Introduction of moving sectors for flow-centric airspace management

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***Abstract*—The introduction of free routing, flights in urban areas, and concepts for automated flight operations demand new concepts to provide safe and efficient airspace management. As coordinated operations in airspace will reduce the controller workload, flights should be grouped according to their interventions and by their similarity in planned and predicted trajectories. These groups should be controlled by a single entity, which follows this group and coordinates interaction inside the group and with adjacent groups. We propose the concept of moving sectors as a key element for efficient and flow-centric operations. For this purpose, the fundamentals for the geometric design of the sector are developed, a complexity measure is adapted to evaluate several aircraft group constellations, and finally, different implementations are evaluated based on simulated aircraft movements in the Singapore Flight Information Region. Our results indicate that the evaluation metric is appropriate and the investigated air traffic exhibits different opportunities to integrate moving sectors. The adapted complexity metric will be validated with operators in the next step to provide a tool for automated aggregation of moving sectors.**

***Keywords*—flow-centric operations, complexity, moving sector, controller workload, airspace management**

I. INTRODUCTION

Various concepts have been developed and tested concerning efficient management of traffic flows, such as flight-centric operations [1]. In this context, a sector-less air traffic management (ATM) concept aims at a decentralized approach where individual flight is controlled along the entire trajectory [2]. As in actual military operations, an air traffic controller is responsible for a limited number of flights between departure and arrival airports. It is assumed that an air traffic controller can monitor a maximum of six flights simultaneously (cf. [3]). Validation scenarios show only slight improvements over current procedures [4]. Especially for more complex traffic scenarios, a higher workload is to be expected despite support by advanced controller working position [5]. Dynamic sectorization, as proposed by [1], demonstrates an appropriate solution to handle a different amount of traffic over the day of operations. In these studies, a control area was used and divided into four sectors. Starting from a real traffic sample, the optimal size, shape, and position of each sector were optimized. The resulting sector geometries are shown in Fig. 1 and emphasize the change of the sector shape depending on traffic demand over the day of operations. The key optimization parameter was the harmonization of the controller task loads, followed by a small variation of task load during operations. For the mathematical optimization, a genetic algorithm was proposed, which combines the parameter good solutions to find better solutions. The idea of shifting sector boundaries can also be seen as a proposal to hand over flights earlier or later to balance controller workload individually and inside an air navigation service provider (ANSP). This approach is already used by controllers and doesn't require changes in operational procedures. Controllers can now receive automated support to determine the best handover times, taking into account a harmonized workload. This also enables them to actively adjust their workload.

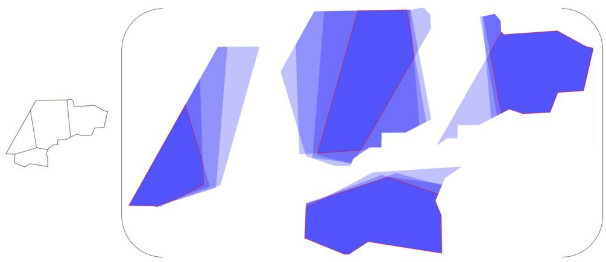

Figure 1. Airspace management area (left). The four sectors have slightly different shapes to adjust to actual traffic patterns (right), where the core area (assigned under each traffic demand) is marked in deep blue.

The concept of flow-centric operations will be a key enabling technology to address the challenges of free route airspace [6, 7] and to maximize airspace utilization. The idea behind this concept is that the less heterogeneous and the more ordered the traffic flows are, the easier it is for a controller to manage the traffic scenario. Moving sectors within these flows will enable the provision of safe, user-oriented, and prioritized air traffic services.

The paper is structured as follows. After the introduction, we present our methodology for building a moving sector in Section II and derive a metric for calculating the complexity of the traffic scenario covered by this innovative sector approach. To operationalize the approach, flights simulated with AirTOP in the Singapore Flight Information Region (FIR) were used and implemented in a developed simulation environment (Section III). This facilitates the use of a variety of evaluation metrics and sectorisation approaches. In Section IV, the developed approach is applied to the Singapore FIR.

An algorithm for creating moving sectors is provided, along with initial results concerning operational specifics. The paper concludes with a discussion and outlook (Section V).

II. Model approach

A. Geometric design

The geometric area of a moving sector could be derived from a (weighted) average position of the aircraft group, surrounded by a safety distance. Future aircraft positions are considered in creating the sector geometry. In that case, a corridor approach is more efficient than a circular approach because it maximizes spatial coverage without allocating unused space (see Fig. 2).

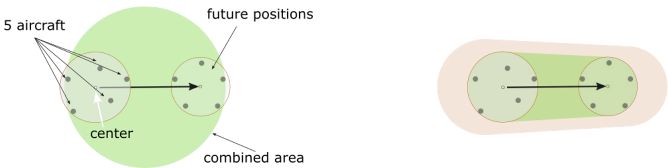

Figure 2. Derive a control area (green) by the use of simplified geometric elements (left). A convex hull covers expected flight paths better and extruding the area (orange) could add an appropriate safety distance (right)

As future positions are predicted from the current location, speed, and flight direction, these positions have an inherent uncertainty, which increases over the look-ahead time. This could be covered by an increasing safety area around each aircraft or the group shape (see Fig. 3).

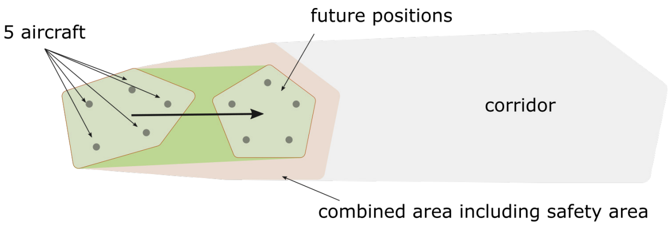

Figure 3. Combing current and future positions to a corridor with minimum sector area.

In contrast to dynamic sectorization, which creates a sector structure by central points of adjacent areas and Voronoi diagrams [1, 8, 9], the presented approach limits the area to be managed to a minimum. To integrate moving sectors into airspace and to interact with adjacent sectors, the Voronoi approach could be used to allocate additional airspace around the moving sector (see Fig. 4). This involves (a) determining the future positions of the grouped aircraft, (b) computing a convex hull and its centroid considering safety margins, (c) creating a Voronoi structure, and (d) combining the Voronoi cells of the respective groups into a corresponding sector. This could lead to an improperly formed structure, which could be corrected by creating a convex hull around the sector (see Fig. 4, bold line). Fig. 4 shows that the convex hull reduces the number of considered points at the adjacent cells, which is computationally cheap and fast to implement. At this point, however, it is necessary to verify that this adjustment does not intersect the safety area of the adjacent sector.

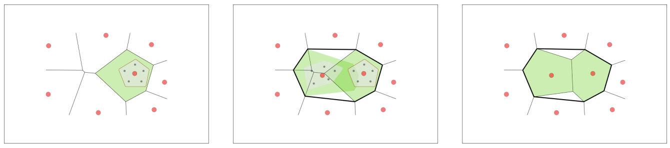

Figure 4. Combining related Voronoi cells using current and future positions (green cells) and adjacent sector centers to structure a moving sector: (left) five individual flights are grouped and center positions (red dots) are used to create a Voronoi structure, (middle) centers of current and future positions are used to create individual Voronoi structures that are combined into a convex hull, (right) both centers of current and future positions are used simultaneously to create a Voronoi structure that is combined into a convex hull.

B. Flow structures

Air traffic is typically structured by designated flight paths. Introducing the free route concept does not eliminate the similarity of flights heading in the same direction with matching altitudes and speeds. Flow-centric operations facilitate the joint control of clusters of aircraft that share characteristics such as proximity in space or similar speed vectors (cf. [10]). Efficient airspace management requires a flow-oriented alignment of routes from the point of view of controllers and airspace capacity.

Consequently, flow structures are detected in the traffic patterns, and appropriate candidates for grouping are identified along each flight path (preceding and following aircraft). Nearby flights are also listed as potential grouping candidates. For these nearby flights, it is assumed that the controller would aim to manage all flights near minimize limitations when dealing with conflicts.

To enable (partially) automated detection of traffic flows by cluster algorithms (cf. [11, 12]), two approaches were tested to identify similar aircraft trajectories: (1) clustering of trajectories based on their lateral characteristics and (2) using a tree structure to store intermediate locations and find a set of similar locations. As air traffic is a rule-based and structured system, flights have route legs with a significant distance, and routes on city pairs are comparable over the day of operations, the tree structure provides an appropriate and fast approach to detect traffic flows. As Fig. 5 shows, even in free route scenarios hypothetically implemented in the Singapore FIR (see Sec. III) common points could be identified (marked with orange pentagons) and be used for indexing and group allocation. Points can be added automatically or manually, for example, at locations where routes come closest, at crossing points, or whenever individual trajectories have changed (e.g., a flight level change). Density-based spatial clustering (DBSCAN, [13]) is applied to cluster these points by their spatial proximity to simplify the point structure, and the centroid of each cluster is stored in the tree as a reference point. Incorporating these points into a tree structure helps to identify frequently used route segments as the basic flow structure (cf. [6]).

The necessary foundations for implementation have been established by defining the sector geometry and integrating traffic flows to identify aircraft that could be added to a

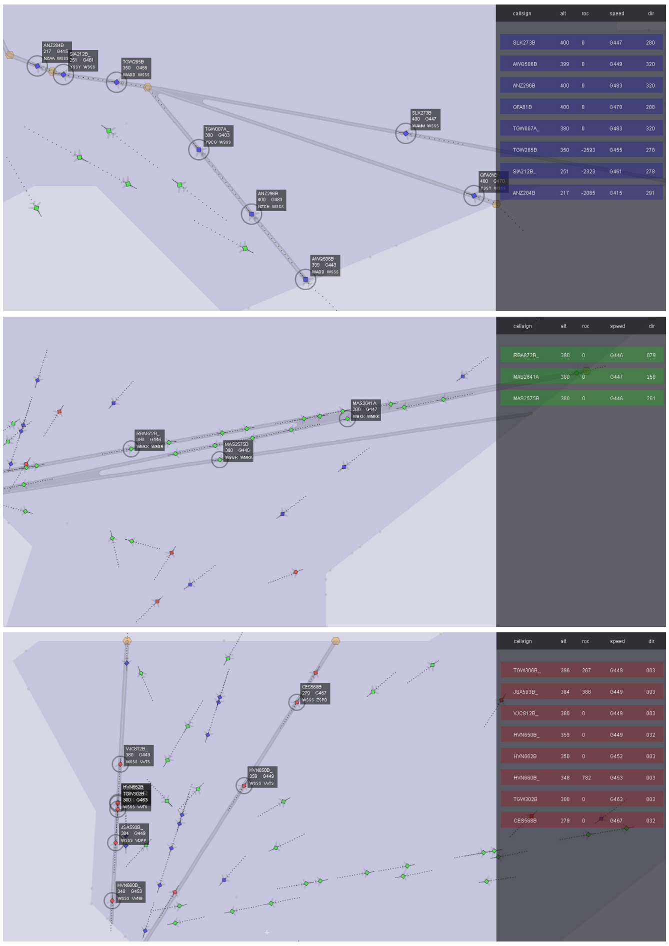

Figure 5. Three different flow configurations. Top: arrivals (blue) converge to a common entry point. Middle: Transitions (green) with long straight route elements. Bottom: diverging departures (red) with destination-based exit points.

moving sector. Next, a controller-centered evaluation of the respective group configuration has to be performed. In this phase, an algorithmic evaluation of the traffic scenario must be performed, covering the essential factors of complexity from an airspace controller's point of view.

C. Complexity measures

To develop a methodology and provide an implementation for moving sectors, an appropriate set of aircraft is assigned to these moving sectors based on each sector's complexity and the controllers' workload. Several measurement sources were identified (cf. [14–19]). The importance of these measurements was tested in operational scenarios with air traffic controllers to identify the most driving factors for complex traffic situations, which are increasing the controller workload (cf. [20]). Unfortunately, most publications do not allow reproduction of the derived complexity values for several reasons, e.g., the weighting of the individual components is not given [18] or contradictory correlations are shown but used anyway (e.g., increasing rate of climb of the aircraft decreases the overall complexity [14]).

In our approach, we decided to adapt and implement the complexity metric provided by [19], which is appropriately defined and covers a comparable number of individual measurements. The factors are defined as follows.

ACT - Aircraft count n, each aircraft in the corresponding sector is counted.

DNS - Density of aircraft in the sector (1), as the amount of airspace used by the active aircraft in relation to the airspace left for additional aircraft. We define A_{ac} as a circle area with a radius of 5 NM and A_{sec} is the area of the sector.

$$\text{DNS} = nA_{\text{ac}} / \left(A_{\text{sec}} - nA_{\text{ac}}\right) = \frac{1}{\frac{A_{\text{sec}}}{nA_{\text{ac}}} - 1} \tag{1}$$

CPA - Closest point of approach (2), to describe the additional monitoring effort if aircraft are flying close to each other. Here, the lateral distance $d_{\text{lat}_{ij}}$ between aircraft i and j is used to increase the CPA value by 1 if $d_{\text{lat}_{ij}}$ is under 8 NM and by 0.5 if the lateral distance is between 8 and 13 NM.

$$\text{CPA} = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \begin{cases} 1.0 & \text{if } \; d_{\text{lat}_{ij}} < 8 \text{ NM} \\ 0.5 & \text{if } \; d_{\text{lat}_{ij}} \in [8\,\text{NM}, 13\,\text{NM}) \\ 0.0 & \text{otherwise} \end{cases} \tag{2}$$

ANG - Convergence angle α (3), describes the severity of a potential conflict in a given time interval (8 - 15 min ahead) by using the expected crossing angle. This angle is transferred with the function f_{score} to a score with a value of 1 at 0° and 180° and minimum value ($s_{\min} \geq 0$) at 90°. We define f_{score} as a modified cosine function. We use a time interval of 10 minutes to detect a crossing point: c_{ij} is 1 when flight paths are crossing in the time interval; otherwise, it is 0.

$$\text{ANG} = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} c_{ij} \; f_{\text{score}}(\alpha_{i,j}) \tag{3}$$

$$f_{\text{score}}(\alpha) = \frac{1}{2}\left(cos2\alpha + 1\right)\left(1 - s_{\min}\right) + s_{\min}$$

NBR - Neighbor count (4), an additional measurement to emphasize the reduction of flexibility when a controller has to solve a potential conflict (aircraft within 10 NM radius, lateral) and at similar flight levels (within a range of 2000 ft, altitude).

$$\text{NBR} = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \begin{cases} 1.0 & \text{if } d_{\text{lat}_{ij}} < 10\,\text{NM}, d_{\text{alt}_{ij}} < 2000\,\text{ft} \\ 0.0 & \text{otherwise} \end{cases} \tag{4}$$

PRC - Conflict near sector boundary (5), reflecting a reduced time to solve the conflict before handing over participating flights and for having coordination efforts with the adjacent sector. If there is an intersection of flight paths detected (see definition of convergence angle), the point of conflict (*PC*) is calculated, and the shortest distance of this point to the sector boundary (*SB*) is calculated $d_{\mathrm{PC,SB}}$.

$$\mathrm{PRC} = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \begin{cases} 1.0 & \text{if } c_{ij} = 1, d_{\mathrm{PC,SB}} < 10\,\mathrm{NM} \\ 0.5 & \text{if } c_{ij} = 1, d_{\mathrm{PC,SB}} \in [10\,\mathrm{NM}, 20\,\mathrm{NM}) \\ 0.0 & \text{otherwise} \end{cases} \tag{5}$$

COD - Climbing or descending aircraft are connecting different flight levels, which increases the potential interactions. Each aircraft with a positive (climb) and negative (descent) rate of climb (roc) in the sector is counted.

$$\mathrm{COD} = \sum_{i=1}^{n} \begin{cases} 1.0 & \text{if } |\mathrm{roc}_i| > 0 \\ 0.0 & \text{otherwise} \end{cases} \tag{6}$$

VDF - Track variation (7), a measure of the variability of aircraft track angles (β, in degrees) within a specific sector of airspace. It quantifies the diversity of flight directions in the sector, with aligned flights (low track variation) indicating that aircraft are traveling in similar directions, which can facilitate the formation of traffic groups.

$$\mathrm{VDF} = \sqrt{\frac{2}{n(n-1)} \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} (\beta_j - \beta_i)^2} \tag{7}$$

STR - Airspace structure (8), use of a rectangle with major and minor axes (see Fig. 6), designed to meet a minimal width criterion. This rotated and bounding rectangle facilitates the determination of the primary traffic flow direction and allows for the calculation of the heading deviation for each aircraft relative to the major axis (γ_i, in degrees). The aspect ratio r of the rectangle is used as the weighting factor.

$$\mathrm{STR} = \sqrt{\frac{r}{n} \sum_{i=1}^{n} \gamma_i^2} \tag{8}$$

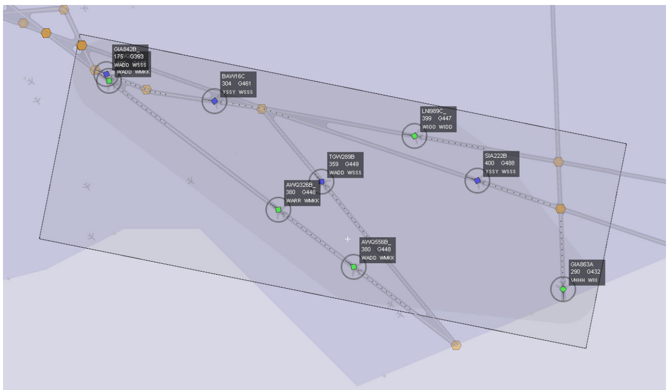

Figure 6. Selected flights forming a sector, which is covered by a rectangle with minimal width. The traffic flow should be aligned with the major axis to reduce the complexity of the traffic scenario.

The complexity score C is determined by weighting the individual factors. Each weighted factor is limited to a maximum of 10 (cf. [19]). We limit the weighting factors to two decimal places, as this is sufficient for an initial evaluation of different traffic scenarios.

$$\begin{aligned} \mathrm{C} = {} & 0.02\,\mathrm{ACT} + 0.33\,\mathrm{DNS} + 0.05\,\mathrm{CPA} \\ & + 0.11\,\mathrm{ANG} + 0.04\,\mathrm{NBR} + 0.08\,\mathrm{PRC} \\ & + 0.11\,\mathrm{COD} + 0.07\,\mathrm{VDF} + 0.07\,\mathrm{STR} \end{aligned} \tag{9}$$

To provide an additional measure of workload *W*, (10) is used to determine the time required to control the airspace by the number of ascending n_a, descending n_d, and cruising n_c flights [21]. An overload is assumed if the value exceeds 2520 seconds (42 min, 70% of an hour), a heavy load is found to be between 41-32 minutes, and a medium load between 31-18 minutes [22]. While (10) is designed for the peak hour (over a specific period, such as an aviation season) [21], it can also be used as an indicator to evaluate different traffic scenarios.

$$\begin{aligned} W = {} & 193.9 + 45.2\ n_c + 46.2\ n_a \\ & + 3.8\ n_d n_c + 1.6\ n_d n_a + 5.3\ n_a n_c \end{aligned} \tag{10}$$

Many of the factors have shortcomings in specific scenarios so the complexity of the traffic scenarios could be under- or overestimated. Also, the transfer of aircraft in the moving sector leads to discontinuities in the complexity assessment (see Fig. 7), as the sector design changes accordingly. Thus, the proximity to the sector boundary also seems to be only a limited suitable measure for evaluating moving sectors.

Figure 7. Changing the orientation of the rectangle (major axis) is done by adding only one flight (QFA24B, upper right), which in this case also halves the complexity value.

The above factors contain basic experiential knowledge of the controllers and allow an initial assessment of the complexity of a traffic situation to be managed. Of course, this list is not exhaustive and other/similar factors are also used, adapted to the respective object of investigation, and calibrated with local controllers. At the same time, we should avoid finding new definitions only to better differentiate very locally observed features. Unfortunately, it is thus very difficult to determine a general set of parameters, but it is necessary for comprehensible research in this field. Also, intuitive factors like speed or altitude variations often do not turn out to be relevant for the determination of complexity [19], but are assumed to be important factors. Nonetheless, different configurations (grouping of flights) to form moving sectors can be well distinguished. In future research, the evaluation factors for complexity will be adapted and, if necessary, extended with a focus on the moving sectors.

D. Discussion

Track variation, as introduced in (7) [19], is very sensitive, especially in counterflow situations. If only one aircraft from a parallel counterflow is added to the group, *VDF* jumps to very large values close to its maximum. Furthermore, the *VDF* dominates the total score. No clear discrimination can be made in a subsequent group expansion. In Fig. 8, six flights are heading east (north flow) and three flights are heading west (south flow). When flights from the south flow are added (from the right to the left: AXM9147B, MAS2631B, AXM5131B_) the *VDF* value changes from 0 with no flights from the counterflow to 6.7, 8.2, and 8.9, respectively. Directed, separated, and closely parallel flows should not result in that high measure of complexity from our current perspective.

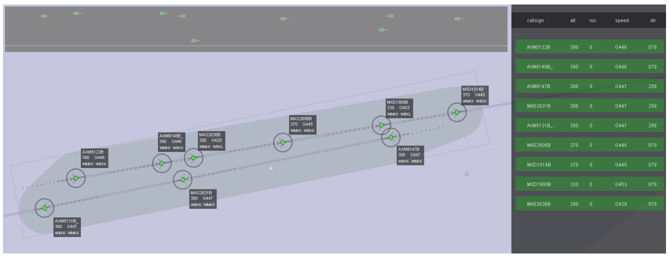

Figure 8. Parallel traffic flows in the Singapore FIR consist of flights with opposite flight directions. These flights are separated by flight levels and lateral paths.

For this reason, similar definitions for the calculation of track variation were examined, and the circular standard deviation (11) was selected as the new *VDF** indicator (cf. [23, 24]).

$$R = \sqrt{\left(\sum_{i=1}^{n} sin\ \beta_i\right)^2 + \left(\sum_{i=1}^{n} cos\ \beta_i\right)^2}$$

$$\mathrm{VDF}^* = \sqrt{-2\ ln\left(\frac{R}{n}\right)} \tag{11}$$

Considering the previous case, *VDF** results in a significantly smaller increase when adding the counterflow flights. Complexity values of 0.8, 1.2, and 1.4 were reached. As this aligns with the magnitude of the indicators overall, the *VDF** is initially considered without any additional weighting. The weighting of factors will be tested in later studies, independently of the current research on moving sectors. Upon examining *VDF* behavior, a strong correlation with the *STR* was observed, and both values demonstrated a similar order of magnitude in comparable grouping scenarios. The introduction of *VDF** has mitigated this effect. In some cases, the general definition of track variation can result in misleading conclusions. For example, when two aircraft are approaching each other, the track variation measure will be very high, but this can be reduced by adding a crossing aircraft to the group. In these special cases, however, metrics for convergence and possible conflicts (e.g., *ANG*, *CPA*, *NBR*) counteract this effect.

E. Additional factors and combination approach

Flights operated collectively should demonstrate comparable behavior to that of the entire group. This is indicated by the variance of the distance between the aircraft over a given time (relative velocity vector).

1) Initially, flights with constant spacing and proximity are merged into subgroups, acting as one flight.
2) Newly identified flights are evaluated for their fit within the identified subgroups or, if necessary, are assigned to a new group.
3) To determine whether more efficient groupings can be created, a reorganization is evaluated by constant optimization to reduce the controller workload.

The development of a moving sector starts with an initial setup (set of candidates) and then gradually constructs a sequence of flights to be included.

III. Simulation Environments

A. Traffic scenarios

As a preparatory step for the implementation of moving sectors, traffic scenarios having the following characteristics are engineered separately using AirTOp. The air traffic largely adheres to the double and free route traffic scenario (cf. [25]) with a minor modification to reflect local routing constraints within the context of area control in the Singapore FIR. The study examined the impact of changing two important factors of air traffic: traffic volume and lateral routing. Traffic volume points to the demand for air traffic in ASEAN airspace and has two levels: pre-COVID19 and double demand, reflecting a projected traffic demand for the late 2030s. Furthermore, routing has two different procedures: conventional ATS routing rules and free routing. The latter assumes direct routing via TOC (transfer of control) waypoints at the boundaries of the flight information region (FIR). For the simulation, 15 consecutive days are simulated with each day starting at 00:00 UTC and ending at 23:59 UTC. The period covers a representative peak season, namely 13-27 December 2019. The Official Airline Guide (OAG) flight schedule data for the period in December 2019 was used as a reference for traffic pre-COVID19. The timing of arrival patterns of inbound traffic (departures from the airport to the moving sectors or lateral arrivals from adjacent airspaces) is based on a hypothetical agreement among stakeholders assuming a longitudinal time interval of 4 minutes. The lateral route planning assumes free routing in each FIR in the Southeast Asia region, maintaining the TOC points at the FIR boundary. The route is determined by the flight plan data, specifically the origin and destination airports. The shortest direct path within the FIR network graph is taken for each flight. In the prior study [25], we used these traffic scenarios to identify areas of high traffic demands (hot spots), which have to be managed by air traffic controllers (see Fig. 9).

As the traffic scenarios and simulation results have been previously used in other studies, we will also use them in this study for comparability and transferability of results. The

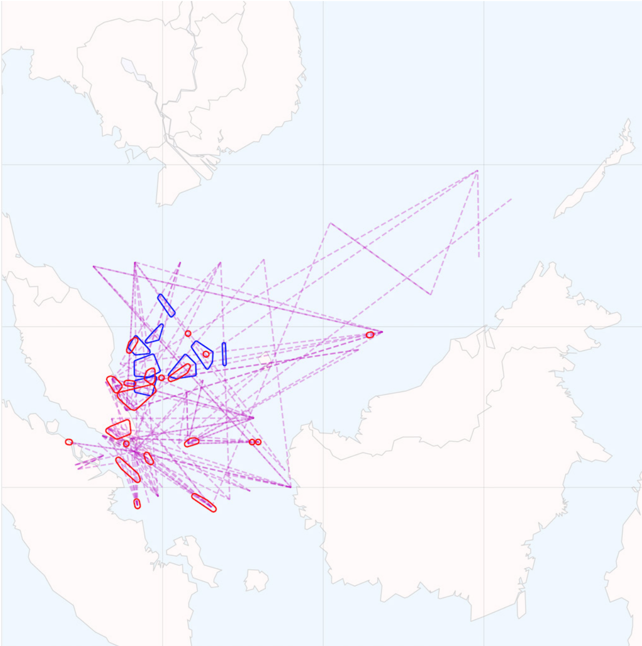

Figure 9. Simulated hotspots under a hypothetical Free Route Airspace traffic scenario based on complexity in the planned trajectories (blue) and geographical clusters of potential conflict in a Fast-Time Simulation study (red); the pink dashed lines indicate the simulated traffic routing [25].

moving sectors will form part of an overall solution and will allow for better management of the free-route traffic and optimal use of existing capacities. Certain significant operational aspects have been intentionally excluded for later investigations. For instance, it is currently excluded to consider the feedback from sectorisation to flight management (e.g., bundling of grouped aircraft for flow-centric operations), but this will be progressively implemented in later studies.

B. Evaluation environment

The developed environment (see Fig. 10) is capable to import AirTOp files into a database and prepare the data for fast replay and systematic evaluation of the air traffic scenarios. Filters on the left side allow to narrow down the number of aircraft displayed, so higher altitudes or different types of traffic (e.g., arrival (blue), departure (red), and overflights (green)). Selected flights are listed on the right-hand side with their call signs, flight levels, climb rates, speeds, and directions. The flights are arranged in descending order by altitude. The main purpose of these filters is to display flights concisely in time and space. Flights can be selected individually, in groups, or automatically (e.g., by proximity, similar orientation, within certain complexity limits).

Each selected flight is labeled with its call sign, altitude, and ground speed on the central screen (which can be zoomed in). Solid and dotted lines represent the expected movements of the flight, based on its flight direction and past positions. The current layout and color scheme is primarily to display as much data as possible, but the modular design allows the displays to be reconfigured to be used as controller stations.

The altitude band at the top of the central screen provides an overview of the flight level of the selected aircraft. Potential conflict areas are highlighted with orange lines here and as orange hexagons on the central screen.

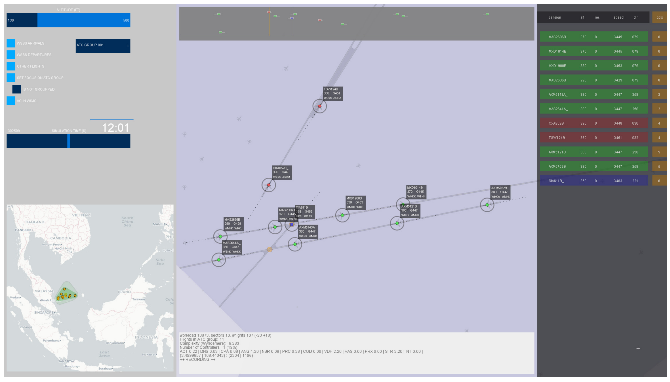

Figure 10. Development of an evaluation environment for the creation of moving sectors.

At the bottom left, a map of the area and the geometric layout of the currently active group are shown. Positions of other groups are highlighted by their centroids. A console at the bottom of the central screen provides information about the traffic scenario and the results of the complexity evaluation. The results of the complexity assessments and the created group constellations can be saved and used for further analyses.

IV. Application

The methodology for creating a moving sector is as follows.

a) Select a flight i from all active flights ac as the central element of the moving sector through manual selection, initially based on the expertise of the operator, and later through algorithmic optimization.

b) Establish two lists comprising nearby flights within a maximum distance of $d_{\max}$, sorted by distance L_D and track deviation L_T.

$$L = \{j \,|\, j \in \text{ac}, j \neq i,\ d_{i,j} \leq d_{\max}\}$$

$$L_D = \text{sort}(L, d_{ij}) \tag{12}$$

$$L_T = \text{sort}(L, |\beta_j - \beta_i|) \tag{13}$$

Based on the defined metrics, the primary contributors to complexity are route variance (*VDF**) and airspace structure (*STR*). This results in minor changes to complexity C for flights that follow a similar route. It is assumed that spatially close flights should be grouped regardless of the increase in complexity. The concept behind this is that the air traffic controller can resolve potential conflicts more effectively by having control over all flights affected by conflict resolution. This results in the following procedure for group creation.

- get next flight $j_{L_T} \in L_T$, add to group G_T ($G_{ij_{L_T}}$)
- calculate complexity $C_{ij_{LT}}$ of temporary group G_T
- get next flight $j_{L_D} \in L_D$, add to group G_D ($G_{ij_{L_D}}$)
- calculate complexity $C_{ij_{LD}}$ of temporary group G_D

- if $C_{ij_{LD}} < C_{ij_{LT}}$, add j_{LD} to G_i; otherwise, add j_{LT}
- remove added flight j from L_T and L_D
- stop if C_{ij} exceeds $C_{\max}$ (to be defined)

The algorithm is demonstrated through an example traffic scenario involving multiple flights (refer to Fig. 11). The scenario comprises three southbound flights (blue), three nearly parallel but diverging flights to their right (green), two flights from the south heading north (green and red), one flight from east to south (green), and one flight that has already passed the group located in the northeast (red). As indicated in the metric, flights on the same route are added first, followed by flights with similar directions. The three counter-flowing flights are considered last because they create areas of potential intersection, resulting in a higher complexity score.

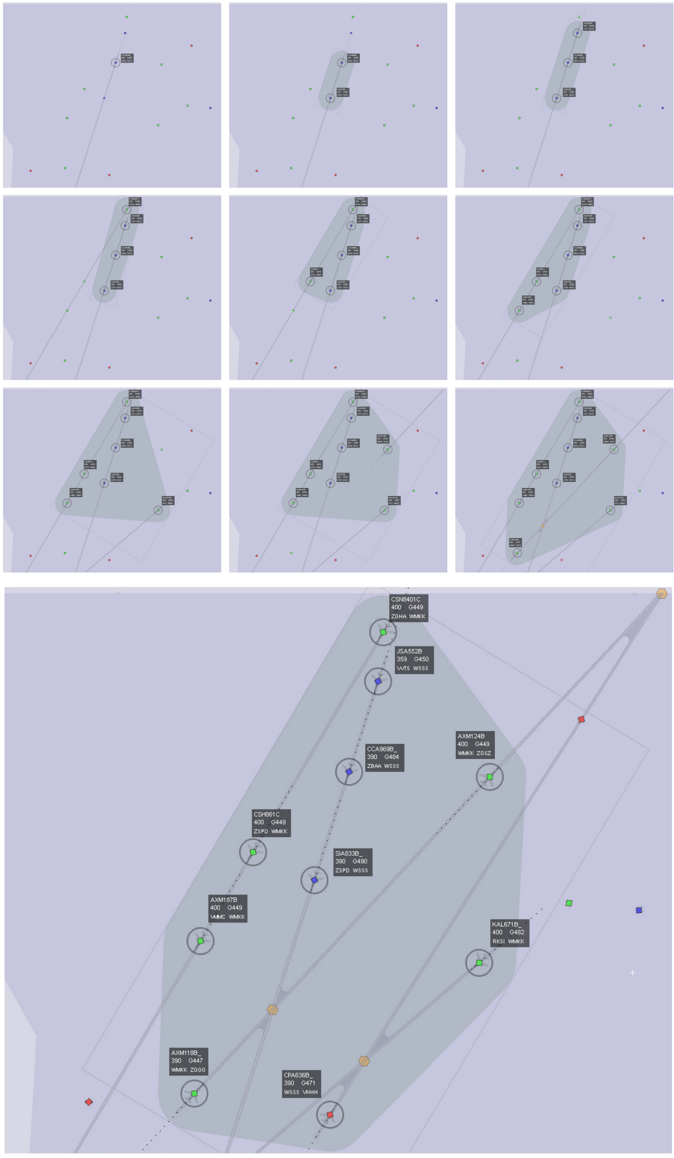

Figure 11. Creation of sector structure considering 9 flights around a pre-selected flight (top). In each step (from left to right), the flight that adds the least complexity to the group is added. The final group constellation (below) shows intersections inside the sector, which allows the controller to manage these within his area of responsibility.

The growth in group size correlates with a progression in complexity, as shown in Fig. 12. The complexity of the sector significantly increases when adding flights in similar directions that are not on the same route (marked by the green area). The complexity level increases from 0.1 to 1.3, approximately. Furthermore, the integration of aircraft flying in an opposite direction leads to a significant increase in complexity of about one point in each case.

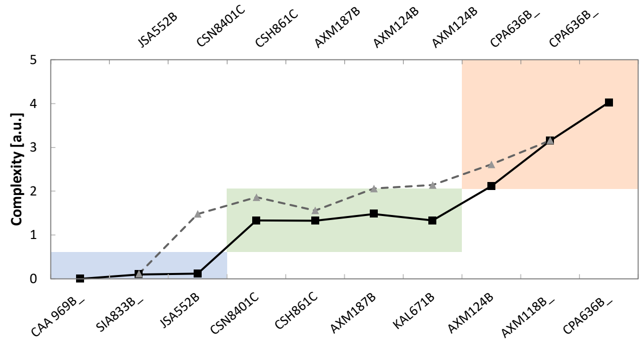

Figure 12. The black line indicates the lower complexity boundary for a given group size (major x-axis) and the dotted grey line shows the increase of the complexity if an alternate (second best) flight would be added (secondary x-axis, top). As the background color indicates, three blue flights are added first (low complexity) followed by four green flights (higher complexity level). The red background indicates a significant increase in complexity.

The example provided is a static sectorization created at a point in time. The concept of the moving sector is that it moves over time and the controller follows the now consolidated traffic. It is beneficial to the controller that the groups remain unified and maintain a certain level of complexity, so future points in time must also be considered when creating the moving sector. Fig. 13 shows the progress of two moving sectors over time. One sector includes all the flights of the traffic sample, while the other sector is limited to southbound flights only.

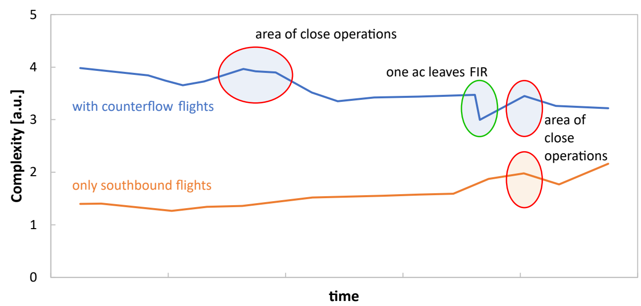

Figure 13. Evolution of the complexity value of two different moving sector configurations. The progression shows significant changes when aircraft leave the moving sector and when aircraft approach each other.

The complexity in each sector increases when some flights converge (monitoring and conflict resolution tasks must be performed) and decreases as the situations are resolved (cf. Fig. 14). Over time, the complexity of the first sector decreases (coming from a high level), and the other increases (coming from a lower level). This is indicated in Fig. 14, because there are approaching points (orange color) near the sector boundary.

Figure 14. Moments of increasing complexity due to convergence of flights within the moving sector: (left) considering all aircraft, (right) only southbound flights.

Within the provided traffic scenarios, there are several opportunities to introduce moving sectors. The easiest way is to use long corridors because they exhibit low complexity. Fig. 15 shows two corridors with complexity values of 0.32 (9 eastbound flights) and 0.22 (6 westbound flights), respectively. If these flights are all combined into one sector, the complexity increases to 3.82 due to the high (maximum) track variation. Therefore, if traffic flows are clearly separated (independent corridors), the complexity per corridor should be determined first and then aggregated to an overall complexity measure in a second step. In the case of flows, there is also the effect that the center of the sector may not move much, but the flights of the respective corridors move away quickly. Since the flows contain no increasing or decreasing traffic, the calculation of workload (10), only shows a value of 14.5 min, indicating low workload (cf. [22]).

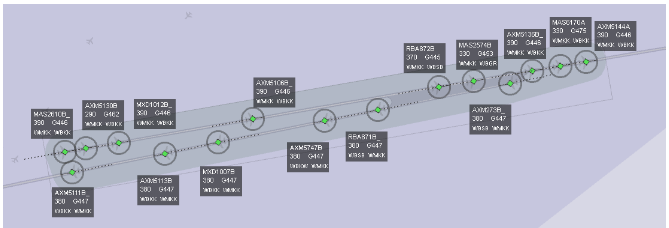

Figure 15. Two separated flows: eastbound (north) and westbound (south).

V. Conclusion

We introduced the concept of moving sectors and implemented the concept in an evaluation environment. We applied the concept to different scenarios using simulated traffic in the Singapore FIR. First, we needed to create a metric that would allow us to evaluate the complexity of different traffic scenarios. Unfortunately, there are few comprehensible approaches published in the literature. In most cases, the results are calibrated to specific scenarios, but without an exact mathematical description of the input variables used. A change between the metric and imperial system in air traffic (ft, m), alternate use of angles (rad or degrees), and undocumented mathematical functions are the most common reasons why we have not been able to apply these metrics. Based on [19], we developed an adjusted metric for sector complexity, which allows us to establish and evaluate moving sectors. In terms of flow-centric management, the next step will be to establish a feedback loop between the moving sectors and traffic management. Major challenges will be: (1) designing ATCos' operations and interfaces among their working positions, and (2) controlling air traffic flow itself to compose ideal patterns of the traffic. On the second challenge, we have been developing a novel modeling and simulation approach to mitigating air traffic complexity while controlling aircraft departure and arrival flow at potential hotspot areas. The aim will be to better align traffic with the new sector concept, thereby reducing controller workload and increasing capacity.

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