Automatic Airspace Sectorisation: A Survey *

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Abstract

Airspace sectorisation provides a partition of a given airspace into sectors, subject to geometric constraints and workload constraints, so that some cost metric is minimised. We survey the algorithmic aspects of methods for automatic airspace sectorisation, for an intended readership of experts on air traffic management.

1 Introduction

Airspace sectorisation provides a partition of a given airspace into a given (or upper-bounded, or minimal) number of control sectors, subject to geometric constraints and workload constraints, so that some cost metric is minimised. We parametrise the concept in Section 2.

Airspace sectorisation is not to be mixed up with airspace configuration, which provides a schedule for the grouping and splitting of elementary sectors into control sectors that are suitable for a given number of available controllers and the expected traffic structure. This survey does not cover papers showing how to compute such sector opening schemes, such as the works of [Barbosa-Póvoa et al., 2001, Verlhac and Manchon, 2005], even though there is an overlap between both problems. Configuration is by definition a (pre-)tactical action, whereas sectorisation is either strategic or (pre-)tactical, depending on the inputs, so that a sectorisation model can in principle be re-used within a configuration model. However, a configuration model also has time variables for scheduling purposes and aims to minimise the total delay over a given time interval, but these temporal aspects are absent from sectorisation. Further, a configuration model includes a transition cost incurred at every switch between configurations, but static sectorisation

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does not consider such a cost. Hence a configuration model is much harder to re-use properly for a sectorisation model, as projecting away time variables and re-configuration costs most likely enables a better model.

This paper is a survey of automatic airspace sectorisation methods. To the best of our knowledge, there is only one prior survey, namely [Zelinski and Lai, 2011], which actually replaces two prior surveys by the first author of that survey. To distinguish our survey from that survey, our survey has the following caveats:

- Our survey is intended for experts on air traffic control (ATC) and air traffic management (ATM) and is thus not self-contained: technical jargon (in use at EURO-CONTROL for instance) as well as the rationales behind existing procedures and investigated research topics are assumed to be known by the reader. For definitions of concepts such as elementary sector, control sector, air traffic control centre (ATCC) = area control centre (ACC), functional airspace block (FAB), ATC functional block (AFB), sector capacity, sector load, etc, see [Allignol et al., 2012] for instance.
- Our survey is written by experts on computing science: no evaluation of the realism of the combination of inputs, parameters, outputs, and experiments of automatic airspace sectorisation tools is made, as that is the realm of ATM experts. See [Zelinski and Lai, 2011] for a comparison of six of the methods discussed in our survey.
- Our survey is only about the algorithmic aspects of airspace sectorisation tools: for instance, we discuss no papers giving only rationales for the constraints and objective functions that can be used in sectorisation.

We do not claim that our survey is complete. Indeed, the literature is growing rapidly nowadays. However, many papers are archived at pay-sites that we (as academic computer scientists from a university without a transportation research centre) have no free access to, so it takes some effort to get hold of these papers. Also, some conferences seem to accept papers that are almost devoid of the technical details that would in principle allow the reader to reproduce the results, so it is hard to compare such papers to the others. Whenever an author (team) has published multiple papers, we examine the most recent publication (that we could find).

The rest of this survey is organised as follows. In Section 2, we introduce the classification criteria used in the survey proper, which is in Section 3. In Section 4, we conclude.

2 Airspace Sectorisation: Classification Criteria

Our survey in Section 3 of the literature on airspace sectorisation is structured around the following classification criteria.

Approach. We distinguish between two approaches to airspace sectorisation.

- In a graph-based model, a graph is constructed whose vertices represent the intersections of the existing trajectories, and whose edges thus represent segments of the existing trajectories. The core problem of sectorisation is then essentially the NP-complete combinatorial problem of graph partitioning [Garey and Johnson, 1979]. A graph partition does not define the sector boundaries, so actual sectors have to be constructed from the resulting vertex sets in a geometric post-processing step.
- In a region-based model, the airspace is initially partitioned into some kind of regions that are smaller than the targeted sectors, so that the combinatorial problem of partitioning these regions in principle needs no geometric post-processing step.

Frequency. Airspace sectorisation can be invoked with different frequencies:

- Static: Sectorisation is strategic or pre-tactical.
- *Dynamic*: Sectorisation is tactical, but occurs at pre-determined times (so as to be different from configuration).

Input Granularity. Region-based models can start from regions of (any combination of) different granularities:

- A mesh of blocks of the same size and shape.
- ATC functional blocks (AFBs).
- Elementary sectors, namely the ones of the existing sectorisation. This leads to a further distinction [Zelinski and Lai, 2011]:
 - Base-line: The output sectorisation should be reasonably close to the input one, usually because the sectorisation is dynamic and bears a transition cost.
 - Free-form: The output sectorisation can be arbitrarily far from the input one.
- Control sectors.
- Area of specialisation (AOS).
- Air traffic control centre (ATCC).

Output Granularity. An airspace sectorisation can be computed at different levels of granularity:

- Elementary sectors.
- Control sectors.
- Functional airspace blocks (FABs).
- Area of specialisation (AOS).
- Air traffic control centre (ATCC).

Dimensionality. An airspace sectorisation can be computed in different (numbers of) dimensions:

- 2D: The sectorisation is only defined (and tested) in two dimensions (longitude and latitude), with the generalisation to 3D being considered to be straightforward.
- 2.5D: The sectorisation is only computed in two dimensions, because layers of the 3D airspace are considered to be independent.
- 3rd D: The sectorisation preserves the 2D boundaries of the input regions but can readjust them in the third dimension (altitude).
- 3D: The sectorisation is computed in three dimensions.

Constraints. Airspace sectorisation aims at satisfying some constraints. The following constraints have been found in the literature, so that a subset thereof is chosen for a given tool:

- Balanced workload: The workload of each sector must be within some given imbalance factor of the average across all sectors.
- Bounded workload: The workload of each sector must be below some upper bound.
- Balanced size: The size of each sector must be within some given imbalance factor of the average across all sectors.
- Minimum dwell time: Every flight entering a resulting sector must stay within it for a given minimum amount of time (say two minutes), so that the coordination work pays off and that conflict management is possible.
- Minimum distance: Each existing trajectory must be inside each resulting sector by a minimum distance (say ten nautical miles), so that conflict management is entirely local to sectors.
- Convexity of the resulting sectors. Convexity can be in the usual geometric sense, or trajectory-based (no flight enters the same sector more than once), or more complex.
- Connectedness: A sector must be a contiguous portion of airspace and can thus not be fragmented into a union of unconnected portions of airspace.
- Compactness: A sector must have a geometric shape that is easy to keep in mind.
- Non-jagged boundaries: A sector must have a boundary that is not too jagged.

For each sector, there are three kinds of workload: the *monitoring workload*, the *conflict workload*, and the *coordination workload*; the first two workloads occur inside the sector, and the third one between the sector and an adjacent sector. The quantitative definition of workload varies strongly between the surveyed papers. In the following, the word "workload" refers to the sum of all three workload terms, but we will specify the actually used workload terms whenever they can be inferred from a paper.

Constraint Types. Airspace sectorisation constraints can be of different types:

- A hard constraint must be satisfied, whereas a soft constraint can be violated, although its satisfaction earns a numeric bonus.
- An *explicit* constraint is part of the model, whereas an *implicit* constraint is enforced by side effect, either because it is logically *implied* by the explicit constraints or because its satisfaction is an *invariant* of the solution process.

Cost Function. Airspace sectorisation aims at minimising some cost. The following costs have been found in the literature, so that a subset thereof is combined into the cost function for a given tool, the subset being empty if sectorisation is not seen as an optimisation problem:

- Coordination cost: The cost of the total coordination workload between the resulting sectors must be minimised.
- Transition cost: The cost of switching from the old sectorisation to the new one must be minimised.
- Workload imbalance: The imbalance between the workload of the resulting sectors must be minimised.
- Number of sectors: The number of sectors must be minimised.
- Entry points: The total number of entry points into the resulting sectors must be minimised.
- If any of the constraints above is soft, then there is the additional cost of minimising the number of violations of soft constraints.

A workload cost results from applying a function to the workload to which it pertains; if this is the identity function, then we talk of coordination workload rather than coordination cost.

Technology. An airspace sectorisation model can be implemented using (any combination of) different algorithm design methodologies or optimisation technologies:

- Stochastic local search (SLS), see [Hoos and Stützle, 2004] for instance.
- Constraint programming (CP), see [Rossi et al., 2006] for instance.
- Mathematical programming (MP), such as integer programming (IP) and mixed integer programming (MIP).
- Global optimisation (GO).
- Evolutionary algorithms (EA).
- Computational geometry.

- Ad hoc algorithm design.
- etc.

Hybrid optimisation technologies are becoming increasingly powerful, witness the hybridisation of CP with SLS [Van Hentenryck and Michel, 2005], called constraint-based local search (CBLS), and the hybridisation of CP with MP and GO [Hooker, 2011].

Test Scale. An airspace sectorisation tool can be tested at different scales:

- Continental: A (large fraction of an) entire continent is sectorised, such as the European Civil Aviation Conference (ECAC) area, or its core countries along the London-Frankfurt-Rome axis.
- AOS: An existing area of specialisation is (re-)sectorised.
- ATCC: An (existing) ATCC is (re-)sectorised.

Test Data. An automated airspace sectorisation tool can be tested on different kinds of data:

- Historical data stem from archives of actual flight data.
- Extrapolated data is computed from historical data according to some forecast of future flight patterns and volumes.
- Artificial data is generated randomly according to some (ideally realistic) model of flight patterns and volumes.
- Simulated data results from fast-time simulations of historical or extrapolated flight schedules.

3 Survey

In the following, we survey the (in our opinion) most important papers, proceeding in chronological order, breaking ties by alphabetic order on the surname of the first author. Unless otherwise indicated, each constraint is hard and explicit. A word flagged with a question mark ('?') means that we think it is correct but found no explicit confirmation for it in the discussed paper.

3.1 [Delahaye et al., 1998]

Criterion	Value
Approach	graph-based
Frequency	(any)
Input granularity	(not applicable)
Output granularity	(any)
Dimensionality	3D
Constraints	balanced workload, minimum dwell time, minimum distance,
	trajectory-based convexity, connectedness
Cost function	minimal coordination workload
Technology	EA: genetic algorithm
Test scale	ATCC
Test data	artificial

This is one of the oldest and most cited lines of research on sectorisation. No quantitative definition is given of the workload of a sector. In the post-processing to the graph partitioning, 3D Voronoï diagrams are used to define precisely the 3D borders of sectors. Problem instances of up to 400 vertices that are to be partitioned into up to 100 sectors are solved in reasonable time.

3.2 [Yousefi and Donohue, 2004]

Criterion	Value
Approach	region-based
Frequency	any
Input granularity	hexagonal mesh, each side of a hexagon being 24 NM
Output granularity	elementary sectors
Dimensionality	2.5D
Constraints	balanced workload, convexity (soft), reasonable average dwell
	time, connectedness, compactness (soft)
Cost function	minimal variation of workload among sectors
Technology	MIP: facility location problem (number of sectors is not fixed)
Test scale	continental: USA; initial experiments are with an ATCC
Test data	extrapolated: TAAM simulation of one day of traffic

Workload is the sum of four components: the horizontal movement workload, the conflict detection and resolution workload, the coordination workload, and the altitude-change workload. The horizontal movement workload is determined by the number of aircraft in a sector and the average flight time. The conflict detection and resolution workload is based on conflict detection using the type of conflict and the conflict severity. The coordination workload is determined by the type of coordination action including voice call, clearance issue, inter-facility transfer, and tower transfer. The altitude-change workload is determined by the type of sector altitude clearance requested. No details are given on how to compute the workload, but the reader is referred to [Yousefi et al., 2003], where more details are given, but the definitions still depend on unspecified adjustment factors. The tool, TAAM, used to simulate the traffic produces workload estimates based on a

model of control workload. The airspace is divided into three layers: FL0 – FL210, FL210 – FL310, plus FL310 and above. No details are given of the constraints and cost function, nor is there any definition of what it means to minimise the variation of workload among the sectors.

3.3 [Tran Dac et al., 2005]

Criterion	Value
Approach	graph-based
Frequency	(any)
Input granularity	(not applicable)
Output granularity	(any)
Dimensionality	2D
Constraints	balanced monitoring + conflict workload, minimum dwell time,
	minimum distance, trajectory-based convexity, connectedness
Cost function	minimal coordination workload
Technology	hybrid of CP and SLS
Test scale	ATCC
Test data	random

Building on the model of [Delahaye et al., 1998] (except that the coordination workload is not considered within the balance constraint), this work develops a CP model (rather than an EA one), introducing propagators for new global constraints and introducing new branching heuristics. The monitoring and conflict workload of a sector is the number of aircraft entering the sector. The coordination workload of a sector is the number of aircraft leaving the sector for an adjacent one. To solve large instances, the problem is solved with a hybrid algorithm obtaining first a good solution with an SLS heuristic and then locally improving the solution with an exact CP formulation on small subsets of the sectors. Geometrical sectors are then built with triangulation techniques similar to the ones used by [Delahaye et al., 1998]. Problem instances of up to 1000 vertices that are to be partitioned into up to 80 sectors are solved in reasonable time.

3.4 [Bichot and Durand, 2007]

Criterion	Value
Approach	region-based
Frequency	static
Input granularity	elementary sectors
Output granularity	ATCCs or FABs
Dimensionality	3D
Constraints	balanced monitoring + conflict workload (within a factor of 2),
	balanced size (within a factor of 2)
Cost function	minimal coordination workload
Technology	SLS: fusion-fission metaheuristic
Test scale	continental: 11 core ECAC countries of Europe
Test data	historical

This work¹ tackles sectorisation at a larger granularity, namely the design of ATCCs or FABs from the existing elementary sectors (along mostly national boundaries), so as to enforce regional cooperation in the seamless management and control of traffic flows in the ECAC zone. The monitoring and conflict workload of a sector is the daily number of aircraft entering the sector. The coordination workload of a sector is the daily number of aircraft leaving the sector for an adjacent one. A novel meta-heuristic, called *fusion-fission* and inspired by the corresponding phenomena in nuclear physics (but described in detail only in a French-medium journal), is shown to be particularly well-suited to solve this problem. It seems to outperform consistently very powerful graph partitioning libraries and outputs FABs that much improve on the coordination workload and imbalance of the current ATCC partition of ECAC.

3.5 [Conker et al., 2007]

Criterion	Value
Approach	region-based
Frequency	static
Input granularity	square mesh, dimension not defined
Output granularity	elementary sectors
Dimensionality	2D(?)
Constraints	equal complexity density across sectors (soft)
Cost function	(none)
Technology	ad hoc algorithm: k -means clustering, with an SLS heuristic
Test scale	continental: USA, west of the Mississippi
Test data	extrapolated: by simulation of traffic patterns based on pre- dicted traffic demands

A combination of two existing tools [Bhadra et al., 2005, Wanke et al., 2004] and specialised algorithms is proposed. The aim is to give a tool chain that assists the semi-automated design of new sectors. The workload is defined in terms of a complexity density metric that is not defined in any detail. For the full definition of complexity density the reader is referred to an unpublished MITRE Corporation memo. The algorithmic phase has three components: a modification of k-means clustering [Lloyd, 1982] to produce an initial sectorisation; a hand-crafted SLS heuristic to improve the workload balance; and straightening of the sector boundaries. Many of the technical details of the algorithms are missing. Much of the effort is dedicated to tool support to allow human experts to assess the given sectorisation. Two tools are described: airspaceAnalyzer, which simulates air traffic controllers to assess the workload balance of the new sectorisation; and sectorEvaluator, which allows experts to assess the quality of a given sectorisation and modify its sectors.

¹This paper is classified by [Zelinski and Lai, 2011] as work on configuration, but we disagree and include it in our survey.

3.6 [Martinez et al., 2007]

Criterion	Value
Approach	combination of graph-based and region-based
Frequency	static
Input granularity	(not applicable)
Output granularity	control sectors
Dimensionality	2D
Constraints	bounded workload
Cost function	minimal number of sectors
Technology	ad hoc algorithm based on spectral clustering
Test scale	continental: USA
Test data	historical: ASDI (aircraft situation display to industry) data

Definitions of workload are not considered in any detail. Instead workload balancing is done in terms of the peak traffic count in a sector based on an unspecified time interval. The constraints and the cost functions are defined by ad hoc algorithms. The algorithm is in three stages: first, flight data is used to construct a network of flight flows that correspond to frequently flown routes; then spatial cells are assigned to nodes of the flow network based on a nearest neighbour, where each node in the flow is weighted by the number of flights passing through that node; finally, the flow network is partitioned into smaller and smaller sub-graphs until all sub-graphs have a workload cost below a certain threshold. Since the partitioning problem is NP-hard, a heuristic based on spectral techniques [Simon, 1991] from graph theory is used.

3.7 [Brinton et al., 2009]

Criterion	Value
Approach	region-based
Frequency	static
Input granularity	square mesh, each side of a square being 1NM
Output granularity	elementary sectors
Dimensionality	2D
Constraints	non-jagged boundaries (soft), bounded workload
Cost function	minimal number of sectors
Technology	hybrid: computational geometry and SLS
Test scale	continental USA
Test data	not specified

The definition of workload is based on dynamic density, of which there are multiple definitions in [Kopardekar and Magyarits, 2002], but the one used in this study is not specified. The algorithm has three stages: an initial clustering of flight tracks to produce an initial air-space partition; a grid-based approach, where grid cells can have zero, one, or many clusters, is used to grow cells containing clusters to candidate sectors; and finally an SLS algorithm is used to simplify or straighten the sector boundaries and to combine candidate sectors while keeping the peak dynamic density below a certain limit.

3.8 [Drew, 2009]

Criterion	Value
Approach	region-based
Frequency	dynamic
Input granularity	elementary sectors: free-form
Output granularity	control sectors
Dimensionality	3D
Constraints	bounded workload, connectedness
Cost function	minimal number of sectors
Technology	MIP
Test scale	ATCC: Cleveland high sectors
Test data	historical

The workload of a sector is the maximum number of aircraft simultaneously present in the sector over a 15-minute interval; it has a sector-specific upper bound called the monitor alert parameter (MAP). The absence of a shape constraint, such as compactness, is noted to lead to convoluted control sectors. The presence of symmetries in the solution space is noted, but no way is proposed to exploit them.

3.9 [Leiden et al., 2009]

Criterion	Value		
Approach	region-based		
Frequency	dynamic: every 15 minutes to	o 24 hours	
Input granularity	one AOS or ATCC: base-line	one AOS or ATCC: base-line	
Output granularity	control sectors		
Dimensionality	3rd D		
Constraints (shared)	connectedness, lower-bounded height (2 FL)		
Constraints (specific)	balanced workload (fixed number of sectors)	(none other)	
Cost function	(none)	minimal number of sectors	
Technology	ad hoc algorithm design: greedy algorithm		
Test scale	AOS or ATCC: USA, above FL240		
Test data	historical		

The workload of a sector is the number of aircraft simultaneously present in the sector over an unspecified time interval; it has a sector-independent upper bound called the monitor alert parameter (MAP). If workload exceeds the MAP, then a horizontal splitting of the sector must be performed, but how to do this has not been investigated yet. The algorithm works in two modes, as indicated in the table above. Either way, the algorithm picks the best solution from a greedy bottom-up phase and a greedy top-down phase through the considered airspace. The transition cost between two sectorisations is the number of aircraft that must be transferred into a new sector; this metric is used for evaluating computed sectorisations, but currently not while computing them. The experimental

evaluation confirms the expectation that capacity increases with the frequency of resectorisation, but also concludes that the transition cost must be built into the constraints or cost function.

3.10 [Li et al., 2009]

Criterion	Value
Approach	graph-based
Frequency	static
Input granularity	(not applicable)
Output granularity	control sectors
Dimensionality	3D
Constraints	balanced workload, bounded workload, minimum distance, con-
	nectedness, compactness
Cost function	(none)
Technology	ad hoc algorithm: spectral clustering, convex hull, shortest path
recimology	(number of sectors is not fixed)
Test scale	ATCC: Atlanta
Test data	historical

The workload of a sector is a weighted sum of its monitoring workload (presumably including the conflict workload) and coordination workload, though it is not made clear how these terms are quantified. Special care is taken in the geometric post-processing step to obtain sectors with smooth boundaries and good shapes. Excellent results are obtained, in the sense that the current sectorisation of Atlanta is outperformed on almost all metrics in both the average case and worst case.

3.11 [Bloem and Gupta, 2010]

Criterion	Value
Approach	region-based
Frequency	dynamic
Input granularity	elementary sectors: base-line
Output granularity	control sectors
Dimensionality	3D
Constraints	bounded workload (soft), connectedness, convexity (soft)
Cost function	minimal workload $cost + transition cost$
Technology	approximate dynamic programming
Test scale	AOS and ATCC: Cleveland super-high sectors
Test data	historical

The workload of a sector is the maximum number of aircraft in the sector during the considered time step divided by a sector-specific upper bound called the monitor alert parameter (MAP). The transition cost between two sectorisations is the number of new control sectors compared to the previous time step. The uncertainty of trajectory prediction is explicitly taken into account. Excellent results are obtained, in the sense that the current sectorisation of Cleveland is outperformed.

3.12 [Gianazza, 2010]

Criterion	Value
Approach	region-based
Frequency	any
Input granularity	elementary sectors
Output granularity	control sectors
Dimensionality	(not applicable)
Constraints	connectedness
Cost function	minimal number of sectors + workload predictions obtained from the neural network
Technology	complete search via branch-and-bound
Test scale	ATCC: five French ATCCs
Test data	historical data

The workload of a sector is defined using a neural network trained on historical traffic data and sectorisations. The work considers combinations of elementary airspace modules to build an optimal airspace partition. The work differs from other papers in this survey in that it uses a neural network to predict workloads of configurations and tree search together with branch-and-bound techniques to explore intelligently all possible combinations of elementary sectors in order to find the optimal combination.

3.13 [Sabhnani et al., 2010]

Criterion	Value
Approach	region-based and graph-based
Frequency	dynamic
Input granularity	elementary sectors: free-form
Output granularity	control sectors
Dimensionality	2D with extensions to 2.5D
Constraints	balanced monitoring + conflict workload, compactness, minimum distance, convexity, and two other operational constraints (see text below)
Cost function	minimal coordination workload
Technology	hybrid: computational geometry, graph theory, and MIP
Test scale	ATCC
Test data	simulated data

The focus is to extend previous work [Mitchell et al., 2008] to build sectors that satisfy controllers (operational criteria). It is argued that while workload balance is an important goal, the validity of the sector shapes is also important. The major operational criteria that are addressed are that: standard flows should cross sector boundaries (almost) orthogonally; critical merge-and-conflict pairs should remain sufficiently inside sector boundaries (minimum distance); no more than three sectors should come together at the same point; and the shape of the sector show be more or less convex. The definition of workload is as in [Mitchell et al., 2008], where three possible metrics are considered: peak workload, which is the maximum number of aircraft simultaneously in a sector; average

workload, which the average number of aircraft present in a sector; and coordination workload, which is the number of instances during an unspecified time interval where an aircraft crosses the boundary of a sector.

3.14 [Xue, 2010]

Criterion	Value
Approach	region-based
Frequency	static
Input granularity	elementary sectors: free-form
Output granularity	control sectors
Dimensionality	3D
Constraints	(all in the cost function)
Cost function	maximal average dwell time; maximal distance of intersection points from sector boundaries; maximal distance of dominant flows from sector boundaries; minimal number of flights with short dwell time; minimal variance of sector peak flight counts
Technology	hybrid: computational geometry and EA: genetic algorithm
Test scale	ATCC
Test data	simulated data

There is no explicit definition of workload. The algorithms use a mixture of computational geometry (Voronoï diagrams) and genetic algorithms with a post-processing step using iterative deepening search to improve the resulting sector designs.

3.15 [Jägare, 2011]

Criterion	Value
Approach	region-based
Frequency	(any)
Input granularity	hexagonal or square mesh (arbitrary size) and AFBs
Output granularity	elementary sectors
Dimensionality	3D
Constraints	balanced monitoring + conflict workload, minimum dwell time, minimum distance, trajectory-based convexity
Cost function	minimal number of entry points
Technology	CP
Test scale	ATCC: Europe
Test data	extrapolated, by ASTAAC

This work is close in spirit to [Tran Dac et al., 2005], but takes a region-based approach (rather than a graph-based one). It also takes a CP approach, but without hybridisation, and also introduces propagators for new global constraints. The monitoring and conflict workload of a sector is the number of aircraft entering the sector. The coordination workload of a sector is the number of aircraft leaving the sector for an adjacent one. The data for the experiments is provided by the *Arithmetic Simulation Tool for ATFCM*

and Advanced Concept (ASTAAC) tool of the EUROCONTROL Experimental Centre. This tool actually pre-clusters some regions into AFBs according to additional constraints (sufficient distance from potential conflicts and trajectories to sector boundaries). Experiments were run on up to a few hundred thousand small regions, to be partitioned into five sectors. In comparable run-times on the same machine, the constraint program produces much better sectorisations than NEVAC Sector Builder, which is a greedy algorithm that comes with ASTAAC (but is unpublished) and considers the trajectory-based-convexity and minimum-dwell-time constraints to be soft and yet does not systematically yield fewer sector entry points. Since two hard constraints, connectedness and compactness, were not implemented yet, the resulting sectors are sometimes disconnected or of highly irregular shapes, so that current air traffic controllers would be very uncomfortable in working with them. The work is currently being revisited with us (who supervised this thesis work), with the following targeted profile:

Criterion	Value
Approach	region-based
Frequency	(any)
Input granularity	hexagonal or square mesh (arbitrary size) and AFBs
Output granularity	elementary sectors
Dimensionality	3D
Constraints	balanced monitoring + conflict workload (soft), minimum dwell time (soft), trajectory-based convexity (soft), compactness (soft), connectedness
Cost function	minimal violation of soft constraints
Technology	SLS: CBLS
Test scale	continental: Europe
Test data	extrapolated, by ASTAAC

3.16 [Kulkarni et al., 2011]

Criterion	Value
Approach	region-based
Frequency	static
Input granularity	hexagonal mesh, each side of a hexagon being 24 NM
Output granularity	elementary sectors
Dimensionality	3D
Constraints	balanced workload, compactness(?)
Cost function	(none)
Technology	ad hoc algorithms: knapsack, set covering, etc.
Test scale	continental: USA, above FL240
Test data	extrapolated, by PNP

The paper completely lacks definitions and algorithmic details. It is claimed (partly in the title) that approximate dynamic programming as well as control theory are involved, but it is not apparent where.

4 Conclusion

Sectorisation would benefit from further modelling in order to adapt better to the design of FABs, taking into account more realistic operational constraints, such as compatibility constraints between upper and lower airspace, and those of [Sabhnani et al., 2010] and [Xue, 2010]. The implementation of airspace optimisations that alter the shape of basic control sectors implies a heavy cost in controller training, as controllers are highly specialised in the management of their specific sectors and it takes several years to qualify them on new sectors. Moreover, the redesign of ATCCs would induce a new dispatch of radar data and probably the building of costly new infrastructures to host them. Contrary to lighter optimisations that only concern current control structures without modifying them, like the optimisation of opening schemes changes in airspace design have very important transition costs and must be very carefully planned.

From an algorithmic viewpoint, a clear conclusion of this survey is that constraints should more often be used in the *process* of computing a sectorisation, rather than only in evaluating the *results* of a sectorisation algorithm. We argue that mature optimisation technologies, such as CP and MP, should be used more often. On the one hand, they offer high-level modelling facilities, so that one can make *explicit* the constraints and cost function. On the other hand, they offer off-the-shelf solving algorithms that operate directly on such models. In other words, there is a clean separation of concerns between the declarative aspect of modelling and the procedural aspect of solving, and highly tuned algorithms can be re-used. Such a plug-and-play paradigm allows a much nimbler prototyping exploration of the algorithm design space, which is crucial in an area such as sectorisation where suitable sets of constraints and cost functions still have to be identified.

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