

Advisory Algorithm for Scheduling Open Sectors, Operating Positions, and Workstations

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Air traffic controller supervisors configure available sector, operating position, and workstation resources to safely and efficiently control air traffic in a region of airspace. In this paper, an algorithm for assisting supervisors with this task is described and demonstrated on two example problem instances. The algorithm produces configuration schedule advisories that minimize a cost. The cost is a weighted sum of two competing costs: one penalizing mismatches between configurations and predicted air traffic and another penalizing the effort associated with changing configurations. The problem considered by the algorithm is a shortest path problem. The parameter determining the relative importance of the two competing costs is tuned by comparing historical configurations with corresponding algorithm advisories. Furthermore, some operationally-meaningful metrics are computed with the results of simulations of the algorithm for various values of this parameter. Two example problem instances for which

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appropriate configuration advisories are obvious were designed to illustrate characteristics of the algorithm. Results demonstrate how the algorithm suggests advisories that appropriately utilize changes in airspace configurations and changes in the number of operating positions allocated to each open sector. The results also demonstrate how the advisories suggest appropriate times for configuration changes.

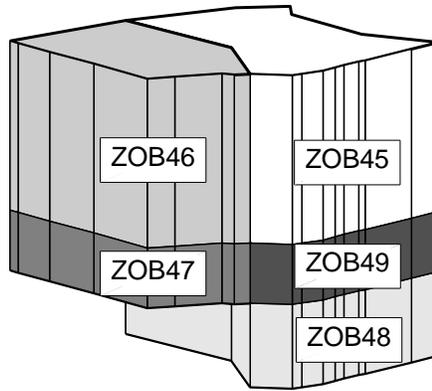
I. Introduction

IN current air traffic management operations, airspace is partitioned into predefined volumes called *sectors* to facilitate the division of responsibilities between air traffic controllers. An *airspace configuration* maps a set of sectors to a set of *open sectors* such that each sector is assigned to exactly one open sector. A team of air traffic controllers, staffing one to three *operating positions*, monitors each open sector. At least a radar (also known as R-side) operating position is allocated to each open sector. A radar associate or data (also known as D-side) operating position can also be allocated to an open sector. Although rare, a third operating position can be allocated to an open sector. When more operating positions are allocated to an open sector, the tasks associated with controlling traffic in the open sector are divided among more controllers. An *operating position configuration* specifies how many operating positions are allocated to each open sector in a corresponding airspace configuration. Furthermore, each open sector is monitored from a particular *workstation* consisting of seats for air traffic controllers, a radar scope, plugs for headsets, and other equipment used by controllers to monitor traffic. Which workstation is utilized to monitor an open sector can influence how much work is involved when the open sector is changed by adding or removing sectors from it. A *workstation configuration* specifies which workstation is utilized for monitoring each open sector in a corresponding airspace configuration. Together, corresponding airspace, operating position, and workstation configurations will be referred to simply as a *configuration*. An *Area of Specialization* (or just *area*) is a set of sectors that a group of controllers are certified to control and that are permitted to be combined into larger open sectors [1]. For example, the shapes of the five sectors in area 4 of Cleveland Air Route Traffic Control Center (ZOB) as of 20 October 2011 are shown

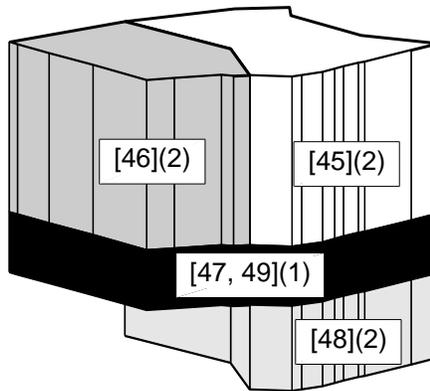
in Fig. 1 (a). The shapes of the open sectors in a sample airspace configuration are shown in Fig. 1 (b) and the floor layout of corresponding operating position and workstation configurations is shown in Fig. 1 (c). The airspace configuration contains four open sectors. Three of these open sectors each consist of airspace from only a single sector (ZOB45, ZOB46, and ZOB48). These three open sectors are each allocated two operating positions (indicated by the number in parentheses in Figs. 1 (b) and (c)). The fourth open sector consists of the combined airspace of sectors ZOB47 and ZOB49 and it is controlled by a single operating position. In Fig. 1 (c), the two workstations on the left side are used for the four operating positions corresponding to the open sectors consisting of ZOB45 and ZOB46. The workstation at the top of the right side is used by the R- and D-side operating positions controlling the open sector consisting of ZOB48. Finally, the single R-side operating position controlling the open sector consisting of ZOB47 and ZOB49 is using the bottom workstation on the right side.

Area supervisors select configurations of the available sector, controller personnel, and physical air traffic control equipment resources so that expected traffic demand is safely and efficiently managed. Allocating these area resources for safe and efficient operations involves both 1) selecting configurations that encourage engaged but not overworked controller personnel and 2) avoiding disruptive transitions between configurations [2]. In a typical area, a supervisor might change the airspace configuration one to three times in the early morning, once or twice during the day, and one to three more times in the late evening. Additionally, the supervisor might change the workstation or operating position configuration at several other times (while keeping the airspace configuration constant). For routine operations, the selection of area configurations may not be particularly challenging because traffic and operating position availability patterns do not change much from day to day. However, the selection of configurations may become more difficult in off-nominal conditions, such as when traffic flows change in response to weather, when some equipment fails, or when there is a shortage of available operating positions.

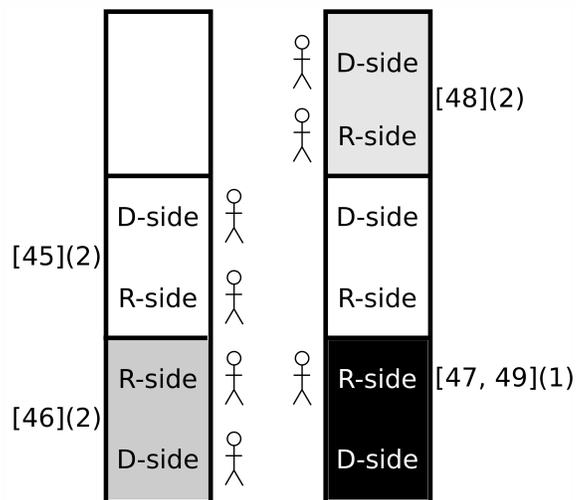
Several algorithms that suggest airspace configurations have been proposed [3–19]. Some of these algorithms support tactical decision-making [3–5, 16, 18, 19], but the rest focus on pre-tactical or strategic decisions concerned with staff planning. Fewer algorithms related to operating position or



(a) Sectors.



(b) Sample airspace configuration.



(c) Sample operating position and workstation configurations.

Fig. 1 Sectors and sample configuration of ZOB area 4.

workstation configurations have been proposed. A controller task load-based approach called "positions to traffic" for determining how many operating positions should be allocated to each open sector is analyzed by the Transportation Research Board in Ref. [20]. This approach was developed by MITRE for long-term staff planning, not tactical decision-support. Relationships between workload metrics, controller staff levels, and National Airspace System performance are investigated by Kamble in his PhD thesis, but he stops short of proposing an algorithm for determining the number of operating positions that should be allocated to each open sector [21]. Tien proposed a mixed-integer programming problem and solution method for suggesting airspace configurations that minimize the predicted or expected value of the number of operating positions [17, 18]. His approach utilizes a statistical model that estimates the probabilities that one or two operating positions will be allocated to each open sector, given the characteristics of the traffic in the open sector. An extension of this problem can also enforce requirements on the length of time between changes to open sectors. This work does not attempt to simultaneously optimize operating position or workstation assignments along with airspace configurations because it ignores workstations and treats operating position assignments as an exogenous random process outside of the control of the optimization. However, some related work by Tien does simultaneously propose both airspace configurations and corresponding operating position configurations when sector boundaries are permitted to be specified arbitrarily in an attempt to match predicted air traffic demand [22].

In this research, an algorithm that computes a configuration schedule advisory is developed and some example results are presented. For each time step in a planning time horizon of around two hours, a configuration schedule advisory specifies a configuration consisting of a set of open sectors, the number of operating positions allocated to each open sector, and a workstation to be used for managing each open sector. The algorithm is an extension of the algorithm for suggesting airspace configuration schedules proposed in Ref. [19]. While Tien's approach in Refs. [17] and [18] suggests airspace configuration schedules that consider likely corresponding operating position schedules, the algorithm proposed here simultaneously suggests airspace, operating position, and workstation configurations. The algorithm proposed here is not designed to suggest appropriate or minimal safe levels of staffing, as is done in MITRE's positions to traffic work [20] and in some previous work by

the authors of this paper, Tien, and others [3–5, 17, 18]. The algorithm does not enforce restrictions on the time period between changes to open sectors, as Tien proposes in Ref. [17], but rather imposes a traffic-dependent cost on configuration changes. This cost on configuration changes ensures that configuration changes are only proposed when they generate sufficiently safer and more efficient operations by producing open sectors with traffic levels that keep controller personnel engaged but not overworked.

The remainder of this paper is structured as follows. In Section II, the inputs and outputs of the algorithm are specified. Section III describes how the algorithm poses determining a configuration schedule as a shortest-path problem. Then, the dynamic programming solution method used by the algorithm to solve this shortest-path problem is briefly described in Section IV, and some alternative solution methods are mentioned. Default cost function parameters selected based on descriptions of operational procedures, subject-matter expert feedback, and historical data are documented in Section V. Section VI presents the impact of variations in an important parameter on some operationally-meaningful metrics and compares the metrics for algorithm-generated and corresponding historical configurations. Specifications of and results for two example problem instances are in Section VII. Finally, Section VIII contains conclusions.

II. Algorithm Inputs and Outputs

The inputs and outputs of the proposed algorithm are specified in Fig. 2. One input is traffic predictions. The traffic predictions must be specified at a level of detail sufficient for the calculation of the cost, which is discussed in sub-section III.D. As defined in this paper, this cost function requires a prediction of which flights will be in each sector at each traffic time step.

Another input is a schedule of the valid configurations that the algorithm can advise at each time. Some configurations are never valid and so will never be part of the valid configuration set. For example, an open sector that is a complicated shape involving a variety of altitude levels might be confusing because it can be difficult to keep track of which altitude levels are part of such an open sector in various lateral regions. Any configuration including such an open sector could be specified as permanently invalid. Alternatively, some configurations might only be temporarily valid

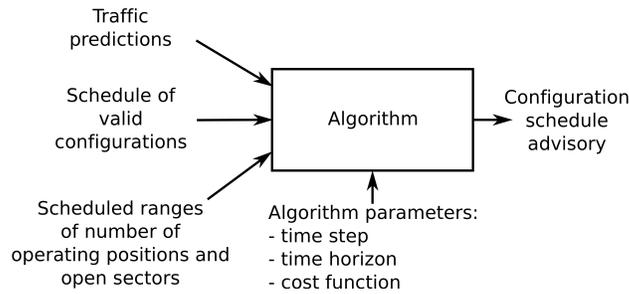


Fig. 2 Algorithm inputs and outputs.

or invalid. For example, a supervisor may know that a controller will be trained on a particular open sector for a period of time. Changes to that open sector in this period would interrupt the training, so only configurations including that open sector would be valid during this period of time. A baseline valid set of configurations could be pre-specified and then modified as needed by the supervisor.

A third input is scheduled ranges of the number of operating positions and the number of open sectors. The scheduled range of the number of operating positions specifies the total number of operating positions that can be allocated to open sectors at each time in the airspace under consideration. This range should be driven by the number of available controllers. Default values for these constraints could be derived from a staff management system such as the Cru-ART system currently used by the Federal Aviation Administration, but such a default schedule could be adjusted by the supervisor. The scheduled range of the number of open sectors could be used, for example, to specify that only a certain number of open sectors are possible when there is an equipment outage. Neither of these scheduled ranges are required inputs; the algorithm can be run such that any number of operating positions or open sectors are allowed.

The final input is a set of algorithm parameters. One parameter specifies the length of the time step used to discretize time. The algorithm can specify a different configuration at each configuration time step, but it usually does not due to a cost that penalizes changes in configurations, also known as *reconfigurations* (see sub-section III.D.2). Another parameter specifies the time horizon of the configuration schedule advisory. Due to uncertainties in traffic predictions, it is unlikely that this time horizon would exceed three hours. Other parameters that impact the algorithm cost function

also must be specified; these will be discussed in more detail in sub-section III.D and Section V.

Finally, the algorithm outputs a configuration schedule advisory. At each configuration time step in the time horizon, this schedule assigns each sector to exactly one open sector and allocates one (R-side) or two (an R-side and a D-side) operating positions to each open sector. Each open sector is also assigned to a workstation.

The algorithm consists of (i) a problem statement that represents the problem faced by the supervisor as quantified by the input data, and (ii) a solution method that then solves the problem to produce an appropriate configuration schedule advisory. These two components are discussed in the next two Sections.

III. Problem Statement

The problem stated here attempts to capture the relevant issues involved in determining a configuration schedule that will facilitate safe and efficient operations for predicted air traffic. The problem statement consists of decision variables, data, constraints, and an objective. The problem is first described informally and then it will be stated in detail in sub-sections III.A–III.D.

For each time period during a time horizon of interest, a configuration advisory suggests a configuration that describes how to allocate the available resources in an area. The configurations must respect problem constraints, such as constraints on the number of operating positions available at each time. The problem statement encourages the selection of an advisory that facilitates safe and efficient operations by specifying a cost function to be minimized. The problem cost function attempts to quantify and penalize any way that a configuration might not facilitate safe and efficient operations for the predicted traffic as well as any way that changes in configurations require effort that may inhibit safe and efficient operations. The cost function used in this paper is a relatively complicated function involving 25 parameters. The function complexity was increased as subject-matter experts identified deficiencies in previous, simpler cost functions that prevented those functions from leading to useful configuration advisories.

One dimension of the resource allocation described by a configuration is the airspace configuration: the way in which sectors are grouped into open sectors. For example, a configuration advisory

might suggest a configuration with two sectors combined for the first hour and then suggest a configuration in which this open sector is split into two smaller open sectors for the second hour. Splitting an open sector can be disruptive and may not facilitate safe and efficient operations for a period of time near the split. However, this open sector split might be worthwhile if the larger open sector contains too much traffic for safe and efficient operations while the two new open sectors are predicted to experience traffic levels that are neither too low nor too high. A second dimension of the resource allocation is the operating position configuration: the number of operating positions allocated to each open sector. For example, rather than splitting a busy open sector, a configuration advisory might suggest a configuration in which a second (D-side) operating position is added to the open sector. This usually involves less effort than splitting a sector, and certain levels of traffic in an open sector might be too high for a single operating position but just right for two operating positions. A third dimension of the resource allocation is the workstation configuration: which workstation is utilized for monitoring each open sector. The effort and disruption caused by a change in configurations depends in part upon which workstation is used for each open sector. For example, when an open sector is split into two smaller open sectors, the amount of effort and disruption involved depends largely on the number of flights that must be transferred from the control of one operating position to another. When an open sector is split, this number of transferred flights will depend on which workstation is used to control each of the two new open sectors. If one new open sector is busier than the other, the configuration change will probably be easier if that new open sector utilizes the same workstation as was used for the previous, larger open sector.

Which individual controllers will work at each operating position is another dimension of configurations. This dimension is excluded from the problem statement because factors that influence this dimension, such as controller skill and personality, may be difficult to quantify. This dimension of the configuration schedule is left for the supervisor to determine without the assistance of an advisory.

The decision variables, data, constraints, and cost function that make up the problem statement will now be described in detail. The problem statement attempts to model the resource allocation problem faced by area supervisors such that problem solutions will help supervisors make

configuration decisions that facilitate safe and efficient operations.

A. Decision Variables

To facilitate the search for a configuration schedule, the time horizon of the schedule is broken into K discrete configuration time steps $k = 1, 2, \dots, K$ of length Δ minutes.

The decision variables C that make up a configuration schedule advisory are C_k for $k \in \{1, 2, \dots, K\}$, where C_k is the advised configuration at configuration time step k . More concretely, a configuration advisory for configuration time step k is $C_k = \{C_k^A, C_k^{\text{OP}}, C_k^{\text{W}}\}$ and it consists of an airspace configuration C_k^A , a corresponding operating position configuration C_k^{OP} , and a corresponding workstation configuration C_k^{W} . For a given set of sectors $S = \{s_1, s_2, \dots, s_{|S|}\}$ under consideration, an airspace configuration consists of a set of open sectors $C_k^A = \{\sigma_1, \sigma_2, \dots, \sigma_{|C_k^A|}\}$. Each open sector $\sigma \in C_k^A$ is itself a set consisting of at least one sector from S . An operating position configuration C_k^{OP} is a function that specifies whether one or two operating positions are allocated to each open sector in the corresponding airspace configuration. Finally, a workstation configuration C_k^{W} is a mapping from open sectors in C_k^A to the set of available workstations W . Constraints on configurations will be discussed in sub-section III.C. The problem involves simultaneously searching over these three dimensions of configurations (airspace, operating position, and workstation).

B. Data

The traffic situation data T is a set consisting of a configuration time step traffic situation data element T_k for each configuration time step. Generally, this traffic situation data must contain any predicted air traffic data required to compute the problem cost function. Although many other cost function formulations are possible, the function specified in sub-section III.D for use in this paper requires that T_k contain a unique identifier for each flight in each sector at each *traffic time step* during configuration time step k . Since air traffic characteristics and their impact on controller workload often change faster than airspace configurations, time is discretized into finer traffic time steps of length δ minutes. Let $\tau(k)$ be the set of D traffic time steps in configuration time step k . Then T_k contains the traffic situation data for each sector during configuration time step k : $T_k = \{T_k^{s_1}, T_k^{s_2}, \dots, T_k^{s_{|S|}}\}$. Here each T_k^s is itself a set containing the traffic situation data in sector

s at each $t \in \tau(k)$: $T_k^s = \{T_t^s\}_{t \in \tau(k)}$. Finally, each T_t^s contains a unique identifier for each aircraft located within s during traffic time step t . Then $|T_t^s|$ is the *sector count* for s at t : the number of aircraft located within sector s at traffic time step t .

Another piece of data required for the problem objective used in this paper is open sector capacities, expressed in terms of a maximum number of aircraft that can safely simultaneously be within each open sector when the open sector is allocated two operating positions. An open sector *Monitor Alert Parameter (MAP)* is used as a capacity bound in current air traffic operations and MAP values for each open sector are the required sector capacity data.

Finally, the initial configuration C_0 and traffic situation T_0 are also required for the problem. These specify the configuration and traffic situation during the configuration time step just before the configuration schedule advisory begins.

C. Constraints

1. Valid Configurations

The configuration schedule C must be in the set \mathcal{C} of all valid configuration schedules. Although \mathcal{C} could be defined more generally, for this paper it is specified as a set of valid configurations at each configuration time step: $\mathcal{C} = \{\mathcal{C}_k\}_{k=1}^K$.

Valid configurations in \mathcal{C}_k must fulfill several fundamental requirements that apply to any problem instance and any configuration time step. Open sectors must be spatially contiguous, for example. Airspace configurations at each configuration time step must assign each sector to an open sector. A sector can be assigned to only one open sector. Only one or two operating positions can be allocated to any open sector. Each open sector must be assigned to a single workstation. A workstation cannot be assigned to multiple open sectors.

Valid configurations can also be specific to certain problem instances and may apply for all or only a subset of configuration time steps. Configurations containing certain open sectors might be denoted as invalid because they are geographically too large to be displayed clearly on a scope. Other configurations might be invalid for some period of time due to temporary workstation equipment outages. More permanent technological limitations, such as radio frequency coverage issues, may

also limit the set of valid configurations. Training sessions may require that certain open sectors be a part of any configuration utilized for certain configuration time steps. This list is not exhaustive; any configuration can be removed from consideration during any configuration time step and for any reason.

Configuration constraints on the number of open sectors and operating positions described in the next sub-section are just a particular type of constraint on valid configurations. They are given special consideration to emphasize that this algorithm does not seek to minimize the number of open sectors or operating positions.

2. Number of Open Sectors and Operating Positions

It may be possible or desired to utilize only certain numbers of operating positions or open sectors at each configuration time step. This type of constraint might result from the number of controllers that are available to be assigned to operating positions during a particular shift. Let $\underline{\lambda}_k$ be a lower bound on the number of open sectors at configuration time step k and let $\bar{\lambda}_k$ be an upper bound on the number of open sectors at configuration time step k . Then the constraint on the number of open sectors can be expressed as

$$\underline{\lambda}_k \leq |C_k^A| \leq \bar{\lambda}_k \quad \forall k \in \{1, 2, \dots, K\}. \quad (1)$$

Similarly, let $\underline{\mu}_k$ be a lower bound on the number of operating positions at configuration time step k and let $\bar{\mu}_k$ be an upper bound on the number of operating positions at configuration time step k . Then the constraint on the number of operating positions can be expressed as

$$\underline{\mu}_k \leq \sum_{\sigma \in C_k^A} C_k^{\text{OP}}(\sigma) \leq \bar{\mu}_k \quad \forall k \in \{1, 2, \dots, K\}. \quad (2)$$

D. Objective: Minimize Cost

The problem objective is to minimize a cost $g(C, T)$ penalizing situations that do not facilitate the safe and efficient control of air traffic in the area. Unlike some previous work, the objective does *not* involve finding appropriate or minimal safe levels of staffing [3–5, 17, 18].

The cost for a schedule is a sum of the costs incurred by the scheduled configuration at each

configuration time step in the time horizon:

$$g(C, T) = \sum_{k=1}^K g_k(C_{k-1}, T_{k-1}, C_k, T_k). \quad (3)$$

For a single configuration time step, the cost is a weighted sum of a single configuration time step *static cost* and a single configuration time step *reconfiguration cost*:

$$g_k(C_{k-1}, T_{k-1}, C_k, T_k) = g_k^S(C_k, T_k) + \beta^R g_k^R(C_{k-1}, T_{k-1}, C_k, T_k), \quad (4)$$

where β^R is the *reconfiguration weight*.

More detailed descriptions of the static and reconfiguration costs are provided next. These cost functions are complex and involve many parameters; a detailed specification of these costs can be found in Ref. [23]. Complexity and parameters were only added to the cost functions when subject-matter expert feedback indicated that simpler versions of the cost function were not sufficient for producing useful configuration advisories. The initial, simpler cost function used for this work is described in Ref. [19].

1. Static Cost

The static cost penalizes configurations with too much or too little traffic in open sectors. Too much traffic can lead to controllers that are too busy to provide safe and efficient control, and too little traffic can lead to controllers that are not sufficiently engaged to provide safe and efficient control. The term "static" is used because this cost is associated with periods when the configuration is static, although of course the traffic changes during these periods. It is the sum over all the open sectors of a static cost computed for each open sector:

$$g_k^S(C_k, T_k) = \sum_{\sigma \in C_k^A} g_k^{S,OS}(\sigma, C_k^{OP}(\sigma), T_k), \quad (5)$$

where $g_k^{S,OS}(\sigma, C_k^{OP}(\sigma), T_k)$ is the static cost for a single open sector σ allocated $C_k^{OP}(\sigma)$ operating positions at configuration time step k while experiencing traffic situation T_k .

Furthermore, the static cost for a single open sector at a configuration time step is itself a sum of a single traffic time step cost $g_t^{S,OS}$ over all the traffic time steps in the configuration time step.

The static cost for a single open sector during a single traffic time step takes on different forms depending on the number of operating positions allocated to the open sector. The function

$g_t^{\text{S,OS,1OP}}(\sigma, T_t)$ is the static cost for open sector σ allocated one operating position at traffic time step t with traffic situation T_t . The corresponding function $g_t^{\text{S,OS,2OP}}(\sigma, T_t)$ is the static cost for open sector σ allocated two operating positions at traffic time step t with traffic situation T_t . These one- and two-operating position static cost functions have identical forms but different parameter values. The functions depend entirely on the *open sector load* $\ell(\sigma, T_t)$, which is computed as the number of aircraft in the open sector divided by the MAP value of the open sector. Each function penalizes open sector loads that are too high or too low to facilitate safe and efficient operations in an open sector. The one-operating position function is

$$g_t^{\text{S,OS,1OP}}(\sigma, T_t) = \left(\underline{\alpha}^{\text{1OP}} \left[\underline{\theta}^{\text{1OP}} - \ell(\sigma, T_t) \right]_+ \right)^{\underline{\gamma}^{\text{1OP}}} + \left(\bar{\alpha}^{\text{1OP}} \left[\ell(\sigma, T_t) - \bar{\theta}^{\text{1OP}} \right]_+ \right)^{\bar{\gamma}^{\text{1OP}}} \quad (6)$$

and the two-operating position function is identical except that it uses different parameters. Here $[a]_+$ evaluates to a if $a \geq 0$ and to 0 if $a < 0$. The twelve parameters in these two cost functions are

- $\underline{\alpha}^{\text{1OP}}$ and $\underline{\alpha}^{\text{2OP}}$: one- and two-operating position *low load weights*,
- $\underline{\theta}^{\text{1OP}}$ and $\underline{\theta}^{\text{2OP}}$: one- and two-operating position *low load thresholds*,
- $\underline{\gamma}^{\text{1OP}}$ and $\underline{\gamma}^{\text{2OP}}$: one- and two-operating position *low load exponents*,
- $\bar{\alpha}^{\text{1OP}}$ and $\bar{\alpha}^{\text{2OP}}$: one- and two-operating position *high load weights*,
- $\bar{\theta}^{\text{1OP}}$ and $\bar{\theta}^{\text{2OP}}$: one- and two-operating position *high load thresholds*, and
- $\bar{\gamma}^{\text{1OP}}$ and $\bar{\gamma}^{\text{2OP}}$: one- and two-operating position *high load exponents*.

Fig. 3 contains plots of the static cost for a single open sector during a single traffic time step when allocated one and two operating positions.

2. Reconfiguration Cost

The reconfiguration cost penalizes reconfigurations, especially reconfigurations that are likely to induce a significant amount of effort for the controllers involved. The reconfiguration cost is the sum of two different reconfiguration costs:

$$g_k^{\text{R}}(C_{k-1}, T_{k-1}, C_k, T_k) = g_k^{\text{R,OP}}(C_{k-1}, T_{k-1}, C_k, T_k) + g_k^{\text{R,W}}(C_{k-1}, T_{k-1}, C_k, T_k). \quad (7)$$

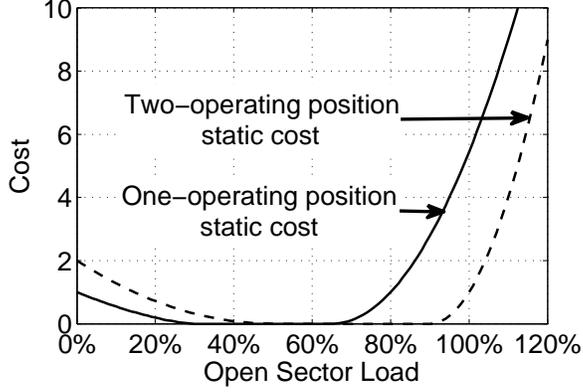


Fig. 3 Static cost for an open sector.

These types of reconfiguration costs are the *reconfiguration operating position cost* ($g_k^{\text{R,OP}}$) and the *reconfiguration workstation cost* ($g_k^{\text{R,W}}$).

The reconfiguration operating position cost $g_k^{\text{R,OP}}$ penalizes changes in the number of operating positions allocated to an open sector when the sectors assigned to the open sector do not change. When a D-side operating position is added to an open sector, certain responsibilities associated with the aircraft in the open sector must be transferred from the R-side operating position to the incoming D-side operating position. Conversely, when a D-side operating position is removed from an open sector, these responsibilities must be transferred from the D-side operating position back to the R-side operating position. The reconfiguration operating position cost attempts to quantify and penalize these efforts, which may distract controllers from safely and efficiently managing aircraft. It is a sum over costs for all open sectors experiencing changes in the number of operating positions but no changes in airspace, and it differentiates between open sectors gaining and losing operating positions. The *reconfiguration operating position gain cost* $g_k^{\text{R,OP+}}$ penalizes effort associated with the addition of a second (D-side) operating position and the *reconfiguration operating position loss cost* $g_k^{\text{R,OP-}}$ penalizes effort associated with the removal of a second (D-side) operating position. The form of these two types of reconfiguration costs are nearly identical. They form of $g_k^{\text{R,OP+}}$ is

$$g_k^{\text{R,OP+}}(\sigma, T_{k-1}, T_k) = \beta^{\text{R,OP+,O}} + \beta^{\text{R,OP+,T}} \left| \bigcup_{\substack{s \in \sigma, \\ t \in \psi_{\pm}^{\text{R,OP}}}} T_t^s \right| \quad (8)$$

and the form of $g_k^{\text{R,OP-}}$ is identical but with different parameters. The *reconfiguration operating*

position gain overhead and *loss overhead weights* $\beta^{\text{R,OP}^+, \text{O}}$ and $\beta^{\text{R,OP}^-, \text{O}}$ penalize the overhead work associated with adding or removing a D-side operating position from an open sector, respectively. Overhead work refers to work that is independent of the number of aircraft in the open sector, such as describing active special-use airspace. Finally, the *reconfiguration operating position gain transfer* and *loss transfer weights* $\beta^{\text{R,OP}^+, \text{T}}$ and $\beta^{\text{R,OP}^-, \text{T}}$ are multiplied by aircraft counts to penalize the aircraft transfer work associated with adding or removing a D-side operating position from an open sector, respectively. Transfer work refers to work that results from transferring responsibilities associated with monitoring an aircraft from one operating position to another, such as indicating that an aircraft has been cleared to climb to a particular altitude. The set $\psi_{\pm}^{\text{R,OP}}$ is a set of traffic time steps surrounding the reconfiguration happening between configuration time steps $k - 1$ and k . It is expressed as $\psi_{\pm}^{\text{R,OP}} = \{(k - 1)D + 1 - \epsilon_{-}^{\text{R,OP}}, \dots, (k - 1)D + \epsilon_{+}^{\text{R,OP}}\}$, where $\epsilon_{-}^{\text{R,OP}} \geq 0$ and $\epsilon_{+}^{\text{R,OP}} \geq 1$ are parameters that determine the number of traffic time steps used to count the number of unique aircraft involved in the reconfiguration.

The other type of reconfiguration cost is the *reconfiguration workstation cost* $g_k^{\text{R,W}}$. When the sectors that make up an open sector change, control of sector airspace and any aircraft within it must move from operating position(s) at one workstation to operating position(s) at another workstation. There is overhead and transfer work associated with this type of reconfiguration. Furthermore, this transfer can be even more difficult when the operating positions giving and receiving responsibility for airspace and aircraft are already busy monitoring other "background" aircraft that are not being transferred. Finally, there is work associated with moving the operating positions associated with an open sector from one workstation to another, even when the open sector airspace and number of allocated operating positions do not change. The reconfiguration cost attempts to quantify and penalize these types of work, and it is the sum of four terms:

$$g_k^{\text{R,W}}(C_{k-1}, T_{k-1}, C_k, T_k) = g_k^{\text{R,W,O}}(C_{k-1}, T_{k-1}, C_k, T_k) + g_k^{\text{R,W,T}}(C_{k-1}, T_{k-1}, C_k, T_k) \quad (9)$$

$$+ g_k^{\text{R,W,B}}(C_{k-1}, T_{k-1}, C_k, T_k) + g_k^{\text{R,W,M}}(C_{k-1}, T_{k-1}, C_k, T_k).$$

The first term is the *reconfiguration workstation overhead cost* $g_k^{\text{R,W,O}}$. It penalizes the overhead work associated with setting up and deploying *new open sectors*: open sectors that were not used in the configuration in the previous configuration time step. The form of this cost is simply a

reconfiguration workstation overhead weight $\beta^{\text{R,W,O}}$ multiplied by the number of new open sectors in the configuration. Therefore, the reconfiguration workstation overhead weight is a cost per new open sector.

The second type of work that makes up the reconfiguration workstation cost is the *reconfiguration workstation transfer cost* $g_k^{\text{R,W,T}}$. It penalizes work associated with transferring aircraft from operating position(s) at one workstation to operating position(s) at another workstation, as quantified by a per-aircraft *reconfiguration workstation transfer weight* $\beta^{\text{R,W,T}}$ multiplied by the number of aircraft transferred. The set of traffic time steps $\psi_{\pm}^{\text{R,W}}$ surrounding the reconfiguration at the start of configuration time step k is expressed as $\psi_{\pm}^{\text{R,W}} = \{(k-1)D + 1 - \epsilon_{-}^{\text{R,W}}, \dots, (k-1)D + \epsilon_{+}^{\text{R,W}}\}$, where $\epsilon_{-}^{\text{R,W}} \geq 0$ and $\epsilon_{+}^{\text{R,W}} \geq 1$ are parameters that determine the number of traffic time steps used to count the number of unique aircraft involved in the reconfiguration.

Transferring airspace and aircraft between operating position(s) at different workstations is particularly difficult when the operating position(s) involved are busy monitoring other background aircraft at the time of the transfer. The *reconfiguration workstation background cost* $g_k^{\text{R,W,B}}$ penalizes the additional effort required due to the background aircraft. It is a per-aircraft *reconfiguration workstation background weight* $\beta^{\text{R,W,B}}$ multiplied by the number of aircraft that are monitored but not transferred by operating position(s) involved in transferring other aircraft. This cost also uses the set of traffic time steps $\psi_{\pm}^{\text{R,W}}$ to count the number of unique aircraft involved in the reconfiguration.

The fourth and final term in the reconfiguration workstation cost quantifies the work associated with moving control of an open sector from one workstation to another without making any other changes to the open sector. This *reconfiguration workstation move cost* $g_k^{\text{R,W,M}}$ is expressed as a per-aircraft *reconfiguration workstation move weight* $\beta^{\text{R,W,M}}$ multiplied by the number of unique aircraft that are in the open sector airspace during the traffic time steps in $\psi_{\pm}^{\text{R,W}}$.

E. Problem Statement Summary

The problem to be solved by the algorithm when generating a configuration advisory is

$$\underset{C=\{C_1, C_2, \dots, C_K\}}{\text{minimize}} \sum_{k=1}^K g_k^S(C_k, T_k) + \beta^R g_k^R(C_{k-1}, T_{k-1}, C_k, T_k) \quad (10)$$

$$\text{subject to } C_k \in \mathcal{C}_k, \quad k = 1, 2, \dots, K \quad (11)$$

$$\underline{\lambda}_k \leq |C_k^A| \leq \bar{\lambda}_k, \quad k = 1, 2, \dots, K \quad (12)$$

$$\underline{\mu}_k \leq \sum_{\sigma \in C_k^A} C_k^{\text{OP}}(\sigma) \leq \bar{\mu}_k, \quad k = 1, 2, \dots, K. \quad (13)$$

The objective in eq. (10) is to find a configuration schedule advisory that minimizes the cost, which is a weighted sum of static and reconfiguration costs. The constraints require that at each configuration time step, a configuration is chosen that is valid (constraint (11)), contains an appropriate number of open sectors (constraint (12)), and contains an appropriate number of operating positions (constraint (13)).

IV. Algorithm Solution Method

This problem can be cast as a shortest path problem. Each configuration option at each configuration time step can be modeled as a node in the relevant graph, and each possible reconfiguration can be modeled as a directed edge in the graph. The starting node for the shortest path problem is C_0 and the destination node can be any of the valid configurations meeting the constraints at configuration time step K . Static costs are node costs and reconfiguration costs are edge costs. Let n be the largest number of valid configurations at any configuration time step: $n = \max_{k \in \{1, 2, \dots, K\}} |\mathcal{C}_k|$. This graph has at most nK nodes and at most n^2K edges. For example, in ZOB area 4, 16 airspace configurations can be used operationally. When operating position and workstation configurations are considered as well, there are $n = 173$ valid configurations of this area. A two-hour time horizon with 5-minute reconfiguration time steps ($\Delta = 5$) would lead to $K = 24$ reconfiguration time steps.

Many algorithms can compute optimal solutions to the shortest path problem [24]. The results in this paper were generated with one of these algorithms (a dynamic programming value iteration algorithm), but other algorithms, such as the A^* algorithm, could also be used to find a minimum-cost configuration schedule. The computational complexity of the dynamic programming value

iteration algorithm is $\mathcal{O}(n^2K)$. For large problems, finding a minimum-cost configuration schedule might be computationally difficult. Fortunately, many algorithms for quickly finding near-shortest paths also exist [24].

V. Default Cost Parameters

There are 25 parameters in the cost function. This section describes efforts at finding default values for these parameters.

A. Static and Reconfiguration Cost Parameters

Default values for the static and reconfiguration cost parameters were selected based on descriptions of operating procedures and also discussions with and a survey of subject-matter experts. The survey contained 13 questions; four questions were related to static cost parameters and nine questions were related to reconfiguration cost parameters. For example, some of these questions asked for estimates of the θ threshold parameters in the static cost. Others asked for estimates of the relative amount of work required to perform certain tasks involved in reconfigurations; these estimates could be used to derive various β parameters in the reconfiguration cost. Experts were also encouraged to provide comments. The survey was sent to nine subject-matter experts. All of the experts had some experience as an air traffic controller and many of them are currently or have been supervisors of an area, meaning that they have made decisions about how to configure sectors, operating positions, and workstations. Completed surveys were returned by five of these experts and four of them answered every question.

There are 12 parameters in the static cost and 12 in the reconfiguration cost. The default values for these parameters are shown in Table 1 and a discussion of the implications of these values can be found in Ref. [23]. For certain parameters, default values were determined by simply averaging the expert responses on a particular question. In other cases, engineering judgment and insights from expert comments were used to derive default values.

Table 1 Static and reconfiguration cost default parameter values.

Static Cost		Reconfiguration Cost	
Parameter	Default Value	Parameter	Default Value
$\bar{\alpha}^{1\text{OP}}$	6.66	$\beta^{\text{R,OP+,O}}$	0.45
$\underline{\alpha}^{1\text{OP}}$	3.33	$\beta^{\text{R,OP-,O}}$	0.01
$\bar{\alpha}^{2\text{OP}}$	10	$\beta^{\text{R,OP+,T}}$	0.6
$\underline{\alpha}^{2\text{OP}}$	2.83	$\beta^{\text{R,OP-,T}}$	0.3
$\bar{\gamma}^{1\text{OP}}$	2	$\beta^{\text{R,W,B}}$	0.5
$\underline{\gamma}^{1\text{OP}}$	1.5	$\beta^{\text{R,W,M}}$	1.8
$\bar{\gamma}^{2\text{OP}}$	2	$\beta^{\text{R,W,O}}$	1
$\underline{\gamma}^{2\text{OP}}$	2	$\beta^{\text{R,W,T}}$	2
$\bar{\theta}^{1\text{OP}}$	0.65	$\epsilon_+^{\text{R,OP}}$	2
$\underline{\theta}^{1\text{OP}}$	0.3	$\epsilon_-^{\text{R,OP}}$	0
$\bar{\theta}^{2\text{OP}}$	0.9	$\epsilon_+^{\text{R,W}}$	2
$\underline{\theta}^{2\text{OP}}$	0.5	$\epsilon_-^{\text{R,W}}$	1

B. Reconfiguration Weight

The reconfiguration weight parameter β^{R} determines the relative importance of the competing static and reconfiguration workload costs in the problem objective. A low β^{R} value will allow more frequent or more costly reconfigurations in order to drive down the static cost. Conversely, a high β^{R} value places more weight on reconfiguration cost, so higher static cost will be tolerated in order to reduce the cost of reconfigurations. In more practical terms, a configuration plan generated by a high β^{R} value would involve fewer or less disruptive reconfigurations, at the expense of over- or under-loaded sectors.

Insight into the sector configuring strategies employed in current operations can be gained by using historical traffic to measure the static and reconfiguration costs incurred by the airspace configurations found in historical data. Then, those costs can be compared to the costs of advisories produced by the algorithm for various values of β^{R} .

Sector configuration and traffic data from ZOB area 4 for 230 non-weekend and non-holiday

days selected from 20 October 2011 to 19 October 2012 were chosen for analysis. Weekends and holidays were excluded because they might involve low-volume or atypical traffic patterns, leading to configuration selections that are correspondingly atypical. For each day, and for 14 values of β^R , the algorithm generated advisories that specify configurations from 6 am to midnight local time. To approximate how such an algorithm might be used in operations, a rolling horizon technique was utilized. An advisory is calculated for the next two hours, but only the first hour is implemented. One hour later, starting from the current state of the area, a new two-hour advisory is calculated and again only the first hour is implemented. This process continues until the end of the time horizon.

The resulting static and reconfiguration costs were recorded for each day and for 14 values of β^R along with the historical costs based on historical traffic and airspace configuration data. Only airspace and workstation configurations were considered because historical operating position data was not available. Hence, static workload cost parameters were selected to produce a cost curve that is roughly halfway between the one- and two-operating position curves in Fig. 3. Also, the airspace configurations available to the algorithm only included the five most common historical airspace configurations. In more than 99.99% of the time under consideration, the historical airspace configuration was selected from these five configurations.

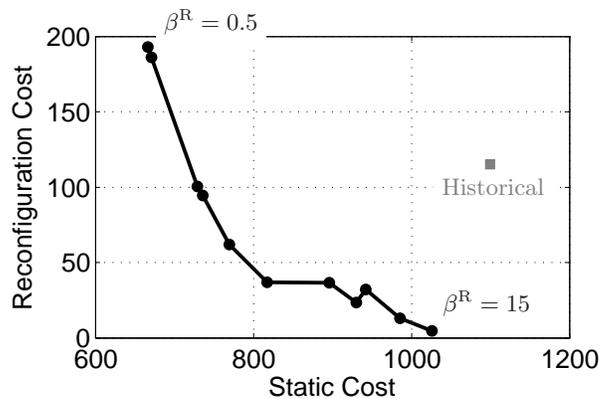


Fig. 4 Cost trade-off curve for 1 May 2012.

An example analysis of a single day is shown in Fig. 4 for 1 May 2012. Various cost values of configuration plans produced by the algorithm are plotted with black dots and connected with a line

that starts at the point corresponding to the smallest β^R value and ends at the point corresponding to the largest β^R value. The costs of the historical configurations used that day are indicated by the gray point. Changing the value of β^R allows for trading off between the competing static and reconfiguration costs.

Since β^R is a parameter that controls the relative importance of static and reconfiguration costs, it is appropriate to compare the *ratio* of static and reconfiguration costs produced by the algorithm to those produced by the corresponding historical configurations. The value of β^R that minimizes the difference between the historical and algorithm cost ratios for all days in the analysis is sought:

$$\beta^{R*} = \operatorname{argmin}_{\beta^R} \sum_{d \in \mathcal{D}} \left| \frac{g^R(\beta^R, d)}{g^S(\beta^R, d)} - \frac{g_{\text{hist}}^R(d)}{g_{\text{hist}}^S(d)} \right|, \quad (14)$$

where $g^R(\beta^R, d)$ and $g^S(\beta^R, d)$ are the respective reconfiguration and static costs produced by the algorithm for day d with β^R , and g_{hist}^R and g_{hist}^S are the historical equivalents. The set \mathcal{D} contains all of the days used in the analysis. As can be seen in the plot of the sum of this ratio error in Fig. 5, the value of β^R that produces the minimum error is 1.75.

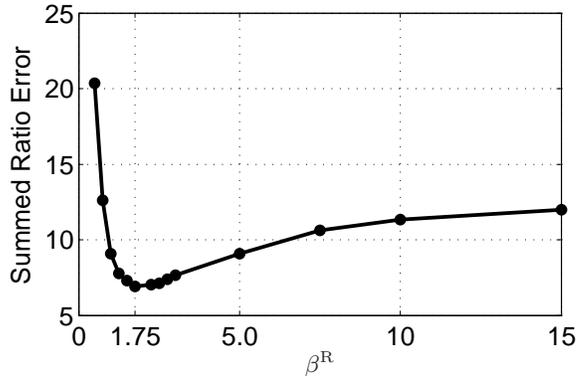


Fig. 5 Summed cost ratio error versus β^R .

VI. Reconfiguration Weight Parametric Study

To gain insight into the impact of the value selected for the reconfiguration weight, a parametric study was conducted. In this study, the simulations described in sub-section V.B were repeated but with three changes. Just five β^R values near the error-minimizing value of 1.75 found in that sub-section were investigated: 1, 1.5, 1.75, 2, and 2.5. One historical non-weekend and non-holiday

day was eliminated from the set of days in sub-section V.B due the use of a configuration other than the five considered in that analysis. This day was considered here because in this analysis the algorithm was permitted to use a larger set of 16 airspace configurations that subject-matter experts indicated could be implemented, even if some have rarely or never been utilized historically. The algorithm was given this additional flexibility because this analysis does not involve the sort of explicit comparison of advisories and historical configurations used to select a default β^R in sub-section V.B. The purpose of this analysis is to determine the impact of changing the value of β^R on operationally-meaningful metrics when any implementable airspace configuration is available to the algorithm.

The first operationally-meaningful metric relates to how much time open sectors experience loads below, in, and above the zero-cost region of the static cost curve (see Fig. 3). In this study, a static cost curve that was between the one- and two-operating position curves was selected because historical operating position data was not available; the zero-cost region of this curve includes open sector loads between 30% and 77.5%. At any given minute, the configuration in place specifies some set of open sectors. At this minute, each of these open sectors is experiencing some level of traffic that leads to an open sector load that is either below, in, or above the zero-cost region of the static cost curve. By keeping track of how many open sectors experience loads below, in, and above this region at each minute, the percent of open sector-minutes spent below, in, and above the region over the 231-day data set can be computed. Large percentages of open sector-minutes in the zero-cost region indicate that the configurations are maintaining open sector loads that facilitate safe and efficient operations.

These open sector-instance percentages are shown in Fig. 6. They are not sensitive to changes in β^R . The advisories produce open sectors that spend 30%–35% of open sector-minutes under, 60%–63% in, and around 6% above the zero-cost region. The historical configurations spend a much larger percentage of the open sector-minutes (70%) below the region and smaller percentages of open sector-minutes in and above the region (29% and 1%, respectively). It is not clear why historical open sectors tend to experience loads that are lower than the preferred load levels indicated by subject-matter experts, but this may be related to operational constraints such as low traffic levels

relative to the number of controllers available to staff operating positions.

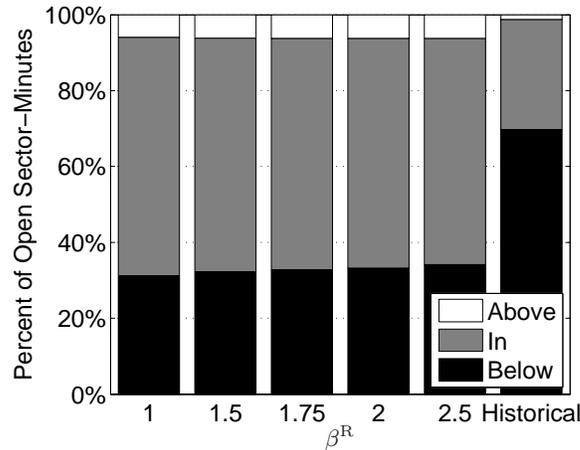
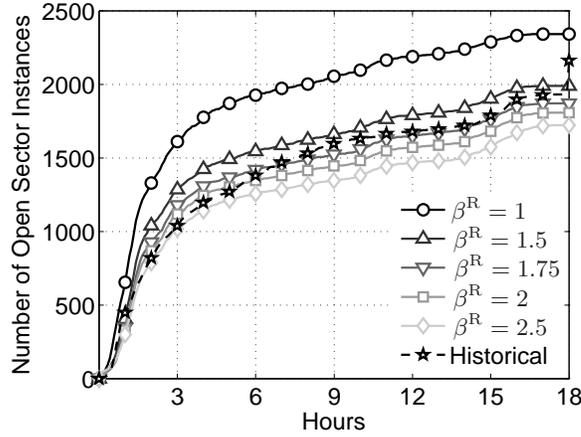


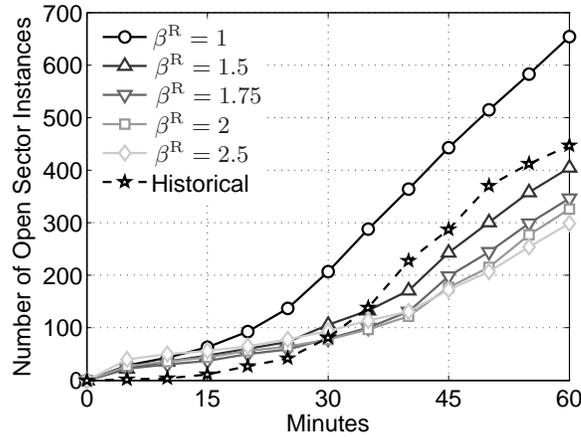
Fig. 6 Distribution of open sector-minutes versus β^R .

The second operationally-meaningful metric investigated is the duration of open sector *instances*. An open sector instance is an open sector that is used in airspace configurations for some duration of time. Each time a reconfiguration changes the airspace configuration, there is at least one open sector present in the new airspace configuration that was not present in the old configuration. This open sector will persist for some period of time, potentially even as other open sectors are changed by later reconfigurations. Eventually, this open sector will no longer be used by a later airspace configuration. The time that the open sector is in use is the duration of the open sector instance. Creating and terminating open sector instances requires some effort, so it is generally preferable for open sector instances to have long durations. Open sector instances with durations less than 60 minutes can be particularly disruptive. Figure 7 (a) shows the cumulative distributions of open sector instance durations for advisories generated with the five values of β^R and also for the historical configurations, and Fig. 7 (b) shows the same distributions but only for instances with durations in the range of zero to 60 minutes. As expected, lower values of β^R generate more open sector instances with shorter durations. The historical distribution falls somewhere in between the distributions corresponding to advisories generated with the five β^R values, except for durations of 30 minutes or less. For example, there are only 11 historical open sector instance durations of 15 minutes or less but between 37 and 63 open sector instance durations of 15 minutes or less in

the advisories (depending on the value of β^R). Even 63 instances over the course of 231 days is only one such instance every three or four days on average, but this advisory behavior may still be undesirable. This behavior may be alleviated in cases where the algorithm is given the flexibility to change the number of operating positions assigned to each open sector. Furthermore, these short-duration open sector instances are less disruptive when traffic is light, but traffic levels are not captured in this metric, so the disruption they induce may not be severe.



(a) Durations up to 18 hours.



(b) Durations up to 60 minutes.

Fig. 7 Cumulative distributions of open sector instance durations.

VII. Example Problem Instances

Two example problem instances were designed to illustrate characteristics of the algorithm. No historical configurations corresponding to these instances are available for analysis because the

constraints and traffic are synthetic and were never encountered in historical operations. However, these problem instances were designed such that appropriate advisories would be obvious, enabling a straightforward illustration of the algorithm’s ability to appropriately suggest different types of configuration advisories at appropriate times. Subject-matter experts have confirmed that there is a small set of obviously-appropriate advisories for each of these instances, and the experts even suggested some of the properties of the example problem instances. Other than the traffic scenarios, the two problem instances are identical.

A. Specifications

1. *Airspace and Time Period*

Algorithm results were generated for two example problem instances based on ZOB area 4. The shapes of the five sectors in area 4 of ZOB as of 20 October 2011 are shown in Fig. 1 (a) and a sample configuration of the area is depicted in Figs. 1 (b) and (c). The 2-hour time horizon selected for these instances ran from 13:00 to 15:00 UTC on 1 December 2011, which is 08:00 to 10:00 local time at ZOB.

2. *Constraints*

Synthetic constraints were constructed to demonstrate characteristics of the algorithm. The synthetic constraints are designed to leave the algorithm with only two possible configurations to choose from, and only a few time steps at which one of these two configurations could be selected.

The scheduled range of number of operating positions specified to the algorithm is shown in Fig. 8. The configuration schedule advisory is required to use 7 operating positions for the first 15 minutes of the time horizon, it can use 7 or 8 operating positions from 13:15 until 14:00 UTC, and from 14:00 to 15:00 UTC it must use 8 operating positions. No constraint specifying a scheduled range of number of open sectors was used in these problem instances. Constraints required that each open sector be mapped to a particular workstation, so the workstation configuration was not separately selected by the algorithm for these scenarios.

The configuration schedule advisories had to satisfy a few other constraints. For the first 15 minutes, the sectors ZOB45, ZOB46, and ZOB48 were required to be open sectors on their own and

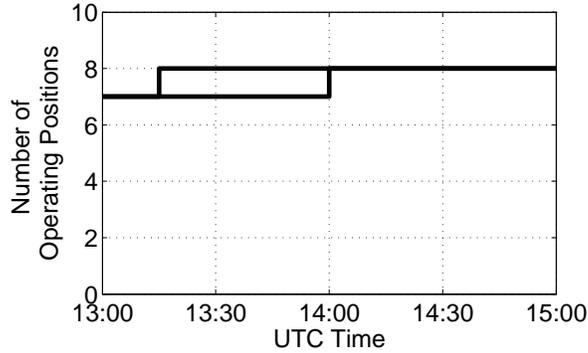


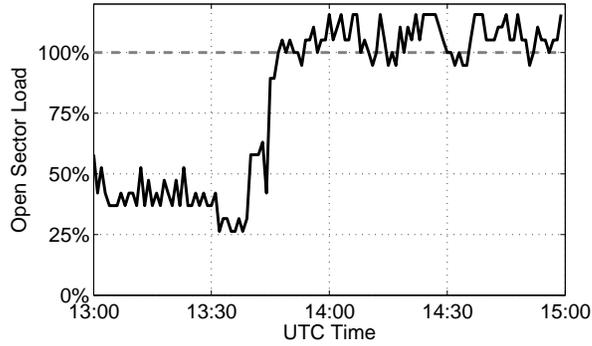
Fig. 8 Scheduled range of number of operating positions.

controlled with two operating positions. Furthermore, during this first 15 minutes, sectors ZOB47 and ZOB49 were required to be combined into a single open sector that was controlled by a single R-side operating position working at the workstation used for ZOB49 when ZOB49 operates as an open sector on its own. This configuration is depicted in Fig. 1 (b) and (c). Other constraints required that sectors ZOB45, ZOB46, and ZOB48 were open sectors on their own and controlled with two operating positions for the entire 2-hour period.

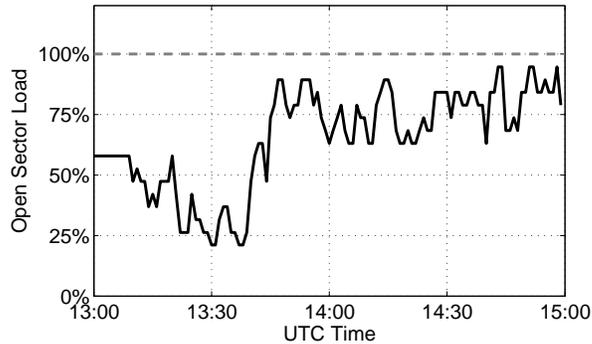
Taken together, these constraints left the algorithm with only two possible configurations that made use of eight operating positions: one in which ZOB47 and ZOB49 were combined into an open sector controlled with two operating positions and one in which ZOB47 and ZOB49 were each an open sector and each controlled with a single operating position.

3. Traffic

Two synthetic traffic scenarios were also constructed to demonstrate characteristics of the algorithm. The traffic scenarios were designed such that one of the two possible configurations would be appropriate for each scenario, and such that there would be only one or two appropriate times for changing the configuration. The aircraft counts for ZOB45, ZOB46, and ZOB48 are not important for understanding the behavior of the algorithm in these instances because the instances were designed with constraints that prevent changes in the configuration of these sectors. Figure 9 shows, for each scenario, the total aircraft counts in ZOB47 and ZOB49 divided by the MAP of an open sector consisting of both of these sectors.



(a) Traffic scenario 1.



(b) Traffic scenario 2.

Fig. 9 Open sector loads for an open sector consisting of ZOB47 and ZOB49.

4. Parameters

The MAP value of ZOB47 is 15, the MAP value of ZOB49 is 19, and the MAP value of an open sector consisting of ZOB47 and ZOB49 is 19. The configuration time step size for these example problem instances was set to $\Delta = 5$ minutes, so there were 24 configuration time steps in the two-hour time horizon. The traffic time step was set to $\delta = 1$ minute. The other parameters were set to the default values specified in Section V. In particular, β_R was set to 1.75.

B. Results

The configuration schedule advisories for these problem instances reveal how the algorithm can appropriately make use of changes in airspace and operating position configurations to respond to different traffic scenarios.

1. *Traffic Scenario 1*

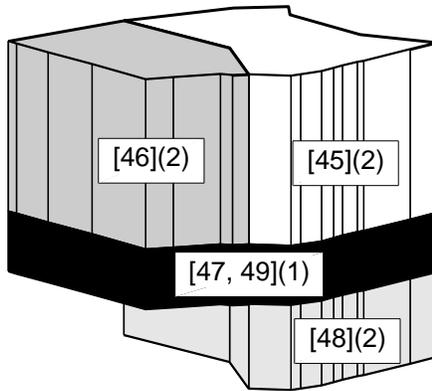
For traffic scenario 1, the configuration schedule advisory is shown in Fig. 10 and the relevant open sector loads are shown in Fig. 11. The number of operating positions allocated to each open sector is shown in parentheses. The schedule advisory uses the required starting configuration between 13:00 and 13:35 UTC. From 13:35–15:00 UTC, the advisory uses a configuration with eight operating positions in which ZOB47 and ZOB49 each operate as open sectors and each is allocated a single operating position. This advisory is appropriate because it operates ZOB47 and ZOB49 as separate open sectors and because the relevant open sector loads in Fig. 11 confirm that the two new open sectors each experience loads that are acceptable when they are monitored by a single R-side operating position. Furthermore, the advisory selects a relatively low-reconfiguration-effort time to perform the required reconfiguration.

2. *Traffic Scenario 2*

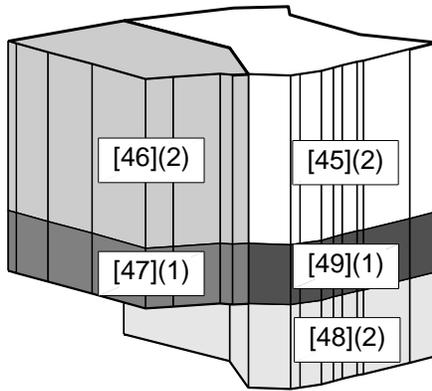
For traffic scenario 2, the configuration schedule advisory is shown in Fig. 12 and the relevant open sector loads are shown in Fig. 13. The configuration schedule uses the required starting configuration between 13:00 and 13:35 UTC. At 13:35 UTC, the algorithm allocates the newly-available eighth operating position to the open sector consisting of ZOB47 and ZOB49 as a D-side operating position. This advisory is appropriate because the open sector load is at an appropriate level for two operating positions during this period (see Fig. 13) and because the advisory selects a low-reconfiguration-effort time for the reconfiguration.

VIII. Conclusions

Air traffic controller supervisors configure available sector, operating position, and workstation resources to safely and efficiently control air traffic. This paper describes an algorithm for providing configuration schedule advisories to assist supervisors with this task. The algorithm takes as inputs traffic predictions and constraints on configurations and then outputs a configuration schedule advisory. The advisory minimizes a cost function that is a weighted sum of a static cost and a reconfiguration cost. Decreased safety and efficiency associated with a mismatch between the predicted traffic and the configuration is penalized by the static cost and decreased safety and



(a) Configuration for 13:00–13:35 UTC.



(b) Configuration for 13:35–15:00 UTC.

Fig. 10 Configuration schedule advisory for traffic scenario 1.

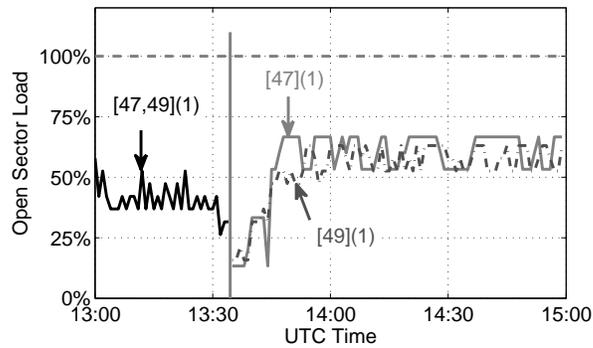
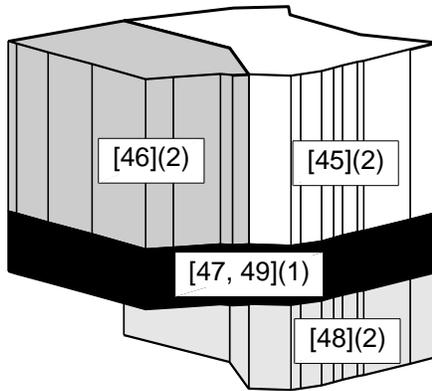
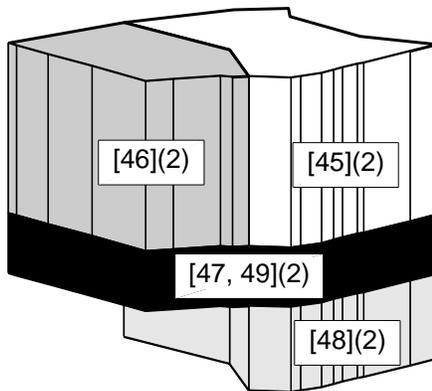


Fig. 11 Open sector loads for ZOB47 and ZOB49 during traffic scenario 1.



(a) Configuration for 13:00–13:35 UTC.



(b) Configuration for 13:35–15:00 UTC.

Fig. 12 Configuration schedule advisory for traffic scenario 2.

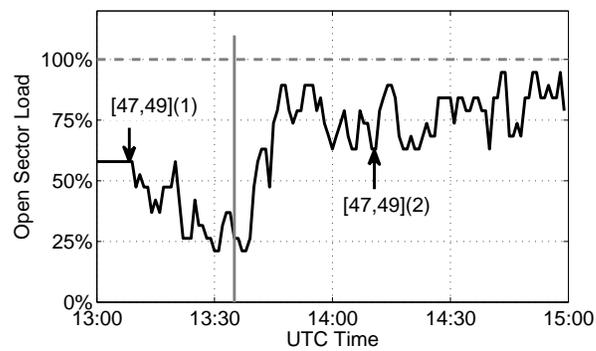


Fig. 13 Open sector loads for ZOB47 and ZOB49 during traffic scenario 2.

efficiency associated with the effort involved in changing configurations is penalized by the reconfiguration cost. The problem considered by the algorithm is a type of shortest path problem. The parameter that determines the importance of static cost relative to reconfiguration cost was tuned by comparing historical configurations to corresponding algorithm advisories. A parametric study of this parameter was also conducted. One investigation in this study revealed that the percent of open sector-minutes spent below, in, and above zero-static cost open sector load levels is insensitive to changes in the parameter. Furthermore, the open sectors in advisories spend considerably less time below the zero-cost load levels and considerably more time in and above these levels than the open sectors used in historical airspace configurations. A second investigation showed that changes in the value of this parameter can lead to corresponding changes in the distribution of open sector instance durations. The second investigation also revealed that the distribution of open sector instance durations in historical airspace configurations is similar to the distribution in the advisories, except that advisory open sector instance durations are more frequently between five and 30 minutes than historical open sector durations. Example synthetic problem instance results demonstrate how algorithm advisories appropriately make use of changes in airspace configurations and changes in the number of operating positions allocated to open sectors. Furthermore, the advisories for these example problem instances pick appropriate times for configuration changes.

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