A PRACTICAL, ROUTE-BASED APPROACH TO AIRSPACE CAPACITY MANAGEMENT

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Abstract

Building on a deployed Air Traffic Flow Management system we focus on published routes as key resources in airspace capacity management, exploring their role in concepts such as linear dynamic density, airside-groundside resource dependencies, exit separation management, CDM, flows, interactive HMI representations of load and system-proposed flow management initiatives.

1 Background

In 2010 Thales delivered its TopSky ATFM (Air Traffic Flow Management) Solution (marketed as FLOWCAT before March 2012) to the South African Air Navigation Service Provider, ATNS, in support of their enhanced ATFM initiative including use during the FIFA Soccer World Cup. The TopSky ATFM Solution monitors traffic load on airside resources such as waypoints, routes, sectors and Air Traffic Control positions having jurisdiction of one or several sectors.

Predictive monitoring of resources enables the early identification of potential load issues and the timely implementation of traffic management initiatives to alleviate them, thus reducing delay, increasing throughput and contributing to improved safety.

A key feature of the system is the ability to conduct real-time, cumulative "what-if" analyses to judge the impact of several traffic management initiatives, such as re-routes and delays, on the load profile of various resources.

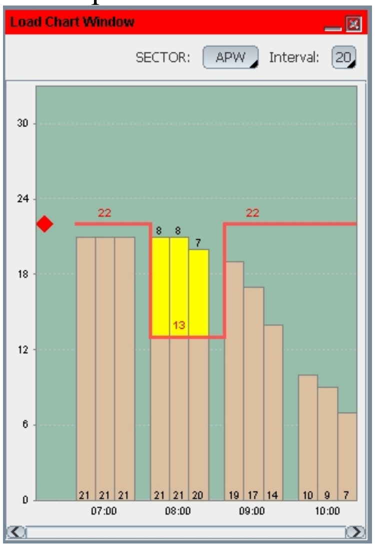

Figure 1: Monitoring load in a sector. The chart updates automatically as flights are delayed or routed around the sector in "what-if" analysis. A pop-up identifies flights in a "bar". "What-if" plays are checked for infringements of aviation separation standards as well as for their impact on load.

Load in sectors of airspace has been the focus of much research, with several dynamic density models being proposed [1]-[3]. Such models attempt to quantify the cognitive load on air traffic controllers by considering factors such as the current and planned manoeuvres of the aircraft under their jurisdiction, their spatial orientation and potential for conflict. However, indicators of sector and position load provide a gross picture at best. There is a need for a set of operational tools that assist in refining broad flow management strategies into concrete tactics that utilise specific resources such as routes.

2 Why Focus on Routes

2.1 Playbooks

Commonly employed re-routes need to be identified and formalised into playbooks that can be used to implement procedures over the long run – such as a set of alternate weather deviation routes.

Playbooks are not only applicable to post-operations analysis. They can also be used during operations as online templates for re-routing individual flights or flows.

Collaborative agreements may allow such re-routes to extend into military restricted areas and neighbouring FIRs (Flight Information Regions).

One of the features of playbooks is to divert excessive traffic from published routes into other sectors to alleviate high demand. However, playbooks cannot address every situation and flow managers should be prepared to create ad hoc routes as necessary.

2.2 Differential Capacity

Routes and feeder fix waypoints are crucial to linking airspace and ground-based resource capacities since realisable throughput is related to downstream constraints – physical, environmental or legislative.

Differential capacity acknowledges that the degree of practical usability of airspace resources such as approach routes, feeder fixes, SIDs (Standard Instrument Departures) and STARs (Standard Arrival Routes) can be constrained by ground-based resource factors such as runway configuration. (To remove some dependencies we assume here that the SIDs and STARs are already de-conflicted to ensure smoother departure and arrival paths.)

In reality, the throughput of an approach sector, say, could be constrained by multiple dependencies on the arrivals and departures at the various aerodromes that it services. Such multiple dependencies mean that the explicit mathematical relationships for differential capacity could be complex and a worthy topic for further research.

A more practical approach is to implement a look-up table of TMA (Terminal Manoeuvring Area) resource capacities indexed by the runway configurations of the major aerodromes in the TMA. We can immediately simplify the model by dismissing smaller aerodromes as contributing only to the higher order terms in a Taylor series polynomial expansion approximating the true differential capacity function.

Figure 2 illustrates the concept for TMA sectors. The table is populated with figures derived from experience and refined during operations to incorporate feedback on the fidelity of the evolving model – i.e. the model is built from data.

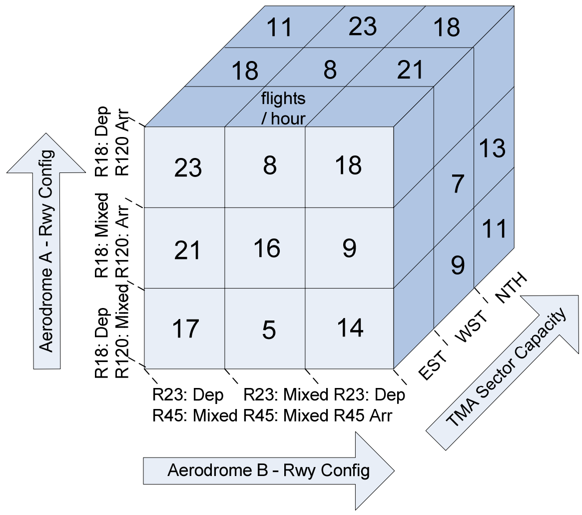

Figure 2: A multi-dimensional cube of gross differential capacities for TMA sectors.

We propose that such models could be extended to specific resources such as major routes and feeder fixes.

It is also worth observing that just as airspace capacity may be dependent on the ground-based runway configurations of the various aerodromes servicing the TMA, so too may ground-based capacities be dependent on restrictions in the overlying airspace.

For example, the early release of reserved airspace that impacts several SIDs may permit the aerodrome departure rate to be increased ahead of schedule. The early departure of flights currently subject to a ground hold needs to be checked in turn to ensure that they do not arrive in TMA or enroute sectors at times of peak load.

Clearly the modelling of capacity-load balancing scenarios must be synchronised between ground-based and airspace resources. Differential capacity highlights the need for integrated what-if modelling.

2.3 Exit Separation

Routes also govern the transition between approach and enroute sectors and the handover to adjacent FIRs. Consider, for example, the exit separation criteria related to a receiving unit's ability to manage inbound traffic. The transferring unit may achieve the required separation by using a variety of techniques (such as speed control along the route) and may impose similar flow restrictions further upstream. In this manner flow restrictions at an exit gate may propagate through much of the airspace all the way back to the departure airport as a ground delay [10].

BOBCAT [17] is an excellent regional example of how to manage airspace gates by allocating ground slots several FIRs distant from the gate. Of more interest to us is an equitable allocation of such ground delays to the various aerodromes departing flights heading for a common exit point – particularly if the flights are under the jurisdiction of different authorities. This is the case, for example, in the Pearl River Delta where the different aerodromes are located in Hong Kong, Macau and the People's Republic of China.

The capacities and utilisation of the various routes to the exit fix are factors in the computation of the delay allocation. These factors are modified during operations by off-route deviations necessitated by weather, congestion and airspace reservations. The problem is complicated by the need to also ensure an equitable distribution of delay amongst airline operators. Ball and Pourtaklo tackle the issue of equitable allocation of airspace resources in [11].

From the perspective of ANSPs (Air Navigation Service Providers) regional ATM (Air Traffic Management) restrictions can be improved through financial and technical assistance which could provide better airspace utilisation. This would be further enhanced through the establishment of a regional ATFM Unit as well as a regional upper airspace control unit.

2.4 Collaborative Decision Making

Airline operators routinely advise their pilots to request changes of level or route from air traffic control in order to optimise flight times. The airline operator may be able to pre-validate the availability and feasibility of such changes by first submitting the request to an automated facility hosted by an ATFM Unit before engaging air traffic control.

Such a scheme would benefit ANSPs as it would reduce the number of re-route requests that have to be manually evaluated and subsequently rejected because they would result in conflict situations.

Airline operators would benefit from improved ANSP responsiveness to re-route requests that have already passed a "first-level" conflict check. Operators would also gain a moderate improvement in their ability to model and optimise their own operations in an environment where constrained resources are shared.

2.5 Network Effects

It is now well understood that local ATFM measures, such as airport CDM (Collaborative Decision Making), imposed on one part of the network modify the traffic observed in other parts of the network.

Eurocontrol has analysed this network effect in detail [6]. It impacts sector capacities, introduces unexpected delays and becomes a key parameter in the decision making process of strategic and pre-tactical capacity planning.

Managing the network effect during the tactical phase usually means reducing the traffic complexity. We believe that routes and associated traffic flows are ideal structures for this purpose.

Some recent research focuses on first simplifying the complex network of actual air traffic routes into major traffic flows (between key city pairs, for example) with the simplified model being more amenable to computational analysis. The final step is to map the results of the analysis back onto the actual route structure. Rebollo and Cruz present an example of this approach for Spanish airspace [4].

Research supported by the Eurocontrol CFMU (Central Flow Management Unit) [7] has demonstrated that analysing the structural limits of the network helps to identify dependencies between different ATM structures. This theory has allowed the CFMU to develop the concept of logical ATFCM (Air Traffic Flow and Capacity Management) functional areas [7] which represent independent ATFCM bodies. Identifying independent ATM structures during the strategic phase is highly beneficial at a tactical level as it ensures that local modifications of such structures have a minimal impact on the overall network.

By applying this theory to the route and flow structures, it is our intention to provide practical tactical tools to enable operational staff to apply local ATFM measures that conform to the dDCB (dynamic Demand and Capacity Balancing) concept currently being developed in SESAR.

Such measures should have limited impact on the network and, used in conjunction with a route playbook, would significantly reduce the possibility of undesirable side-effects, ensuring greater confidence from all actors in the decision making process and speeding up the resolution of local issues without resorting to higher-level mediation.

Another tactic to manage network effects is to propose ATFM actions as early as possible with downstream constraints in mind – as we discuss in the following section.

2.6 Departure Management linked to ATC Slots

As air traffic demand continues to grow upstream demands will become more complex necessitating the application of constraints to ATC (Air Traffic Control) slots in order to achieve holistic network performance.

Constraints of significance to slot allocation in this context include:

- wake turbulence;
- type of aircraft (turbo prop vs. jet);
- airport constraints (parking and terminal capability);
- departure direction after takeoff (left turn, runway heading and right turn);
- runway in use;
- exit separation requirements;
- SIDs and
- routes.

It is proposed, firstly, that the upstream slots would be available or not depending on these downstream constraints and that subsequent slot swaps would also be measured against the constraints.

3 Representations of Route Load

We believe that an intuitive, dynamic representation of load on real (as opposed to idealised [4]) route structures can also deliver utility to flow managers in the pre-tactical and tactical phases of operation.

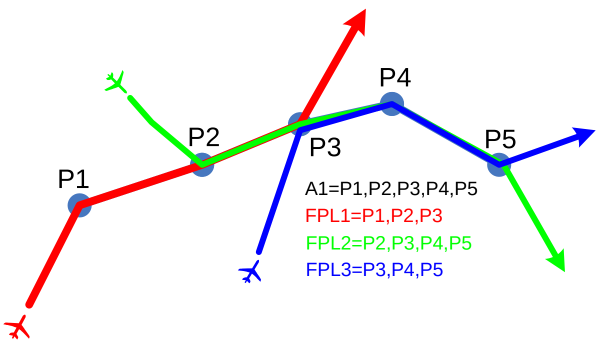

Figure 3: Flights enter and exit the airway at different waypoints. We are interested in both the spatial and temporal distribution of load along a route.

When representing load along a linear resource we are interested in both its spatial and temporal distribution since the use of measures such as speed-control to alleviate congestion at one location along the route may simply move it to another location at a different time.

Graphs are problematic when trying to convey this information. Should a route segment be a flight plan leg or a unit distance? How do you register closely spaced flights that happen to be in adjacent route segments?

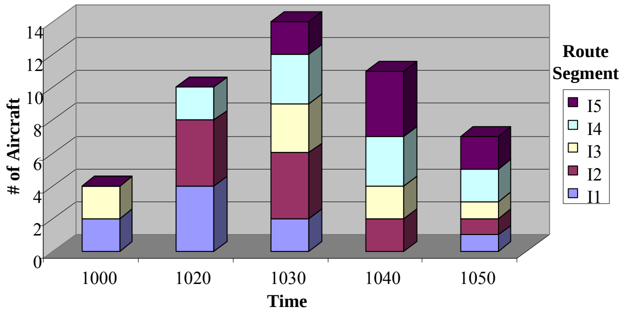

Figure 4: A failed attempt at representing spatial and temporal load information simultaneously. Extensions to 3D to plot time versus unit length versus number of aircraft are even more confusing.

A Future ASD (Air Situation Display) (**Figure 5**) is a more useful *interactive* mechanism than a graph for indicating both the temporal progression of aircraft on a map of the route and the spatial variation of projected load per unit length of the airway.

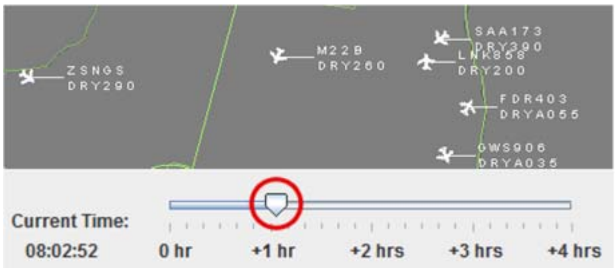

Figure 5: Changing the time variable in "what-if" analysis.

Controllers and flow managers appreciate being able to visualise the spatial orientation of the various flights at a given point in time. A Future Air Situation Display also allows us to indicate aircraft density and potential longitudinal conflicts as heat maps segregated by altitude band.

Considering how to represent future load leads to a discussion of how to accurately predict it in the first place.

4 Predicting Future Load

ATFM systems commonly predict traffic volumes through flight plans filed over the AFTN (Aeronautical Fixed Tele-communications Network) or extracted from a database of RPLs (Repetitive Flight Plans). This leads to a conservative estimate of future demand as airline operators may be late in filing their intentions over the AFTN and not all operators submit RPLs.

Some authorities are considering the use of OAG (Official Airline Guide) schedule data to supplement incomplete RPL databases. Other schemes call for a fixed baseline to be established via the analysis of historical data. Some residual inaccuracy is inherent in all such proposals.

We contend that there is a more pragmatic approach than constructing such representative traffic load models. The suggestion is to simply toggle the demand load bar graph (**Figure 1**) between our best future prediction given the available data and recent historical demand. For example, the graph could plot future predicted demand vs. historical demand data for the last week within the same time frame or the average for the last three months of data. Using a rolling, recent historical snapshot allows us to track seasonal variations in traffic patterns and provides the flow manager with a comparative traffic forecast tool that can be used to improve decisions in the real world without the effort of attempting a perfect prediction of load.

Of course, predicted demand firms up as we approach the tactical phase of operations. However, our objective in capacity-load balancing is to plan an equitable load for the air traffic controller as early as possible (preferable pre-tactically) so that upstream actions can alleviate potential downstream problems such as spikes in load. Early prediction via comparison with recent historical data assists in this regard.

Future load is predicted in the necessary absence of any surveillance data and this impacts how we compute dynamic density.

5 Dynamic Density along a Route

For the last 40 years various studies have been undertaken to describe the relationship between controller workload and ATC complexity. It is acknowledged that the problem is not yet solved and that mastering the human factors aspect remains a major challenge in defining a model of cognitive complexity [8].

We decided to tackle the issue differently and focused our work on the representation of the complexity measure, rather than analysing the validity of the model itself.

5.1 Constructing a Basic Dynamic Density Model

Dynamic density is simply the weighted sum of several judiciously selected complexity factors:

$$DynamicDensity = \sum_{i=1}^{N} \alpha_i \times factor_i \qquad 1$$

To construct a basic model for this exercise we first presented to a panel of three experienced former air traffic controllers several dynamic density formulae from various sources, including [1]-[3], and asked them to select those complexity factor terms within them that they judged to be of greatest operational significance.

Engineers then pruned this selection, rejecting factors that were too complex to be computed in real-time and, more importantly, rejecting those that rely on surveillance data for their computation. Wherever feasible, factors relying on surveillance-derived data were modified to use filed flight plan information instead. For example, for a factor that considers the difference in altitude on entry to and exit from a sector, the Mode C transponder value would be substituted by the Exit Flight Level (if available) or the Cleared Flight Level.

This overcomes the restrictions imposed by some studies [16] and permits our dynamic density model to be applied to predicted load as well, which, in our opinion, is more useful for practical ATFM purposes even if the accuracy of the model is impaired as a result.

5.2 Representing Dynamic Density

Our work then concentrated on representing these complexity factors graphically. Early attempts at a 3-D representation were rejected by our panel of experts and we determined that a 2-D bar chart is just as relevant for displaying route load – *limited to the entire extent of the route per unit time* - as it is for displaying sector load.

With reference to the relationship between ground-based and airspace resources developed in section 2.2 Differential Capacity we are keen to retain the same unit of measurement (number of flights per unit time) for load on all resources even when using dynamic density concepts. This permits a direct comparison of all resources, for example between load on a route and the aerodrome arrival rate. Our representation of dynamic density therefore retains the basic “number of flights” metric.

Since several sector-based dynamic density concepts remain applicable to routes, our representation annotates the basic “number of flights” metric with a colour-coded identification of the key factors contributing to the computation of linear dynamic density. We do not attempt to display a single, computed number for dynamic density corresponding to the value of **Equation 1** as this has limited value for controllers and flow managers.

Initial human factors modelling with our panel of experts indicates that an appreciation of which dynamic density factors (such as climbing and descending aircraft) are at play in a particular load bar, and an identification of the aircraft making a major contributing to these factors, is of more practical value in making an assessment of cognitive workload (as opposed to traffic load).

In the conceptual graph represented in **Figure 6** therefore:

- The length of the bar represents the number of flights in that time bin.
- The colour-coded segments at the bottom edge of each bar represent the *relative* contribution of specific complexity factors to the overall value of the dynamic density metric. For example, if a weighted factor α_i x $factor_i$ contributes 20% of the value of the computed dynamic density for the bar then its colour-coded segment could have a length 20% that of the bar. Other permutations are also possible.

- The sub-graph of aircraft identities at the bottom right of the graph is invoked for a specific colour-coded segment on a bar and indicates which aircraft contribute to the factor that the segment represents, for that particular time bin. It may also be possible to compute the *relative* contribution of each aircraft to the value of the factor.

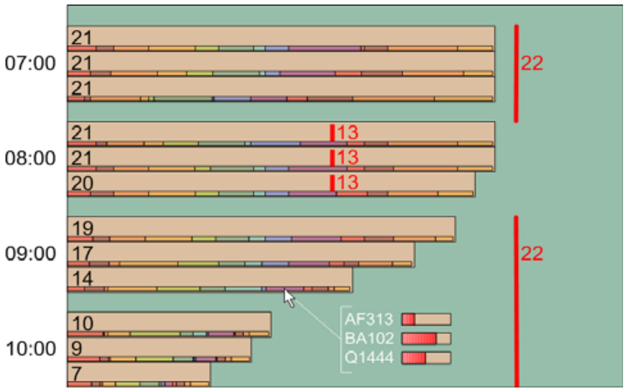

Figure 6: A display of Dynamic Density that attempts to preserve factor information for explanatory power. Colour coding indicates contributing factors. Note the identification of the individual flights contributing to a selected factor (lower right).

5.3 Introducing Dynamic Density Themes

Acknowledging the fact that complexity is context specific, we added the capability to switch between different offline-defined sub-sets of complexity factors (essentially different dynamic density formulae):

$$DynamicDensity(Theme_j) = \sum_{i=1}^{M \le N} \alpha_i \times factor_i \qquad 2$$

The complexity factors grouped into each sub-set correspond to a particular theme. Typical themes include:

- Aircraft count and density.
- Aircraft proximity and potential for loss of separation.
- Aircraft manoeuvres (speed variations, altitude transitions etc.).
- Airspace structure (sector geometry and volume for sector load or route length, RNP status, odd/even direction etc. for route load, number of aircraft in proximity to the sector boundary, handoff workload, etc.).

Themes are not disjoint – composite themes can be constructed that draw on the factors utilised in other themes. Specialised themes can be constructed for current traffic that utilise surveillance data for greater fidelity.

Individual controllers and flow managers can switch themes online in order to tailor their view of the capacity-load situation to individual circumstances. However, keeping in mind that most dynamic density studies originate in the US and Europe, our intent is to use the theme mechanism to explore organisational and cultural preferences for the evaluation and representation of workload. We anticipate that the use of themes will increase the flexibility and adaptability of our solution in the Asia-Pacific market.

More detailed human factors analysis is required before such an analytical tool can be deployed operationally. It is hoped that the use of themes and the what-if modelling mechanism will help us to understand the user's subjective interpretation of each complexity factor in different contexts. This aspect is lacking in most studies which reduce dynamic density to a single dimensionless metric. We are confident that tackling this task for a linear resource first will be simpler than doing so for volumetric sectors.

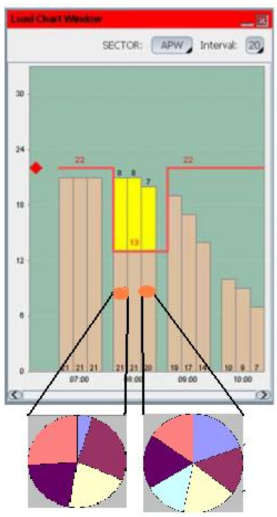

Figure 7: An alternate representation of Dynamic Density.

As **Figure 7** illustrates, we intend to explore alternative representations of dynamic density (such as pie charts or spider charts), but for now the basic mechanism for further study into the underlying human factors has been established.

Figure 8: HMI human factors analysis being conducted at the Thales CASIA™ (Centre for Advanced Studies in ATM) laboratory in Melbourne, Australia ©. Picture used with permission.

6 Flows

Many flow management initiatives are applicable to aggregate flows of aircraft rather than to individual flights.

Automated aggregation and clustering techniques can be used to identify traffic flows during post-operations analysis and for strategic airspace design. As the demand for flexible use of airspace and user preferred routing grows however, tools for the real time identification of flows will become more important.

Several criteria may be specified by which to group similar flights into aggregate flows for collective action, such as the weather deviation shown in **Figure 9**. Of interest is specifying grouping criteria that accommodate minor variations in individual routes while identifying any common exit and re-entry points along the original routes.

To meet this need today, we propose simple and intuitive flow selection criteria with a base level of automation supplemented by a manual mechanism for the graphical selection of multiple flights. The use of the interactive ASD for flow visualisation and re-routing, together with the what–if function supports the mental models (planning, implementation and monitoring) employed by flow managers and controllers [8].

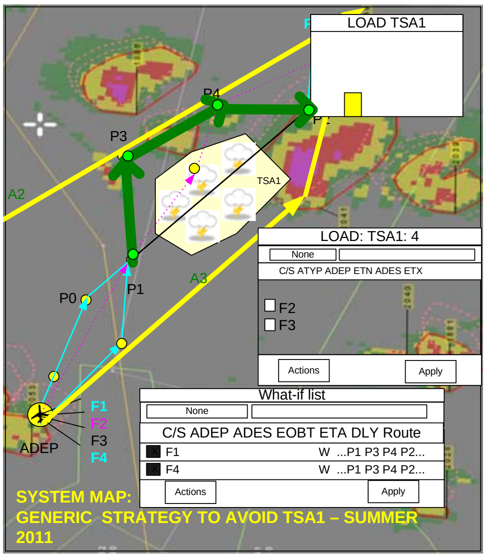

Figure 9: Identifying and routing a flow of four aircraft around a thunderstorm.

The graphical display of the re-routed flows presented in **Figure 9** can be overlaid with user maps indicating possible ATFCM measures agreed in a previous phase of the CDM process.

7 System-proposed Load Balancing Measures

Identifying flows is an important precursor to system-proposed flow management initiatives. Simple measures warn of resource overloading on flight plan filing or modification. We are more interested in system-proposed resolutions of capacity-load imbalance problems.

The TopSky ATFM Solution has a basic CORA (Conflict Resolution Advisory) function for re-routing flights around moving thunderstorms (with predicted heading and speed) and around any flight plan conflicts. An iterative perturbation algorithm governs the generation of delays and alternate routes in a similar manner to the Dynamic Airspace Re-routing Tool presented by Klein and Cook in [12]. Each proposal is then subject to ATM-grade conflict probing to ensure that it resolves the original conflict and does not give rise to new ones.

We seek to enhance this algorithm to consider not only ATM separation standards, but also the load being added to the alternate resources being proposed by the system. In this manner we will be able to generate automated resolutions to capacity-load imbalance problems to complement the current manual modelling capabilities.

Severe imbalances call for a re-sectorisation (the reallocation of pre-defined physical sectors of airspace to ATC controllers) or the use of more modern dynamic sectorisation techniques (the online redefinition of sector boundaries [15]). The automated generation of optimal sectorisation plans has been studied before (see, for example, [14]). Here we propose solutions for less severe problems using a finer resolution that focuses on specific resources such as routes.

Human factors are an important consideration here as well. Following the advice of Eurocontrol [13] we wish to take a "controller-informed" approach to avoid issues with controller acceptance if the computational algorithms lack intuitive appeal due to any mismatch with the controllers' innate heuristics.

8 Probabilistic Extensions

In this paper we have considered the trajectory computed by the TopSky ATFM Solution to be an exact prediction of aircraft position. We believe that this is a reasonable approximation for most ATFM purposes. This premise can be explored by modelling short-to-medium term aircraft dynamics as linear stochastic differential equations driven by a Brownian motion forcing term (uncertainty growing linearly with time).

To apply such a stochastic model we need to determine a unit length by which to uniformly partition the route, taking care to preserve contiguous coverage around waypoints. Such a route surface model is shown in **Figure 10** with colour-coding depicting the predicted, probabilistic density along the route.

Figure 10 also highlights two specific stochastic trajectories terminating in ellipses that represent 99% confidence bounds of the positional uncertainty. For this particular simulation run, the model has computed a 78% probability of loss of separation between this aircraft pair in that segment of the route pointed to by the arrow.

Such probabilistic averages may illustrate potential phenomena that are not apparent from consideration of the nominal (noiseless) trajectories alone. Applications for strategic planning can be readily imagined (modelling airspace structure, determination of resource capacities etc.); however other sources of uncertainty – in particular weather and schedule variations [9] - are likely to predominate in the pre-tactical and tactical phases of ATFM and human-in-the-loop simulation is recommended to determine the utility of probabilistic metrics in this context.

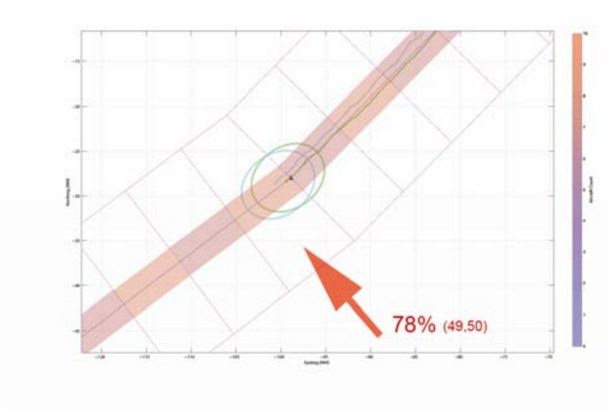

Figure 10: Stochastic aircraft densities and specific trajectories illustrating a 78% probability of loss of separation in the indicated segment between aircraft "49" and "50" of the simulation.

The Brownian motion model is admittedly simplistic and laboratory simulation did not yield good results for look-ahead times longer than an hour. Higher-fidelity models could be used, although the authors are wary of the performance impact on a deployed, real-time system. See [10] for an example of an aerodynamic point-mass model applied to multiple aircraft.

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