

[EN-A-032] Future airspace design by dynamic sectorization (EIWAC 2017)

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Abstract: The future airspace has to provide a reliable infrastructure and operational concept to ensure efficient and safe operations considering both flight-centric operations and the integration of new entrants. We propose an approach for a dynamic sectorization to manage the air traffic demand and flow appropriately. Our dynamic sectorization results in enhancements of the current operational structure (less deviation in controller task load) and leads to a significantly lower controller task load for the newly created airspace. Since future 4D trajectory management demands an efficient consideration of operational (e.g. temporally restricted areas), ecological (e.g. contrail prevention) and economic (e.g. functional airspace blocks) constraints, our dynamic sectorization method contributes to the highly flexible use of current and future airspace. In this paper, we provide an overview of several use cases and describe the working principle of our approach: fuzzy clustering of air traffic, Voronoi diagram for initial structures, and evolutionary algorithms for optimization.

Keywords: airspace efficiency, dynamic sectorization, clustering, evolutionary algorithms, optimization

1. INTRODUCTION

Due to political restrictions, more specifically the federal air sovereignty, airspace structure in Europe is determined by a high level of fragmentation. Furthermore, air space areas are generally not determined by the dynamic traffic flow over the day, but by static constraints (e.g. national borders). The resulting inefficiencies (negative operational and economic effects) are caused by coordination efforts as well as asynchronies between operational concepts and capacity management of the different decision-making units. Concepts such as dynamic capacity balancing target this problem, but do not treat the root cause of having an insufficient airspace design. Based on the liberalization of the aviation markets and as a part of the Single European Sky concept to create a legislative framework for European aviation, the Functional Airspace Block (FAB) approach was introduced by the European commission in order to restructure the European air space. The management of European Air Traffic within a Functional Airspace Block system is one of the main pillars in the Single European Sky concept for meeting future air traffic requirements.

The sectorization of the airspace considers requirements of ATC (safety, capacity, and efficiency), users (unhindered access) and environment (restricted areas over cities, residential areas, etc.) as far as possible. Particularly, ATC demands a sufficient airspace by designing appropriate procedures, routes, or holding areas, and considering operational demands such as handling of mixed traffic, balanced work load, or efficient arrival/departure

sequences. The current allocation of air space areas systematically leads to operational inefficiencies and demonstrates that the task load of the air traffic controllers significantly deviates depending on the air space sector and the traffic demand/flow over the day.

To ensure a more efficient allocation and a harmonized task load distribution, we consequently changed the current paradigm of traffic flow, which is determined by airspace structure, to a dynamic approach of a structure which is adjusted to the traffic flow sequentially. We contribute to the flight-centered Air Traffic Management with a specific approach to dynamically optimize the airspace focusing on the sector structure and resource allocation, considering both operational and economic efficiency targets (e.g. task load, fragmentation of flights by sectors). Therefore, we develop a four-step approach containing 1) economic performance evaluation, 2) fuzzy clustering of traffic flows on the day of operations, 3) generation of a new sector structure based on Voronoi diagrams, and 4) evolutionary algorithms in order to adjust and optimize the new sector structure depending on dynamics demands over the day of operations (see [1, 2]).

Our dynamic sectorization concept enables sector adaptation in a time-dependent way by dynamically adapting the position and shape of the sectors with respect to actual necessities and restrictions (e.g. capacity, task load, controller availability, or stability/resilience). Due to operational determinants and restrictions, the scope will cover upper airspaces only. The developed tool AutoSec is

an essential and superior approach to combining the idea of fully unstructured airspace and today's rigid structures to achieve both a balanced and more efficient use of the airspace. Additionally, the dynamic sectorization may enable efficient strategies to cope with severe weather conditions, temporal closures (e.g. space vehicles, intruders, military), and integration of new entrants (e.g. personal or unmanned air vehicles).

In the context of SESAR's flight-centric operations, we developed a dynamic airspace sectorization (DAS) approach, which differs from the dynamic airspace configuration (DAC) where pre-defined airspace blocks are combined to superior structures [1]. We are assuming a continuous airspace that will be separated without a specific demand for underlying structures but considering both the current/future air traffic flows and the controller's ability to manage all assigned aircraft (e.g. measured by task/work load). We fundamentally changed the common method of 'traffic flow is following the provided structure' to 'a structure follows the traffic flow' paradigm. Furthermore, our approach bridges the gap between structured and unstructured airspace designs and will be a fundamental key element for efficient air traffic operations taking into account both regular and disruptive events.

1.1 Objectives and Structure of the Document

This paper provides an overview of our research focusing on the efficient sectorization of the airspace with a special emphasis on a dynamic adaptation of operational air traffic demands and flows. In the first section, we introduce the common challenge of an efficient airspace design using examples from the European airspace, the consideration of volcanic ash clouds, the integration of space vehicles in highly segregated airspace, as well as the air traffic control in urban environments. In the second chapter, we introduce our methodology in detail, addressing the approaches of fuzzy clustering, Voronoi diagrams, and evolutionary algorithms to analyze, structure, and optimize the airspace respectively. In the following, we introduce our tool environment and results of the exemplary application of dynamic sectorization to a part of the European upper airspace. This paper finishes with a conclusion and an outlook for our future research, implementation, and validation tasks.

2. AIRSPACE STRUCTURE

The air traffic demands an efficient airspace environment, which ensures safe operations considering economic (e.g. cost-efficient air traffic service), environmental (e.g. avoidance of noise or contrails), and operational (e.g. convective weather cells) requirements. In this section, we focus exemplarily on several topics connected to efficient airspace structures with a clear indication that a dynamic sectorization could provide significant benefits to the specific challenge.

2.1 Analysis of European Airspace

Due to the legal and political framework, airspace structure in Europe is characterized by a high level of fragmentation. Basically, boundaries of airspaces, and partly sectors, are determined according to national territories. The current structure of European ATM is expected to lead to inefficiencies caused by coordination efforts, inconsistencies between the ANSPs' strategies and capacity restrictions [3]. Furthermore, the growing number of flight movements, as well as the rising market share of Low Cost Carriers in Europe, pose new operational challenges to Air Navigation Service Providers (ANSPs) and lead to an increasing cost pressure. Consequently, productivity and cost efficiency of ANSPs has gained increasing attention recently [4].

Following the liberalization of the air transport markets and as a part of the Single European Sky (SES) concept, the Functional Airspace Block (FAB, see Figure 1) approach was introduced by the European Commission (EC) in order to restructure the European airspace [5]. Through the consolidation of airspaces and a subsequent adjustment of procedures and technical equipment, nine FABs were constructed to meet future air traffic requirements.

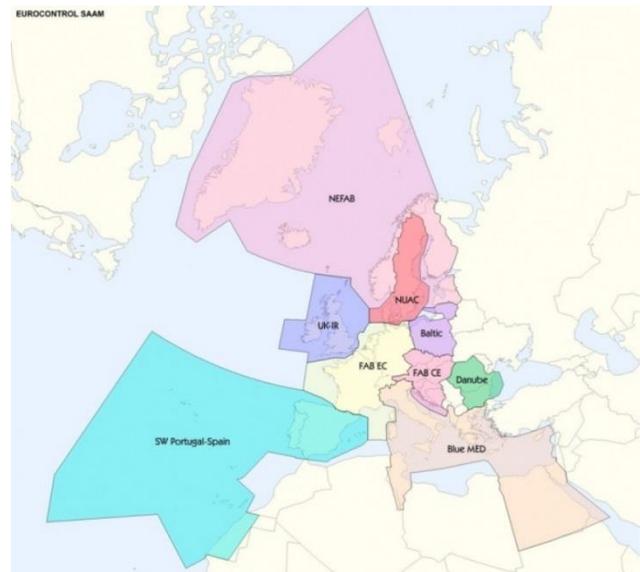


Figure 1 Functional Airspace Blocks (EURCONTROL).

The management of European Air Traffic within a Functional Airspace Block system is one of the main pillars in the Single European Sky concept. However, over the past years, significant problems in implementing this concept could be observed for some FABs. Firstly adopted in 2004, all FABs were scheduled to be operating by 2012. However, just two of the nine FABs have been implemented today. A key underlying rationale of calls for intensified cooperation amongst European ANSPs and for a consolidation of this sector is the assumption that the provision of air navigation services is characterized by

significant economies of scale. However, previous studies show that there is a turning point when diseconomies of scale occur [6, 7]. The reasons derived concern in particular operational procedures, cultural and legal differences, an inappropriate allocation of ANSPs to one FAB and missing incentives in implementation.

Since the fragmented airspace shows inefficiencies as well as the consolidation into FABs, an alternative restructuring of the European ATM is mandatory. Based on the lessons learned through the previous studies, a dynamic sectorization was identified as an appropriate candidate for further improving the ATM efficiency [2].

2.2 Volcanic Ash Cloud

The eruption of the Eyjafjallajökull volcano in 2010 seriously affected the European air traffic system. Airspaces under the control of different Air Navigation Service Providers were affected, such as all Italian flight information regions, Croatia, Albania, Macedonia (former Yugoslav Republic of Macedonia), Serbia, Slovenia, Hungary, Romania, Bulgaria, Bosnia, Herzegovina, Malta, East of Greece, Cyprus, Turkey, Bulgaria, Ukraine and Moldavia.

This specific non-regular situation emphasizes the need for a harmonized and cooperative approach without insistence on national sovereignty of airspaces or predefined airspace structures. In order to predict and prevent similar effects on the European airspace, a test scenario was created. This scenario includes a potential eruption of the Stromboli volcano and contains the ash distribution created for test purposes by the organization committee of the ICAO's regular volcanic ash exercise (VOLCEX 14/01). The simulation was performed using a fast-time simulation tool and the traffic data as well as ash distribution characteristics for 1st and 2nd of April were simulated (see Figure 2).

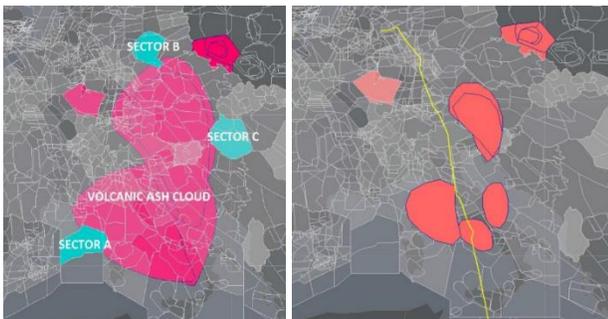


Figure 2 Volcanic ash cloud in European airspace (left) and an exemplarily rerouted flight considering a safety risk assessment (right) [8].

Beside the cross-border effect of the volcanic ash cloud, both the prediction (development of area in time and space) and the specific particle concentration of the affected areas are essential in order to efficiently manage this non-regular situation. To generate reliable flight trajectories around the volcanic ash cloud, an active

airspace management is needed to efficiently use the available, scarce airspace capacity. Furthermore, this will lead to the necessity of re-structuring the airspace to adapt the sectorization to the new trajectories with the target of distributing the controller task load equally between all sectors. The high complexity of this disruptive scenario is primarily driven by the uncertainties in the predictions of the ash cloud and the different handling of regular and non-regular situations. Our approach of a dynamic airspace sectorization is immanently designed to handle these kinds of disruptive scenarios in the same way as regular days of operations.

2.3 Interoperable Air and Space Traffic Management

The expected increasing demand of commercial space transportation will require an interoperable air and space management, where the incoming and outgoing space flights challenge the current segregated airspace in Europe [9]. A seamless and safe integration into the civil airspace is needed to handle a regular pass through of space vehicles (see Figure 3). There are several approaches of future air/space operations, which have to be covered by a comprehensive air/space traffic management, ranging from rocket launch operations up to suborbital flights with capabilities of operating in normal airport environments (e.g. arrival/departure areas, standard runway operations).

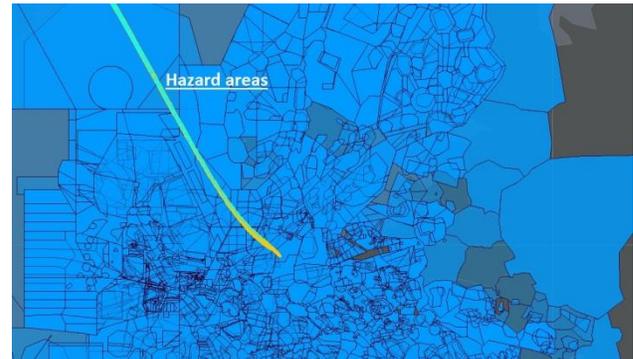


Figure 3 Integration of space flights into European airspace [10].

To enable a reliable mixed air and space traffic management in Europe, the operational airspace concept has to be timely and spatially flexible in order to adapt upcoming changes in the flight path of the space vehicle. In this context, the dynamic airspace sectorization is a key technology in enabling future European landing sides.

2.4 Urban Environment

From a ground-based traffic point of view, the traffic theory indicates three phases of traffic: free flow, bound flow (synchronized traffic), and congestion (wide moving jam) with zones of phase transitions [11]. In the context of traffic management, these zones call for different kinds of management solutions. In comparison to the air traffic, an almost free flow phase could be understood as flights in upper airspace and the synchronized/congested phase is found in the terminal area and on the runway. The different kind of traffic results in different controller

strategies. As an example, controllers like to grant direct to the runway if the traffic density is low, but with increasing traffic, the controllers switch to specific arrival patterns (e.g. trombone structures or holding areas) to efficiently handle the increasing task load.

Due to increasing traffic demand by personal air vehicles, it is expected that a future urban traffic management will primarily have to cope with the synchronized and congested phases, which demands specific adaptation of the accompanied airspace. In the project Metropolis, different kinds of potential airspace designs were tested regarding airspace efficiency [12]. In Figure 4, four different approaches are shown with an increasing airspace structure: free flight (individual conflict solution), layered structure (altitude bands corresponding to heading ranges), zones (today's airspace design), and tubes (road-based concept, separation by speed, direction, and vehicle types). In the context of the project Metropolis, the layer concept offers the best balance with regards to safety, airspace capacity, and efficiency [12].

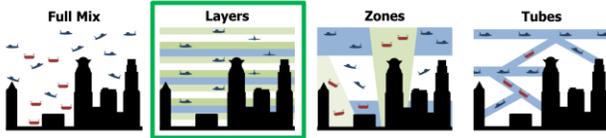


Figure 4 Different airspace designs with increasing structure to integrate personal and unmanned aerial vehicles into an urban environment [13].

If, in the future, the urban area will consist of a significant amount of movements of personal air vehicles, the frequency of traffic will follow the daily time-dependent demand for transportation. As shown for the case of Berlin in Figure 5, there is a clear indication of a highly used infrastructure, which changes over the day (e.g. morning and evening peaks).

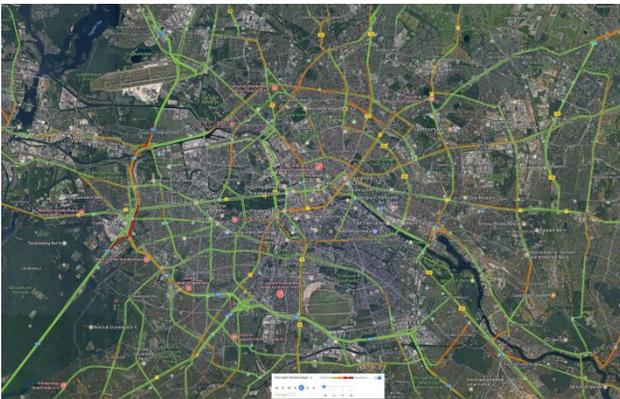


Figure 5 Traffic densities on Friday morning in Berlin using Google Maps' traffic situation display.

In Figure 5, a morning peak is shown in the Berlin road transport system, where red indicates congestion and green is used for free flow conditions. An appropriate airspace design and operational concept have to essentially consider the expected high amount of synchronized air

traffic and should be able to handle the changing air traffic demand through a dynamic and adaptive approach.

2.5 Unmanned Freight Operations

In the context of the DLR research project Unmanned Freight Operations (UFO) [14], we analyzed the implementation of unmanned cargo aircraft flying in a formation for the transport of relief goods starting in Europe and flying to Africa. We assumed that a specific, temporary airspace structure could provide an efficient handling of this formation. In a first step, we used a segregated airspace area for the unmanned cargo relief flight as is done today for military and relief flights as well. This allowed us to evaluate the impact on airspace capacity of such flights [15].

Dynamic adaptation of the sector structure is a prerequisite for allowing more flexibility in airspace segregation. Instead of reserving an airspace part for the whole flight duration, the adaptation facilitates a restructuring of airspace during the segregated flight so that only a specified area around this flight has to be reserved. This reserved area moves according to the actual flight's trajectory and the sectorization of the surrounding unrestricted airspace is dynamically adapted with respect to the residual traffic demand.

3. Dynamic Airspace Sectorization

In section 2 we emphasize the need for a comprehensive airspace management, using examples of special traffic patterns, air traffic influenced by disruptive events, or new operational concepts necessary for future urban environments. All these changes require a re-structuring of the airspace in a more flexible and time-dependent way. The necessity to adapt the current and future ATM system results in new concepts, such as the Dynamic Airspace Configuration (DAC) [16] or Dynamic Airspace Sectorization (DAS) [17]. For a DAC system, the airspace is structured into smaller airspace blocks, which are subsequently combined to form sectors in dependence of the actual traffic situation. The DAS system is not built on a substructure. A completely new airspace structure is designed for each specific traffic situation (continuous in space and time).

Both approaches focus on a harmonized, uniformly distributed task load for and between the airspace controller(s). Thereby, the task load depends on the density of air traffic (movements per area) and on the complexity of the air traffic movements (e.g. level changes, relative speeds). The proposed more flexible and especially time-dependent concepts for air traffic control structures (sectors) will be able to cope with the identified future requirements, even when there is no expert knowledge for future operations. Both the DAC and DAS approach will provide an efficient support to human controllers or controlling systems. It is assumed that

flights in urban environments will fulfill similar requirements to today's flight planning procedures (e.g. communication of flight plan) and the future negotiation of full 4D business trajectories.

3.1 Theoretical Background

In this section, we introduce the basic elements of our DAS approach, which consists of three major steps: clustering of air traffic movements (fuzzy partition), design of an initial airspace structure using Voronoi diagrams, and optimization of the structure with evolutionary algorithms [1, 2].

3.1.1 Fuzzy clustering

The aim of clustering techniques in general is to find a partition of a given dataset. In a fuzzy partition, a datum is not necessarily assigned to a unique class or cluster. Instead, membership degrees are associated with each datum and each cluster. These membership degrees provide information about the ambiguity of the classification. Fuzzy clustering techniques can adapt to both noisy data and not well-separated classes. Although noise will not be a major issue with radar data of flight trajectories which are initially used for the DAS approach, the clear separation of classes might be difficult.

This and our earlier promising results with fuzzy clustering techniques (see [18]) allow us to choose fuzzy clustering techniques for our DAS approach, which is based on optimizing an objective function. The clustering solution consists of cluster centers, i.e. the center of gravity of a cluster with regards to a characteristic distance function, and membership degrees. For an overview on fuzzy clustering and its applications, see e.g. [18] or [19]. For our approach, we use the fuzzy-c-means clustering [20] that is based on the Euclidean distance measure. The resulting centers are used as initialization for the following structuring with Voronoi diagrams.

3.1.2 Structuring approach: Voronoi diagram

A Voronoi diagram [21] is a possibility for structuring an area, depending on a certain number of so-called center points, into sections where every point belongs to the section with the nearest center point. Edges are created of all points which belong to two center points, i.e. the points of an edge have the same distance to the two center points, and vertices are those points which are associated with three different center points. An area containing all points with the same nearest point is called "face".

At first, faces at the boundary of the area of interest are not limited at their outside. A convex hull is added once the faces have been determined. Often this convex hull simply has the form of a rectangle. A more detailed description of our structuring approach is given in [1]. In Figure 6, the area of Norway is used to derive an exemplary airspace design. Starting with a given traffic sample, seven cluster centers were identified and surrounded by Voronoi

structures. The Voronoi diagram provides an inner structure defined by the blue dots in Figure 6 (right).

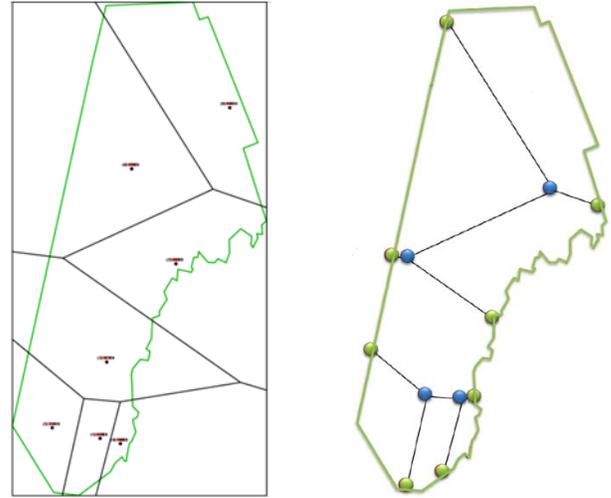


Figure 6 Example of a Voronoi diagram (black) for Norway with seven center points, a square as convex hull (black), country/sector boundary in green. Additional to the blue dots (inner structure), the green dots arise from the intersection of boundaries and edges of Voronoi diagram.

As mentioned before, the application of Voronoi diagrams is limited to areas with a convex hull. In the case of airspace areas, this methodological limitation has to be overcome to provide an operational concept for air traffic control. Therefore, the determination of the initial airspace structure has been extended in such a way that a Voronoi diagram can be adapted to arbitrary boundaries. Hereby, the line-segment-intersecting method was adapted to the problem of intersecting the Voronoi diagram and the boundary of the selected airspace area [1, 21]. Thus, the intersections of edges with the national border provide an additional set of structural elements (green dots) which, together with the blue dots, are subject to the following optimization. Whereas the blue dots could be rearranged inside the boundaries, the green dots can only be moved on the boundary.

3.1.3 Evolutionary Algorithms

The common principles of evolutionary algorithms follow the idea of biological evolution (cf. [22, 23]). In nature, a group of individuals mix their genetic material, especially the information coded in chromosomes, to obtain a better chance of survival in a hostile environment through a higher degree of adaptation. For an evolutionary algorithm, a population of solutions for an artificial problem is coded as sequence (chromosome) of parameters (genes) describing the problem solution. These fundamental principles are transferred to the optimization of a technical/operational environment (cf. [1]). Using a set of available solutions, specific components and parameters are mixed and stochastically mutated to generate a new set of solutions.

The assessment of these new solutions concerning their fitness with regards to an underlying evaluation function

results in a hierarchical order, where the most appropriate solutions are used as the parental generation for the next generation of solutions. In the context of the dynamic airspace sectorization, the idea of evolutionary algorithms is used to optimize the initial airspace structure considering different evaluation functions [1]. These functions are defined depending on the specific research/operational scenario. For the approach of functional airspace blocks, the evaluation function could consider the ANSP productivity (composite flight hours per air traffic controller-hour on duty) or controlled IFR airport movements. Aiming at a harmonized distribution of controller effort in the European network, the evaluation function could include the task load and the variability of task load over the day of operation to efficiently allocate the available expertise.

3.2 Simulation Environment, Tool Chain

The Institute for Flight Guidance of DLR has developed a basic framework of tools which implement the developed DAS concept and enable the creation of a complete new sectorization, considering the current and future air traffic flows and demands.

The new sector structure is dynamically created in three steps (see Figure 7). Firstly, the software tools RouGe (route generator) and PrePro (pre-processor) developed at DLR are used to generate the necessary airspace data (traffic and sector data) based on Eurocontrol’s DDR-2 data, see [24]. In this step, the DDR-2 data are mainly used as a reliable source for air traffic movements. In future operational environments, the air traffic movements will be provided by online ANSP data services, which should consist of historic data (DDR-2), current data, and flight planning data (to predict the air traffic progress). Furthermore, PrePro is used to define the boundary of the airspace area of interest. This could be any connected area of airspace with one continuous boundary (connectedness constraint [17]) independent of national borders.

RouGe uses this boundary generated with PrePro to filter the radar data of the aircraft movements. As mentioned in the theoretical background, the basis for the dynamic airspace sectorization is a combination of a fuzzy-clustering approach (fuzzy c-means [20]) integrated in RouGe, a structure based on the Voronoi diagram [21] and an evolutionary algorithm (EA) [22].

We cluster the air traffic data, use the resulting cluster centers as centers for the calculation of a Voronoi diagram implemented in AutoSec and optimize the resulting diagram (i.e. an initial airspace structure) with the evolutionary algorithm to the air traffic flow [1].

The tool AutoSec uses the inputs from both RouGe (air traffic movements and cluster centers) and PrePro (geographical boundary, smoothed traffic data) to determine an initial sectorization with Voronoi diagrams and optimizes this with evolutionary algorithms.

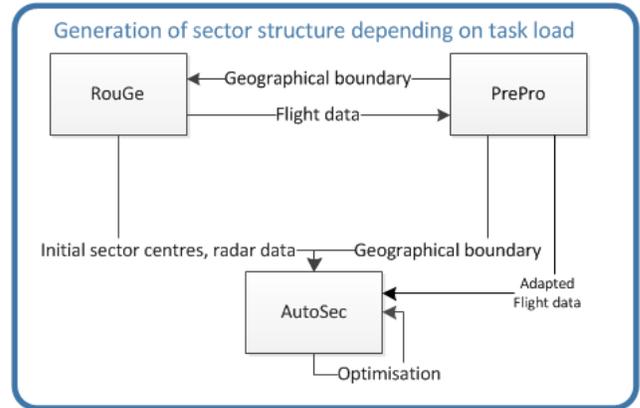


Figure 7 Fundamental structure of framework of tools to create a sector structure (cf. [2]).

3.3 Evaluation Function

The most important and crucial part for our DAS approach is the definition of an appropriate evaluation function for the evolutionary algorithm to optimize the air space structure. Therefore, several evaluation functions with different factors have been comprehensively tested [1] and the following factors were selected for a future application of the developed DAS approach:

- Sum of task load in the investigation scenario,
- Standard deviation of task load (as a measure of uniformity of its distribution),
- Well-formed controlling areas, measured by the standard deviation of interior angles,
- Number of flight intervals caused by the airspace sectors (intersection of flights).

A weighted combination of sum and standard deviation of task load, ideal angle, and number of flights per sector is then used as evaluation function. The calculation is based on a fixed flight plan which remains unchanged during the optimization process. In our investigation scenario, no traffic simulation takes place; operational measurements, such as delay or punctuality, are not taken into account in the evaluation. Including the number of flight intervals per sector indirectly results in avoiding short dwell times of flights in sectors, which is an important constraint seen by several authors for the creation of dynamic airspace sectorizations [25, 26].

Furthermore, the number of flight intervals per sector represents the segmentation of flights over different sectors. The ideal angle is calculated as the sum of standard deviations of interior angles for all sectors related to the optimal mean value of interior angles for the corresponding sector (polygon). Both factors influence the optimization to prefer a more convex structure of the sector. This approach covers the proposed strong convexity constraint, which should be applied to the created sectors to ensure that an aircraft visits every sector

only once. However, today’s operational sectors are not necessarily convex (see Figure 6, green boundary) and our DAS approach is able to handle non-convex structures efficiently.

4. Applications

Within recent work, it was shown that it will be possible to replace ATM experts, who are normally responsible for arranging a system of sectors, with our DAS system, thereby improving the balance of the task load between the observed sectors. For our evaluation experiment, the airspace area EDDYDUTA with four sectors (see Figure 8) was used from flight level 300.

In the first two steps, a Voronoi diagram was created which is shown in Figure 9. The results for the evaluation function for the original sectorization were clearly better than for our start solution with the Voronoi diagram. Nevertheless, when executing the third step and optimizing the start solution, the resulting sectorization (see Figure 10) has much better results for all parts of the evaluation function than for the original sectorization.



Figure 8 Airspace EDDYDUTA with air traffic movements (aircraft trajectories) as blue lines with the current existing sectors. A darker blue color represents a higher traffic density on the trajectories.

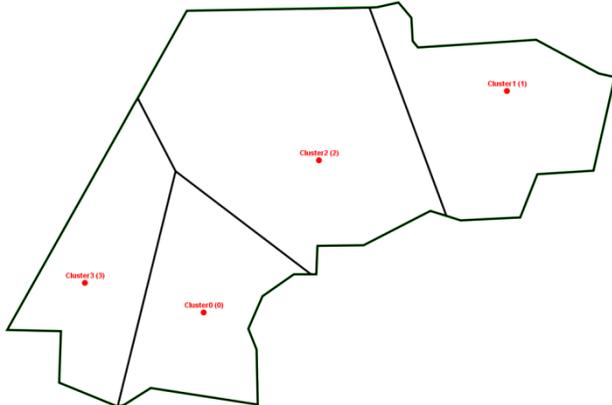


Figure 9 Airspace EDDYDUTA with cluster centers (red dots) as Voronoi diagram adapted to the outer sector boundary.

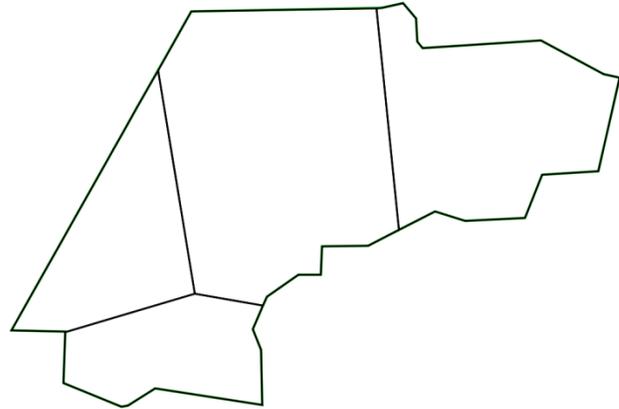


Figure 10 Airspace EDDYDUTA airspace structure after optimization with the evolutionary algorithm.

5. Summary and Outlook

In our paper, we provide an overview of current and future fields of application demanding a dynamic sectorization of controlled airspaces. To enable efficient air traffic operation, we propose a DAS approach considering the air traffic flow (aircraft trajectories) and the complexity of the airspace (measured in controller task load). We implemented three steps to derive the dynamic airspace structure: fuzzy clustering to derive center of gravities for air traffic movements, Voronoi diagrams for initial structures, and evolutionary algorithms to finally optimize the airspace structure with regards to specific evaluation functions.

Using the exemplary airspace EDDYDUTA, we could show that our approach is able to reproduce today’s structure, without bringing in any expert knowledge to the optimization process. It is expected that the aircraft movements used already depend on the current structure and the interdependencies restrict a stepwise improvement of today’s airspaces. Our DAS approach, however, provides a reliable technology for overcoming this limitation and also for enabling scalable concepts ranging from space traffic management to personal air vehicles in urban environments.

To further improve our DAS approach and to proof the concept in the operational controller environment, we have brought our expertise into a new project which is investigating the ecological impact of contrails in comparison to the operational effort needed. In this context, we will provide adaptive airspace structures indicating contrail areas and set up a real-time controller environment to enable an operational interaction between human controllers and our DAS system.

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