits of Algorithm Support in the Airspace Design Process

It was hypothesized that having access to pre-defined airspace configurations that leveraged the computational power of algorithms would enable designers to develop more effective designs with greater ease than in situations without such access and support. One approach to testing this hypothesis was taken in the comparison of airspace volume change that resulted from designs in the Manual BC and Algorithm + Manual BC conditions. Through earlier research, it was found that large changes in airspace volume were associated with lower levels of acceptability and negative impacts on operations as a whole. Results from this comparison supported the hypothesis in that algorithm supported designs consistently resulted in reduced levels of airspace volume change relative to those in the Manual BC condition, particularly in the 7-sector environment. Consistent with earlier findings, participants rated the "goodness" of the final configurations more highly for designs in the Algorithm + Manual BC condition than for those developed manually.

However, when asked to rate the acceptability and ease of the airspace design process, participants were split on whether algorithm support provided benefit. For ratings of relative ease in the design process, half of the participants rated the Manual BC condition as being the "Easiest" and the other half rated the process in the Algorithm + Manual BC condition as the "Easiest." In terms of acceptability of the process, the Manual BC condition was rated as slightly more acceptable. When asked to explain their responses to these questions, an interesting picture emerged that highlighted a struggle between the pros and cons of having algorithm support. Some participants felt that being able to start with an intelligent design solution to the given problem facilitated the design process by accounting for more considerations than they were able to, resulting in designs that required minimal modifications and were rated as better than ones that they developed manually. This pre-defined approach and design was not welcomed by all, however. Some felt that by starting with a pre-existing configuration, their awareness of the "big picture" was degraded and that they felt "pigeon-holed" by the design, obligated to follow the path provided by the design. Others felt that having access to a set of options resulted in excessive time being spent in the decision-making process, particularly when none of the solutions were a "clear standout."

C. Aspects of Good Airspace Design

In the previous 2009 DAC simulation, aspects of good airspace design in the context of airspace reconfiguration began to emerge. Results and feedback from this study provided further support and greater detail on what makes particular designs good or bad, and what strategies in the design development are most effective. In terms of the design, participants favored configurations that resulted in the least amount of airspace volume change. Following this initial consideration, participants cited undesirability for narrow sectors and design aspects that would produce greater workload at the sector level such as jagged edges and panhandles. Participants also provided insight into some of the individual strategies taken in the design process. In terms of accounting for the convective weather in the test airspace, differences in strategy were observed that were equally viable. For example, some participants remarked that their strategy was to completely surround the weather with one sector, which would provide the controller with usable airspace on all sides of the weather for controlling the traffic. Others stated that it was better to split the weather between two sectors, ensuring that there was usable airspace on either side of the weather while better distributing the workload between the two. Another interesting and unexpected design strategy that was explained was in the use of the airspace design as a means of providing an "out" or additional degrees of freedom available for the management of traffic. It was earlier thought that the objective of designing of airspace would always be to produce the most optimal design that would best reduce the peak counts and evenly distribute it throughout the airspace. However, sub-optimal designs in that respect were sometimes enacted because they provided the designer with a more simplified problem and straight-forward approach to its solution.

V. Conclusion

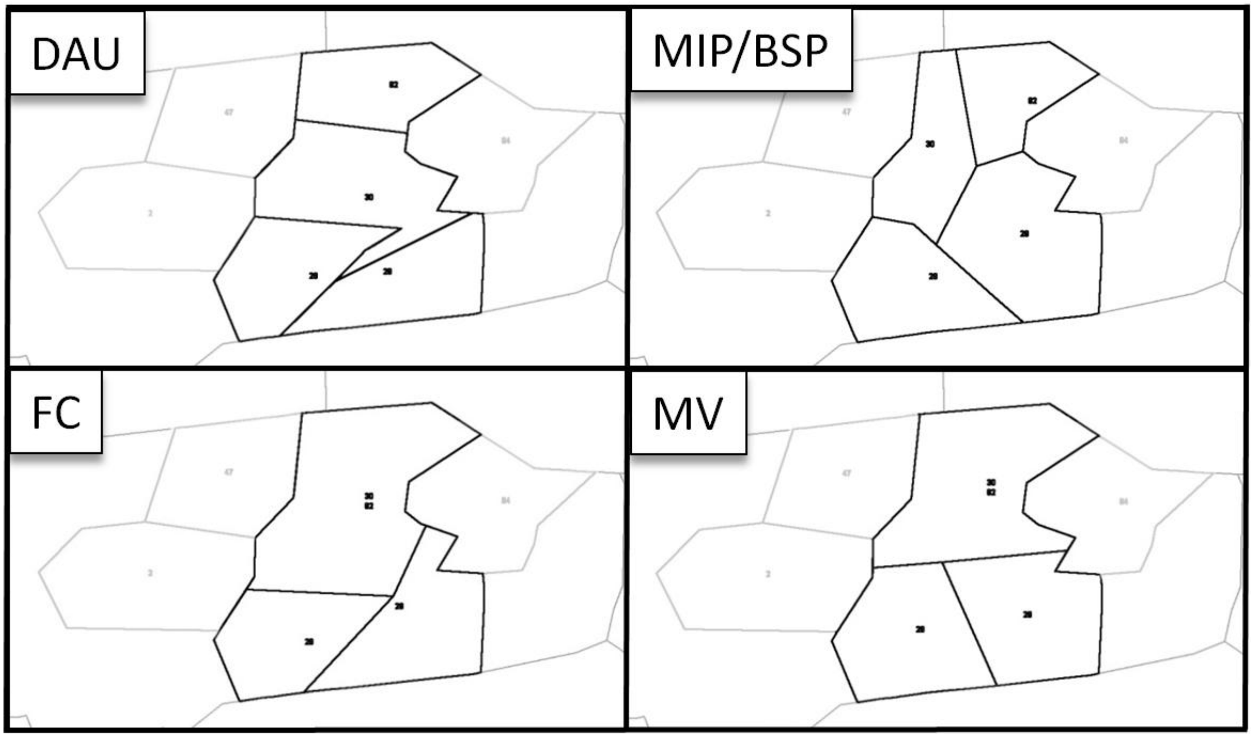
This study sought to explore the potential role that airspace optimization algorithms could play in the FAM concept as well as the benefits that it could provide. Results showed that although there were some issues, algorithm-generated designs produced consistent benefits in terms of peak management and fewer required reroutes. Additionally, algorithm support provided a means for the development of more acceptable airspace designs and overall solutions to the problems presented in this simulation.

In addition to the benefits of algorithm support, a consistent theme observed in the results was that complex environments, such as those presented in the 7-sector problems, posed the greatest difficulty for participants. Based on this observation, perhaps the most effective and useful application of the computational advantages provided by algorithm support is not through a blanket approach to all situations, but applied selectively to difficult and complex environments.

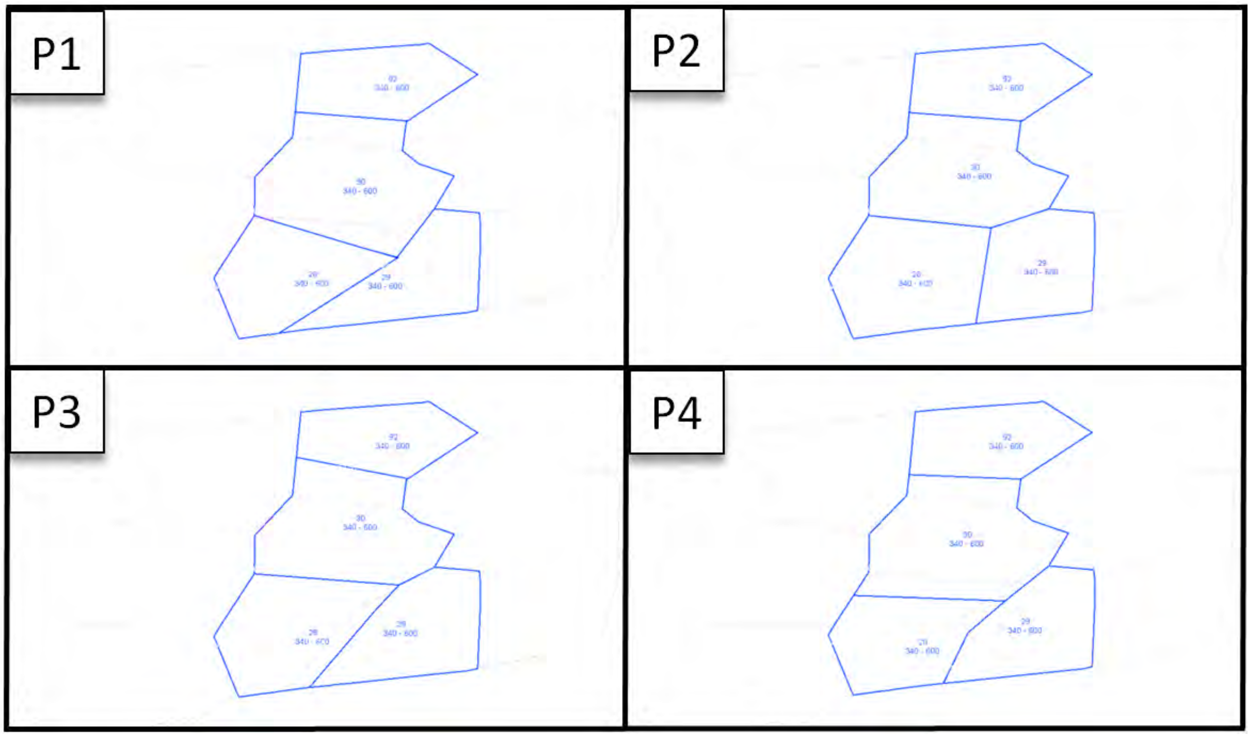
Appendix

A. 4-sector: Scenario 1

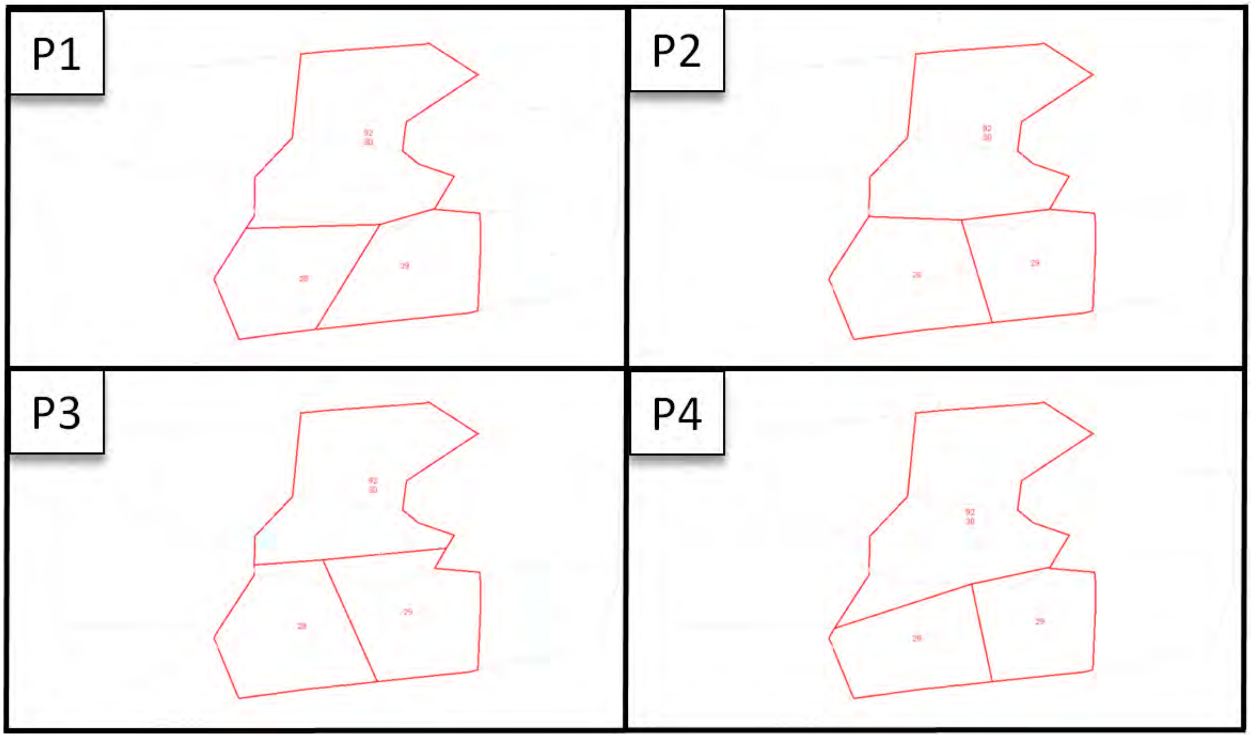
1. *Algorithm Solutions*



2. *Manual Solutions by Participants*

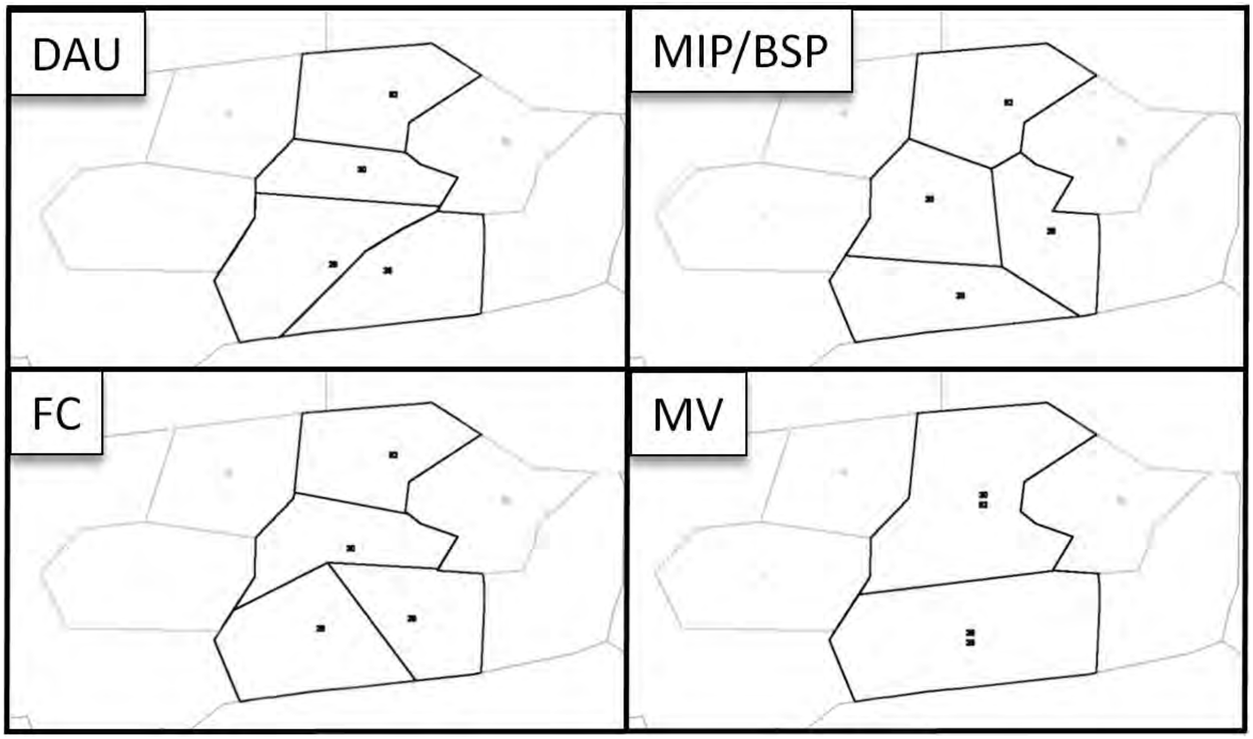


3. Algorithm+Manual Solutions by Participants

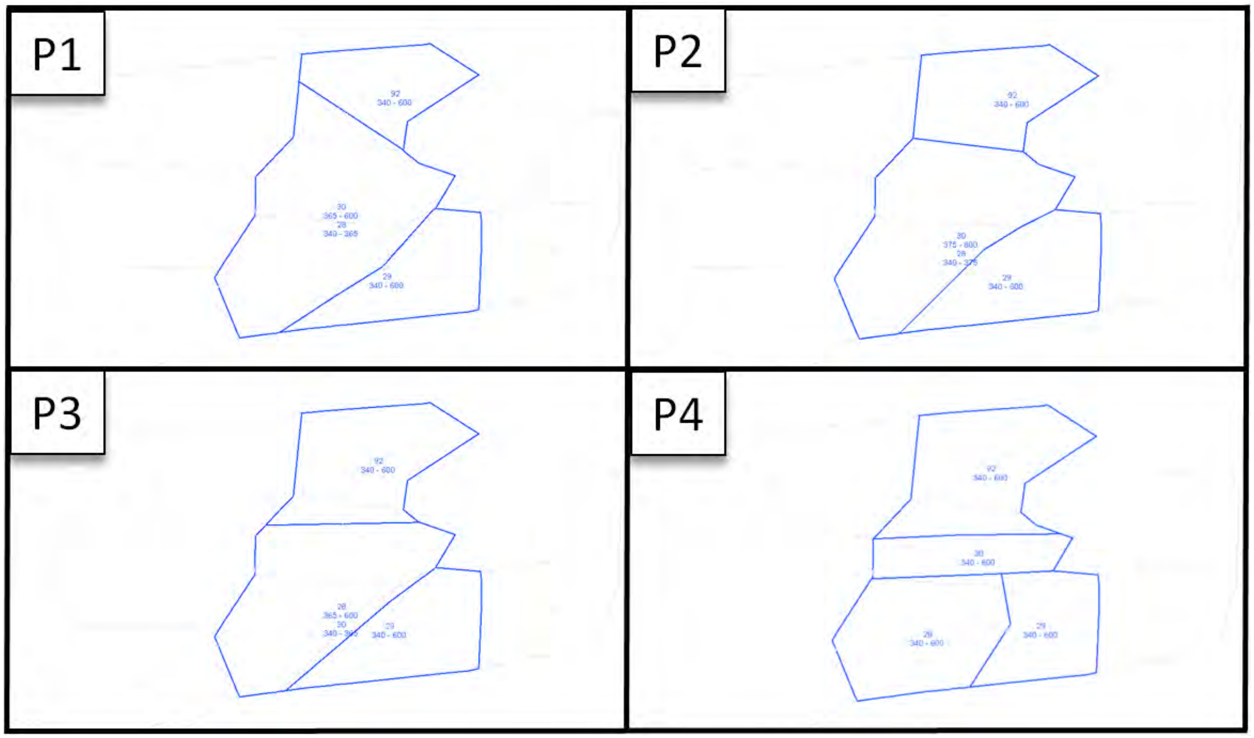


B. 4-sector: Scenario 2

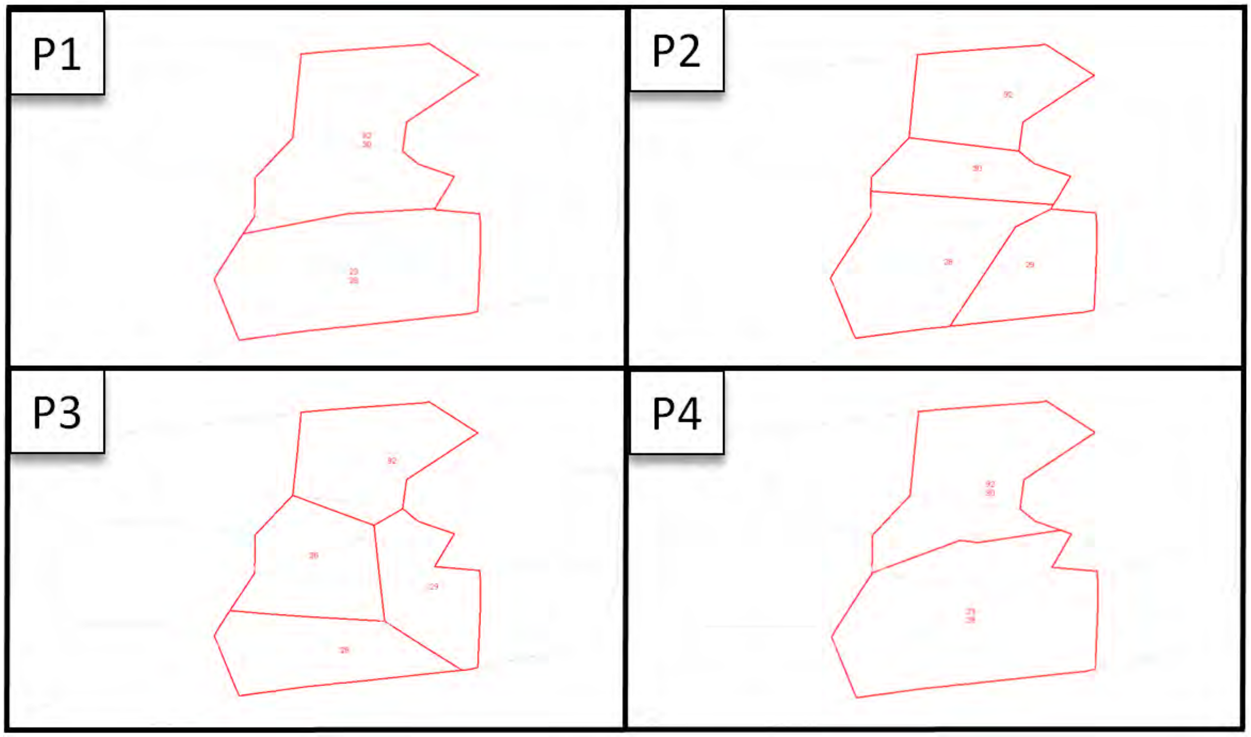
1. Algorithm Solutions



2. *Manual Solutions by Participants*

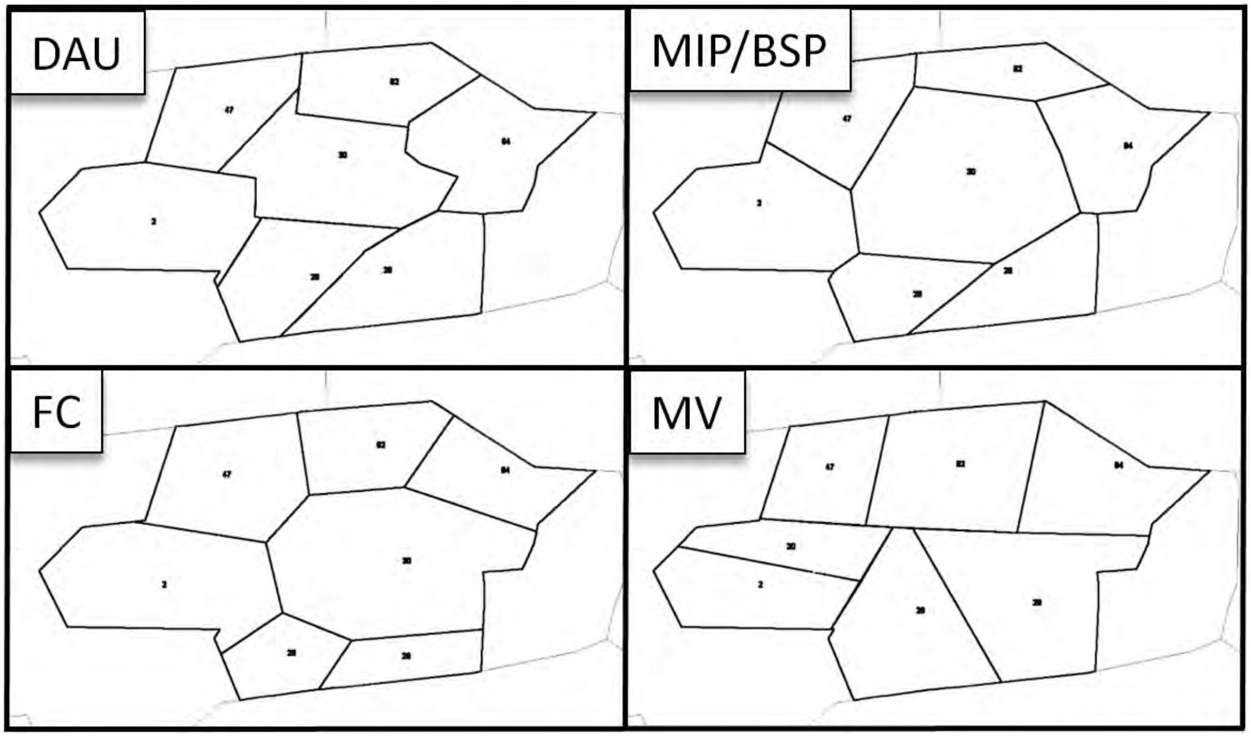


3. *Algorithm+Manual Solutions by Participants*

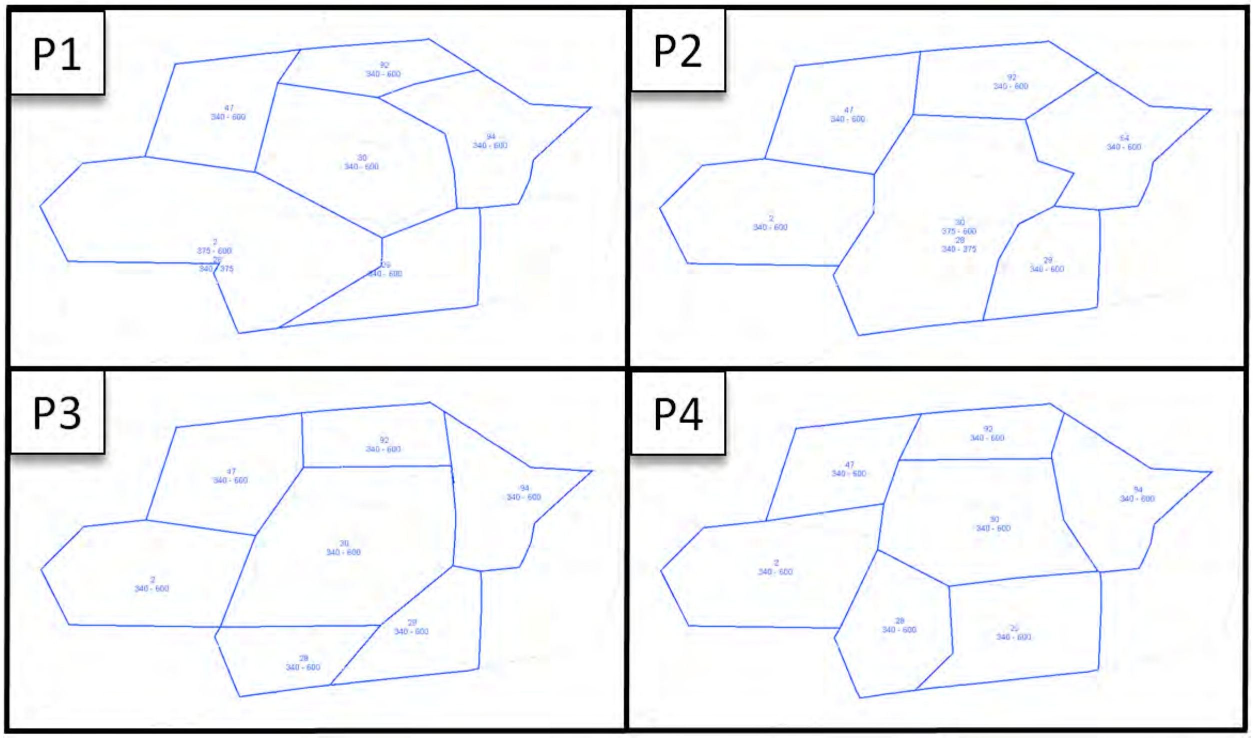


C. 7-sector: Scenario 1

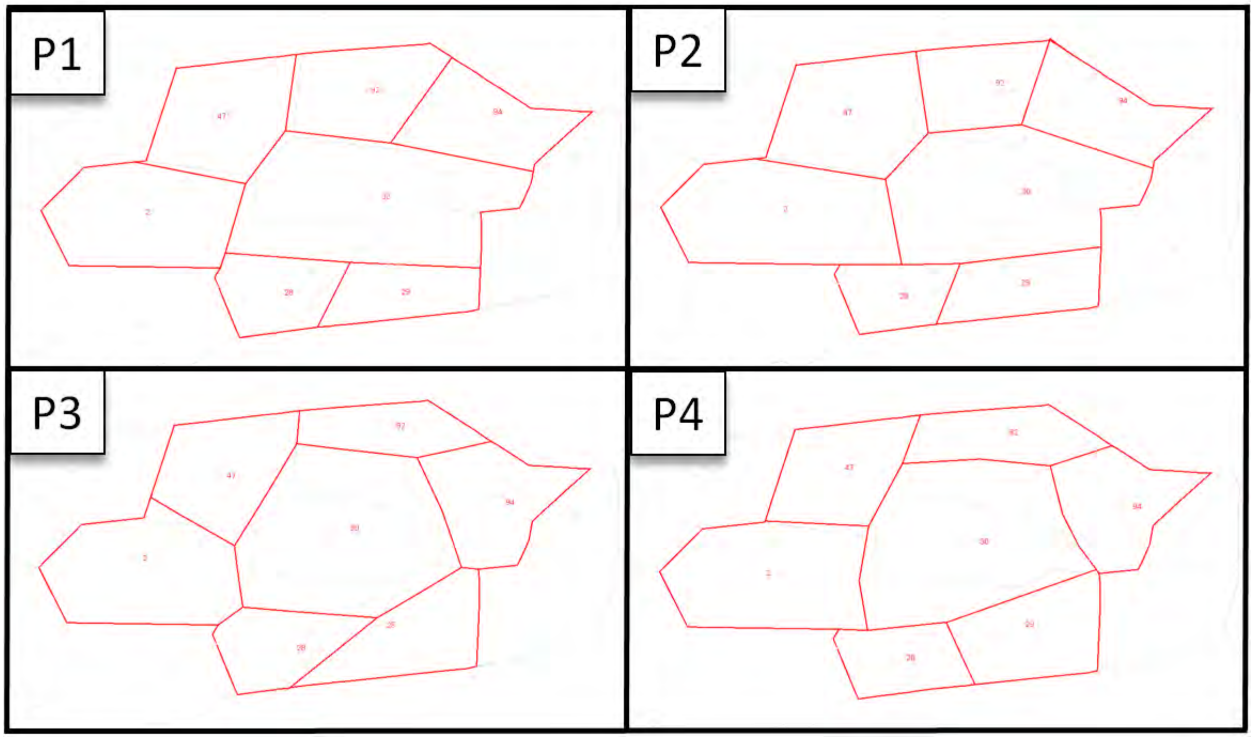
1. Algorithm solutions



2. Manual Solutions by Participants

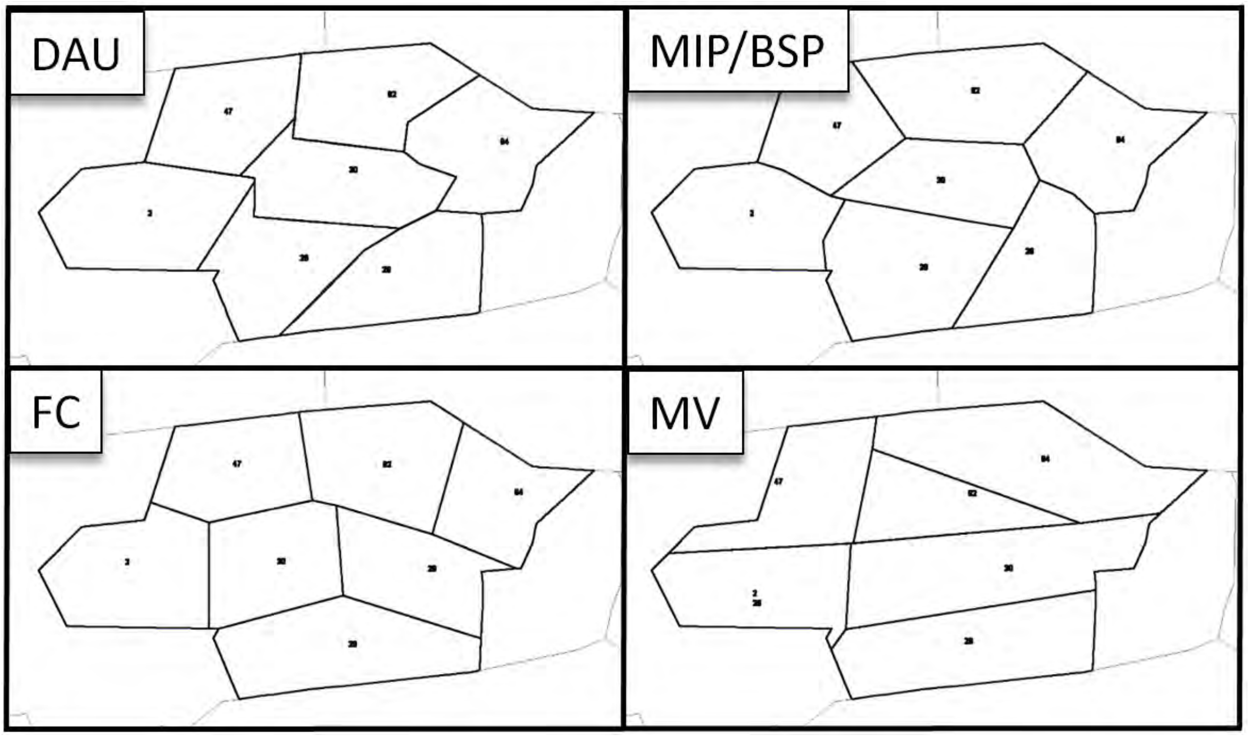


3. *Algorithm+Manual Solutions by Participants*

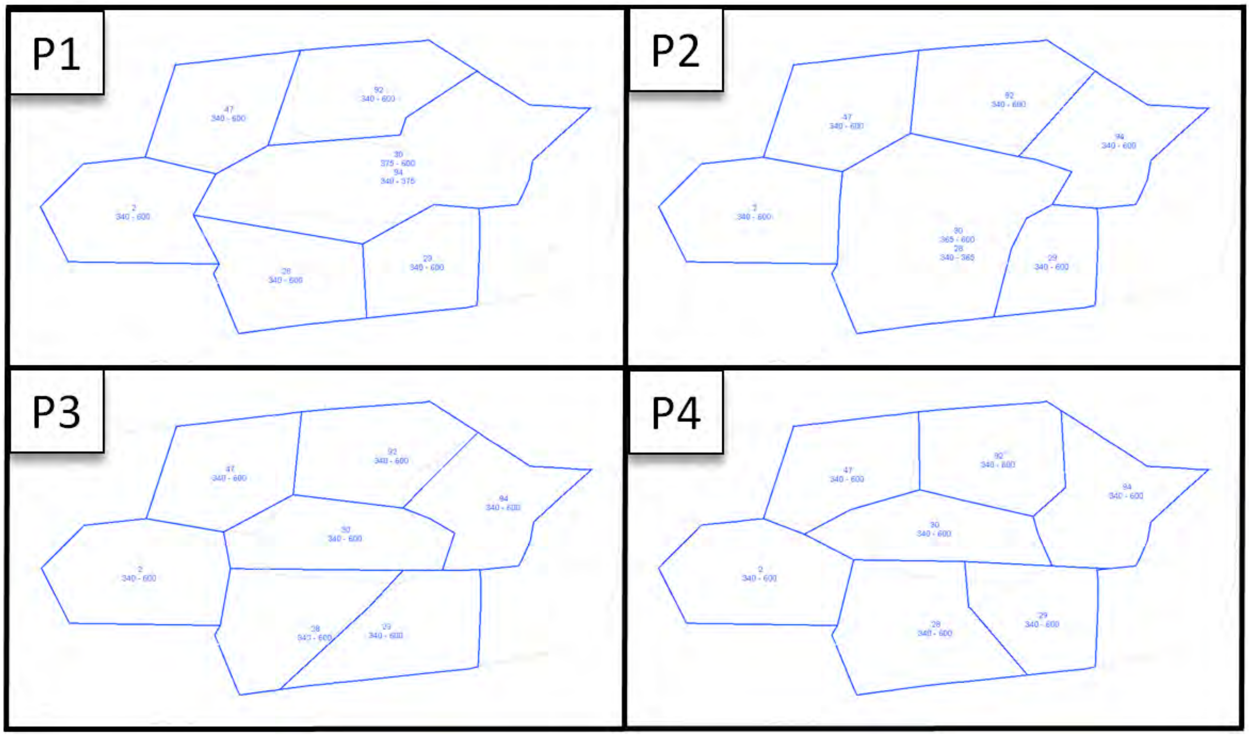


7-sector: Scenario 2

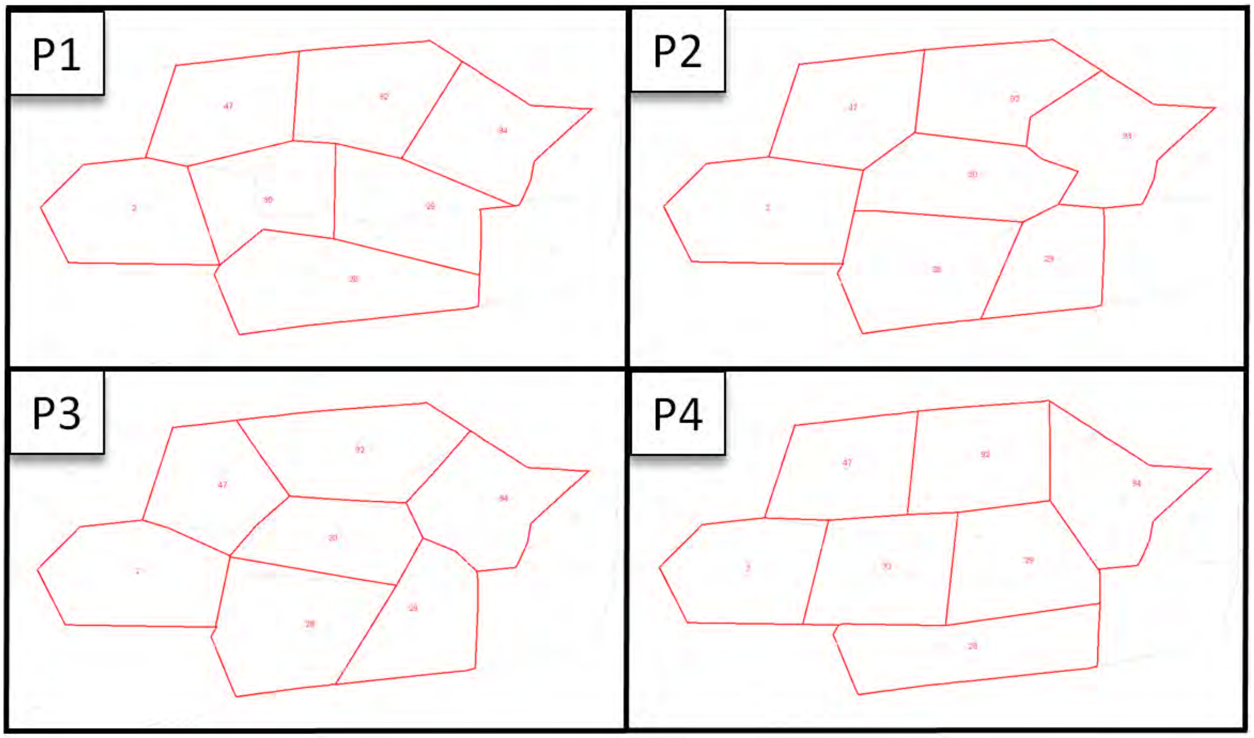
1. *Algorithm solutions*



2. Manual Solutions by Participants



3. Algorithm+Manual Solutions by Participants



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