FULL AUTOMATION OF AIR TRAFFIC MANAGEMENT IN HIGH COMPLEXITY AIRSPACE

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EXECUTIVE SUMMARY

This document contains the findings from a thesis on full automation of Air Traffic Management in high complexity airspace.

Starting point is a literature review that covers research on automation since the late 1960's up to today and extracts the essentials in the fields of academic studies, prototype development and operational implementation in a single overview. It is found that almost all historical approaches are only by tactic aircraft conflict detection and resolution by neglecting the planning parts; the solutions that solvers produce turn out to be counterproductive whilst the human is in the loop and without availability of data link; some of the underlying mathematical models in some solvers are performing very well concerning conflict cluster resolutions when tasked with unrealistic situations but lack realism for modelling the overall air traffic management with all its constraints; and solvers hardly emulate human behaviour so that solutions are often not accepted by the air traffic controllers.

New work on automation must therefore go beyond tactic resolutions and instead integrate all levels of tactic planning where the focus shifts to 'planning for capacity' and 'planning for resolution' and also – but not only – for 'resolution'. The thesis is then formulated as follows:

Full automation of en-route Air Traffic Management in high complexity airspace can be achieved with a combination of automated tactic planning in a look-ahead time horizon of up to 2 hours complemented with automated tactic conflict resolution functions.

That sets the scene to the most challenging environment and the question arises whether full automation is worthwhile the effort. Therefore a business case is constructed with the help of a qualitative cost-benefit study that compares a do-nothing scenario with three automation levels: low-medium-high. The outcome is that safety, capacity, growth and herewith also return on investment are considered best for full automation; whereas investment cost, transition time, feasibility risk and jobs per flight are considered its weakest parts as well as the special cost of a contingency fallback system that is necessary for full automation. This makes it most probable that full automation when it comes will be a continuous transition from increasingly automated human-centred systems, and the decision in its favour will depend on the weights that society gives to the different performances at a moment in time.

The theoretical part of the thesis is on planning under uncertainties. Planning is a psychological process of thinking about the activities required to create a desired goal on some scale and as such is a fundamental property of intelligent behaviour; automated planning is therefore a non-trivial task. That difficulty is further aggravated if the system under consideration is of non deterministic nature as is the case for air traffic, where a view on the system within a look-ahead time horizon of up to 2 hours is inherently incomplete. The incomplete view, also termed partial observability, of the system is caused by the uncertainty of its predicted states like e.g. unknown meteorological conditions, unknown flight delays, unknown airline behaviour, unknown airport and centre capacities, unknown military activities etc. It is therefore useful to conceive a theoretical model which abstracts specificities of planning in Air Traffic Management into a generic planning model. This model is baptised the Planner-Strategy-Plan-Action model.

In the Planner-Strategy-Plan-Action model the planner is the intelligent function that produces plans. For that purpose it uses optimisation processes to plan for the achievement of a goal with minimal cost. The strength of the model is that we can name the strategies that planners may apply to plan in the 2 hours look-ahead time horizon, because these are different strategies from the fields of tactic capacity measures and tactic traffic control. Strategies use different system components on which they apply a wide variety of different actions. This document enumerates strategies for the mentioned planning time horizon, then lists the system components that strategies act upon, and further identifies a long list of possible actions that each strategy could use in its portfolio of possible actions.

Uncertainty is an intrinsic property of to the ATM system and therefore central to the concept of automated planning. Hence, the stochastic part of the system must be understood and modelled, which sets specific constraints for robust planning. A robust plan is stable during its implementation even if some of the underlying assumptions that lead to the plan turn out to be wrong. A plan can also be regarded stable if it only needs some temporary correction and can then be continued to be executed. The planners require a capability to observe uncertainties in the planning time frame and to evaluate the impact on the plan. With bad planners uncertainties translate into unstable plans, where planned actions often change. We elaborate a concept where the planned action itself has a stabilising property and call it vulnerability; the planners can then accommodate to uncertain system states or limited observability by choosing appropriate actions in the right context.

The result of the Planner-Strategy-Plan-Action concept is on two levels:

1. A generic model for planning under uncertainty is presented (Figure 1) that identifies the abstract objects and their relations. We believe that this enriches the current literature for automated planning.
2. Many mappings between the generic model and applications in air traffic management are listed, giving numerous examples of existing and new components of the model.

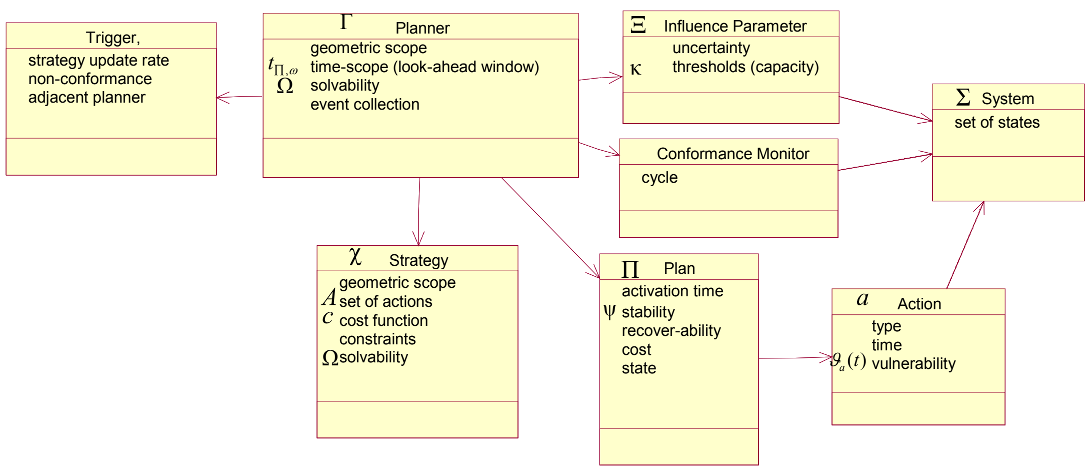

Figure 1: Model for Planner-Strategy-Plan-Action Concept

The second main part of the thesis is comprised of smaller self-containing works on different aspects of the concept grouped into a section on complexity, another on tactic planning actions, and the last on planners:

Two studies on complexity both analyse aircraft conflict situations, because the initial understanding is (was) that solving conflicts is a main success factor of automation systems and it would therefore be useful to have a better understanding of conflicts. One work is an empirical analysis of conflicts based on multiple underlying real and simulated data and creates statistics of conflicts in Europe, resulting in a much better knowledge of statistical distributions of conflicts. The other work shows with graphical analysis based on simulation that conflicts occur in geographical clusters. Even if this knowledge sounds evident at least for operational staff it is yet clarifying the real geographical areas where flows are in conflict instead of showing conflicting pairs as points, which is often the case. Now it can be shown how conflicts are locally clustered, and we conclude that the mission of automatic solvers is the local resolution of clusters or otherwise called bottlenecks. This will lead to a strategy for planning that will be called the 'Organisation of Bottleneck Traffic'.

The next group of studies treats actions that a strategy such as 'Organisation of Bottleneck Traffic' could possibly apply if the objective is to manoeuvre traffic in a time horizon of 5 to 30 minutes.

Tactic clearances can hardly be used in this planning horizon and herewith also tactic solvers are not useful; instead, other actions must be evaluated that could be used for planning solvers – yet we are still acting on individual deterministic aircraft and not on stochastic flows. The candidate actions are speed control, lateral offset, and tactic direct-to. The studies present mathematical fast time models and simulations to evaluate the benefit of the manoeuvres in highest density airspace in Europe. The models have been implemented in one of the best fast time simulators on the scene and are available for other users, so that the verification of the outcome of the studies is possible. Also the setup of the simulations is state-of-the-art using a full airspace model reflecting European traffic and procedures including constraints like letters of agreements etc. The result from the simulations is that speed control and lateral offset are very well performing regarding conflict resolution under uncertainty; whereas direct-to is less performing. I.e. that planners in that time frame dispose of three powerful actions for solving bottleneck clusters with very nice properties regarding uncertainty. We are proud to announce that the speed control and lateral offset studies were first of kind.

Another study focussing on possible new actions is targeting a strategy for ‘Workload Balancing’ by using dynamic sector reshaping to adapt the airspace to fit to the demand. This strategy is to be seen in the context of semi-automation, but it paves the way towards higher degrees of airspace specialisation that could also be part of full automation like segregated automation airspaces. The paradigm is to segregate airspace around bottlenecks with the underlying rationale that not all bottlenecks are at the same level of magnitude at the same time, and therefore airspace portions can be shifted from a lesser active bottleneck to another active bottleneck resulting in balanced controller workload. The airspace design for this study is conducted with a group of sector controllers and supervisors, and the outcome is an innovative airspace design principle supported by tools and simulations which shows that the produced airspace is operationally meaningful and has higher capacity.

The last group of studies relates to planners that apply optimisation techniques to implement strategies. The strategy is on workload balancing with the use of dynamic airspace in order to specialise and segregate airspace. Two studies are developed that can be distinguished by different levels of granularity of their respective building blocks: One treats optimisation of de-collapsing and collapsing sectors as known in today’s Centres; this study explains which steps are necessary and which data to be collected and computed in order to create a successful sector opening schedule, or a plan, for a day. The other study treats fine granular dynamic sectorisation and uses optimisation algorithms for the composition of sectors from atomic building blocks at decision times in the day and creates a plan for the day, where the composition criteria are based on simulated complexity measures. The first study was validated and resulted in new design principles for an operational airspace layout which is currently in implementation in a Centre. The second study on fine granular dynamic sectorisation is also used for new airspace layout drafts, but has not yet reached a level of confidence so that new airspace could also be designed with this method. However, regarding planning with optimisers we have gained new knowledge about workload-balancing as a strategy as well as the implementation of different optimisation techniques because for one study we developed a mathematical complete enumeration method based on Linear Programming, whereas for the second study we implemented algorithms for optimisation. In addition this experience of optimisation for planning did strongly influence the Planner-Strategy-Plan-Action concept to concentrate much more on uncertainty and stability of plans.

In conclusion of this thesis we can say that full-automation will not be reached but an additional contribution into the direction is made. We also state that planning processes for ATM become clearer and can be explained with the generic Planner-Strategy-Plan-Action concept treating planning under uncertainties in Air Traffic Management. Next, the examples given to illustrate this concept will hopefully help to understand the relatively new domains of pre-tactic and tactic planning by enumerating many known or other innovative strategies and actions that can be used. Last not least, manoeuvres like speed control and lateral offset will possibly find their place in operations even when applied as usual clearances because of their very high resolution capabilities under uncertainty.

At the time of finishing the thesis we already start using its findings for a project on automated pre-tactic planning and are looking forward to operational validation of the above mentioned concept.

> *It is not knowledge, but the act of learning, not possession but the act of getting there, which grants the greatest enjoyment.*
>
> *Carl Friedrich Gauss*

Key Words

- Robust Planning under Uncertainty
- Optimisation
- Speed Control
- Lateral Offset
- Dynamic Sectorisation

1. INTRODUCTION

The overall ATM system is evolving, its social, economical and technical environment is changing: The European and world wide traffic is over the years continuing to grow at rates above 3% - 4% per year in the European core area, airlines suffer acid competition and adapt to new travel concepts, the major European airports operate at their capacity limit and will increasingly encounter environmental and other societal constraints, the role of the military has changed, and, finally, the European air navigation service providers operate in a business oriented network with a complete change of the institutional paradigm during the last decade. These changes put very high pressure on the performance of the current and future Air Traffic Management (ATM) system concerning safety, security, capacity, economics and the environment.

One key to the resolution of this problem is automation. Historically, the biggest structural changes due to automation have been introduced in the aircraft with the continuing and ongoing reduction of pilots in the cockpit. Also on the ground ATM system many functions are already partly automated and supported by networked information technology like flight planning in the Central Flow Management Unit (CFMU). However, the function of Air Traffic Control (ATC) has hardly evolved, even though continuous attempts in research have been undertaken for partial automated support - yet the vision of full automation belongs to the domain of science fiction.

1.1 History

Research, development and implementation of automation in ATM have a long history. This chapter presents a brief historical overview.

There is some research that can be classified as pre-historical, not because of its quality, but due to the very early attempts for conflict resolution: TU Eindhoven [1], AERA[2], AIRPAC [3], and CAPE [4] are very early works on conflict resolution, which in principle already cover the entire problem set i.e. integration of planning layers and difficulty to implement conflict detection and resolution algorithms.

STCA[1] was first introduced in Maastricht in 1980. Since then it has been in operation and is deployed at many ATC centres in the world. It has highly contributed to the overall safety of the air traffic control system.

TCAS[2] is operational since 1986 when it was installed and certified on a B-727. Since

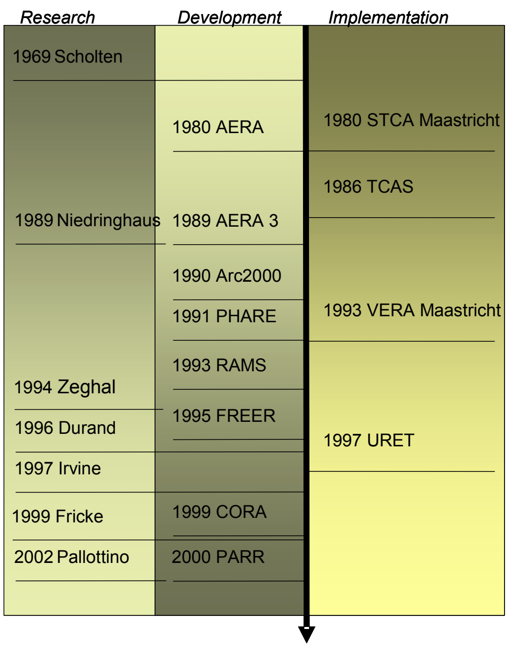

Figure 2: History of CD & R

[1] STCA – Short Term Conflict Alert

[2] TCAS – Traffic Alert and Collision Avoidance System

then it has been progressively mandated. It has highly contributed to the overall safety of the air transport system.

The initial big AERA[3] project was downgraded into 3 phases from which AREA 2 created the URET[4] platform (see below). AERA 3 was targeting for full-automation and implemented some basic algorithms for conflict resolution. The project has been abandoned in 1989.

VERA[5] is a Maastricht tool and operational since 1993. The controller selects a pair of possibly conflicting aircraft. The tool then visualises the selected aircraft with a rubber band between the current positions of the aircraft, and adds icons for the future minimal displacement distances at the predicted aircraft positions. In its early implementation it also provided resolution advisories that have since then been disabled because of too high inaccuracies in the prediction conflicts and hence constantly changing resolutions and advisories.

Arc2000 [5] was conducted in the early 90s in the EUROCONTROL Experimental Centre based on the paradigm of full-automation of ATC. It assumed high precision 4D trajectories. The project resulted in a fast-time demonstrator that comprised a conflict resolution function. The project has been abandoned in 1995 with relatively poor output, but the school has highly influenced following projects.

ERATO[6] is a prototype for a controller working position that was conceived by the French research centre for civil aviation since 1990 [6]. Its underlying concept is the result of research in cognitive engineering, in order to design tools to assist the controller while maintaining a mental picture of the traffic. The two main tools are a traffic filtering function that hides aircraft from the air situation display, and an agenda that visualises potential problems triggered by MTCD[7].

PHARE[8] is the mother of all 4-D trajectory control concepts and was run by European research headed by EUROCONTROL during the 90s (1989 to 1999) [7]. It included en-route and arrival management, full air-ground integration, conflict detection and highly interactive conflict solving (but no automatic resolutions), and multi sector functions for traffic smoothing. The impact of the project cannot yet been estimated, but it can be supposed that many of the ideas will re-emerge once trajectory-based control becomes common practice in ATC centres. The algorithmic part in PHARE was relatively simplistic due to the strong assumption of full 4-D trajectory control and herewith little interest for investigations on how uncertainty must be managed. Successfully demonstrated were several HMI[9] implementations like the highly interactive problem solver (HIPS[10]) and the tactical load smoother (TLS[11]); the proof of feasibility for 4-D FMS[12]; and of sophisticated arrival managers.

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[3] AERA – Automated En-Route Air Traffic Control

[4] URET – User Request Evaluation Tool

[5] VERA – Verification of Separation and Resolution Advisory

[6] ERATO - En-Route Air Traffic Organizer

[7] MTCD – Medium Term Conflict Detection

[8] PHARE – Programme for Harmonised ATM Research in Europe

[9] HMI – Human Machine Interface

[10] HIPS – Highly Interactive Problem Solver

[11] TLS – Tactical Load Smoother

URET [8] is an American platform developed by MITRE that is in operations and implements conflict detection together with some basic advisories. It comprises a prototype function for resolution advisories: PARR[13] [9]. PARR provides conflict resolutions for all six degrees of freedom and ranks solutions by some internal cost criteria. The controller is presented with the ranked solutions and may chose to implement one.

RAMS[14] [10] is a fast time simulator that was initially developed by the EUROCONTROL Experimental Centre in 1992 and since 1997 is held by a small company. It is one of, if not the most complete ATC/ATM model simulator. It comprises constrained based trajectory control based on aircraft performance data and a rule base system for conflict resolutions together with a very rich model for ATM. When resolving conflicts it cares about various constraints like airspace, letter of agreement etc. in order to create feasible trajectories. The solver in RAMS recursively scans the airspace in each sector for conflicts, by using the sectors' separation definition and the trajectory profiler which compiles all airspace constraints into trial trajectories. Further it applies case based reasoning built on an expert system for the selection of manoeuvres; is capable to manoeuvre aircraft in all 6 degrees of freedom; and knows several types of manoeuvres to apply the case base reasoning. These functions contrast with many other demonstrators for conflict resolution and create higher credibility. It will be the tool of first choice for this thesis.

FREER[15] [11] is a project from the EUROCONTROL Experimental Centre from 1995 that transposes the conflict detection and resolution into the cockpit, either fully autonomous, today called self-separation (and other self-something like self-merging, self-sequencing); or co-operatively with the ground. The FREER project as such is stopped but has evolved into many projects for air-ground co-operation and since then an impressive pedigree of publications, prototypes and life-trials has been produced.

DAG-TM[16] [12] by NASA is the American counter-part to FREER. Conceptually it is the predecessor for the current (2008) paradigm in research that integrates trajectory-based control on one side with autonomous aircraft on the other, by providing several concept elements that are complementary and sometimes also competitive. Both FREER and DAG apply the same paradigm when regarding conflict detection and resolution or other automation, which is partial or full decentralisation of the controller functions into the flight deck, with decision support tools for conflict resolutions and other manoeuvres to the cockpit, where part of the community advocates human-out-of-loop decisions. This work will (have to) be continued with the venue of unmanned cockpits or other UAV[17]s.

CORA[18] [13] is a project from EUROCONTROL from 1999 to 2004. Its objective was to provide a support tool to en-route controllers in the area of conflict resolution. Similar to PARR it gives a ranked list of conflict resolutions and what-if visualisations for the implementations of the manoeuvres. The main focus of the

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12 FMS – Flight Management System

13 PARR - User Request Evaluation Tool, Problem Analysis, Resolution And Ranking

14 RAMS – Reduced Mathematical Model Simulator

15 FREER – Free Route Experimental Encounter Resolution

16 DAG TM – Distributed Air Ground Traffic Management

17 UAV – Unmanned (uninhabited) Aerial Vehicle

18 CORA – Conflict Resolution Assistant (project)

project was the man-in-the-loop approach where the computer would provide controllers with solutions that the humans would also favour. The project has produced some prototypes in real-time simulation platforms, with limited functions for the what-if options, yet nice user interfaces, but with very poor algorithmic support.

There is a long list of works for the algorithmic and mostly academic research about conflict resolution. In the historical overview we will only mention those which we believe are key with regard to innovation or impact.

Scholten [1] has the merit to be the first lecture found on the issue and possibly at that moment in time solving a problem that did not yet exist. His work is already giving a complete geometrical description of conflict geometries. The major part of his thesis is dedicated to a semi-optimal solver, where he already tests encounters with 8 aircraft heading on the same point. As if this was not enough he is also the first to experiment with an ‘attracting-repelling’ algorithm, and assumes that the combination of both might be very useful.

Niedringhaus [14] developed the mathematics and heuristics for the AREA and AERA3 projects. The ‘Manoeuvre Options Manager’ contains the solver baptised ‘Gently Strict’. His approach is a geometric solver for both (multi sector) planning and tactic resolutions. The virtue of this work is to consider uncertainty for the conflict detection, by using conflict probabilities with probability distribution functions, and already defining the term conflict probability baptised ‘possiblems’. The solver, however, is not based on uncertainty reasoning as far as we understand it. The work is possibly also the earliest to treat conflict clusters using some graph theory. Being part of the big AERA projects his work has enjoyed high visibility.

Zeghal’s [15] field method uses the concept of attractive and repulsive forces between aircraft and objects, treating them as ‘charged particles’, similar to Scholten. Only level flight and horizontal plane manoeuvres were considered in this initial study i.e. there were no vertical climbs or descents. His thesis is usually considered as the foundation of the attractive-repulsive families of solvers.

Paielli [16][17] in the NASA team around H. Erzberger contributes to the development of CTAS[19], which is an arrival manager (that we have put out of scope in the historical review). The long list of scientific publications as well as the impact on the discussion about automation-against-human-centred approaches should be honoured in this thesis. The particular interest of the work is due to its implementation status and herewith the need to tackle the real requirements that emanate from uncertainty. The overall work also comprises some resolution algorithms for sequencing problems and recently also other conflict resolutions.

Durand and Alliot [18] work on conflict resolution is using Genetic Algorithm for an optimisation of resolution manoeuvres in order to minimise a global multi-criteria cost function encompassing the total number of manoeuvres, the delay due to manoeuvres and the resolution duration. GA[20] are stochastic optimisation techniques developed in the mid-‘70s that mimic natural evolution, with the astonishing property to find good solutions quickly which are often close to the global optimum. The solver is very powerful for conflict clusters and shows to find near to global optima: the conflict detection does treat uncertainty and the solver is capable for vertical as well as horizontal cases; the multi-criteria cost function first resolves the conflict clusters, and then continues to optimise the other parameters

[19] CTAS – Centre TRACON Automation System

[20] GA - Genetic Algorithm

(manoeuvres count, delay, and resolution duration); after the GA solver has found solutions these are further locally optimised with a hill-climber algorithm. Of uttermost interest is the capability of the solver to find the times at which an action is executed on the flights, i.e. it creates an optimised plan of clearances!

Irvine [19] develops an algorithm for a solver that works with recursions of trajectory modifications and conflict detections, which scans the airspace for conflict free trajectories. It takes uncertainties for the conflict detection and the resolution into account; the trajectory profiler is built on a simple yet realistic aircraft model; and the solver would be capable to use other better components e.g. from online systems. The algorithm itself is forward chaining and therefore not optimal in the sense of a global minimum of some costs, but is yet a very powerful solver for conflict clusters in all dimensions.

Fricke [20] represents work from the air-to-air domain that incorporates a geometric conflict resolution model enriched by a risk assessment through probabilistic position error distributions. The computation of both own-ship and intruder trajectories are based on detailed navigation models with complete mathematical description. The use of the probabilistic risk assessment improves the accuracy of short-term conflict detections, reduces the number of unnecessary resolutions and therefore creates resolutions with higher robustness. This probabilistic detection model is since recently used in operational STCA implementations.

Pallotino [21] stands for newer works on geometric resolution techniques using a mathematical optimisation based on MILP[21] which have become possible by improved computing times in the optimisation engine (usually Cplex). The technique consists of defining 1. one or more decision variables, 2. a cost function, and 3. many constraints in the form of linear (in-) equations. E.g. the decision variable that one is interested in are all heading changes of aircraft to optimally resolve a horizontal encounter; the cost function is to find the minimal sum of all deviation angles, and the constraints are all geometrical constraints to avoid conflicts or speed constraints etc. If the problem can be formulated with the linear equation system, then the optimisation engine will find the optimum provided it is not too computing intensive. Even some problems that are known NP-hard can nowadays be solved by this method when programming is smart.

The historical overview above is a subjective selection of works on conflict resolution, possibly from a European viewpoint. Note that we did not select other advances like enhanced flight data processing and multi radar tracking [22], OLDI[22]/SYSCO[23] and CPDLC[24], or arrival mangers. Especially the latter are very interesting for conflict detection and resolution, and also for traffic organisation.

The previous section was partly supported by two useful literature reviews, see [23][24].

The discussion in the next section targets issues from the historical overview to further formulate lessons learnt.

[21] MILP – Mixed Integer Linear Programming

[22] OLDI - On-Line Data Interchange

[23] SYSCO - System Supported Coordination

[24] CPDLC – Controller Pilot Data Link Communications

1.2 Discussion on Historic Approaches

From the historical view emerge a number of discussion points:

- Human in/out of loop: Most projects for conflict resolution retain the human in the loop and aim at providing decision support tools. However, if a medium-term implementation is envisaged, then they suffer from the almost unavailability of data link to communicate clearances automatically to the pilot, which means that the controller is supported during the solving phase but not for the implementation phase e.g. by visualising possible solutions. The implementation phase, however, is much more workload-intensive than the solving phase and air traffic controllers (ATCO) find that these tools add to their workload rather than relieving them. Also, these projects usually suffer from an additional complexity that is to provide solutions in a way humans would expect them or at least accept them. However, very little work is known to us that take this aspect into account and it seems that rarely cognitive solutions or at least expert-based solvers are used but instead geometric solvers, which to our knowledge leads to negative feedback from the users.

  It is therefore suggested to:

  (1.) Enforce the full implementation of data link (which is not in our power) or evaluate alternatives;

  (2.) Develop solvers that in some way represent human behaviour or at least implement an expert rule base.

- Solvers: The list of works on solvers is much longer than presented in the overview and often provides cumbersome reading. Newer reviews and studies try to categorise the work, but no comparison is available yet, nor are best practices worked out. The best solvers show impressive capabilities to solve artificially constructed conflict clusters but there are only a few that implement an airspace model so that more realistic behaviour can be validated. Especially the current trend for mathematical optimisation with a renaissance of geometric models suffers from an intrinsic lack of realism at the presented level of modelling. Also the importance of the optimisation of tactic conflict resolution vis-à-vis a non-optimal resolution is not clear: of course it will be better to try to optimise, but the final value of a solver might lay in other parameters, e.g. workload etc. The presented works rarely consider uncertainty for the conflict detection and resolution, which is yet one of the most important properties of conflicts.

  It is further suggested to improve the realism of the solver model and ease the comparative validation by:

  (3.) Using a full airspace model in which the solvers must satisfy constraints other than the conflict constraints only;

  (4.) Modelling uncertainty for future predictions of traffic and airspace;

  (5.) Using a validation environment for the solver that is widely used and accepted.

- Control versus planning: Traffic that is conflict free is undoubted the most important success parameter of an automation system. With the exception of AERA all other presented historical automation approaches do target tactic conflict resolution as the solely function to achieve automation; with the exception of Durand's solver no other solver issues time plans for optimal resolutions in time. This means that the planning component has been neglected in the past and all focus been on the tactic and instantaneous resolution. However, there are a number of actions that can be planned and executed well in advance in order to minimise the number of tactic conflicts to be solved. Also these planned actions can be other than manoeuvring individual aircraft: sectors can dynamically change to balance workload, flows can dynamically be rerouted to organise traffic inter and intra sector, flows and flights can be organised for higher and safer flow densities etc.

(6.) It is further suggested to use the entire planning functions of the air traffic management system to provide for conflict-free traffic as a complement to tactic conflict resolution.

1.3 Thesis

Conclusion of the discussion is that when considering automation of ATM in high complexity airspace we will go beyond tactic resolutions and instead integrate all levels of tactic planning. The central idea of the thesis will be to investigate the usefulness of extended planning with additional planning functions and actions. The key word will be 'planning for capacity' and not only - but also - 'resolution'. Further we will try to base the work on realistic models concerning traffic uncertainty, and traffic- and airspace models. We will also work on the classical conflict detection and resolution models, but beyond this investigate other functions that are crucial to planning i.e. the description of planning and the actions that can be executed at a time etc.

The thesis can then be formulated as follows:

Hypothesis: Full automation of en-route ATM in high complexity airspace can be achieved with a combination of automated planning in a look-ahead time horizon of up to 2 hours complemented with automated tactic conflict resolution functions.

The benefits of full automation are assumed to be significant additional overall system capacity and safety.

1.4 Outline of Thesis

The thesis is devised into the following sections:

Section 1 is the introduction containing the literature review and the formulation of the hypothesis.

Section 2 defines the scope of full automation as treated in this document. The term complexity is explained for a better understanding of full automation in high complexity airspace. The model of layered planning is used to scope the look-ahead time frame; and other scoping is done e.g. vis-à-vis cockpit automation and multi sector planning. The section ends with a detailed qualitative cost-benefit analysis for full automation.

Section 3 presents the theoretical part of the thesis by the definition of the strategy-planner-plan-action concept. The outcome is a generic abstraction model for planning under uncertainties which should be valid for all planning domains also outside of ATM. The model is linked to ATM for important properties of the model, and the section contains many tables that list and rank ATM object in regard of usage of the abstraction model.

Sections 4 comprises smaller self-containing works on different aspects of the concept grouped into a section on complexity, another on tactic planning actions, and the last on planners:

Section 4.2 on complexity analyses aircraft conflict situations, because the initial understanding is that solving conflicts is a main success factor of automation systems and it would therefore be useful to have a better understanding of conflicts. One work is an empirical analysis of conflicts based on multiple underlying real and simulated data and creates taxonomy of conflicts in Europe. The other work shows with graphical analysis based on simulation that conflicts occur in geographical clusters justifying a new planning strategy baptised 'Organisation of Bottleneck Traffic'.

Section 4.3 presents studies that treat actions that a strategy such as 'Organisation of Bottleneck Traffic' could possibly apply if the objective is to manoeuvre traffic in a time horizon of 5 to 30 minutes. Tactic clearances can hardly be used in this planning horizon and herewith also tactic solvers are not useful; instead, other actions must be evaluated that could be used for planning solvers – yet we are still acting on individual deterministic aircraft and not on stochastic flows. The candidate actions are speed control, lateral offset, and tactic direct-to. In order to compare these with the performance of currently used clearances there are two studies carried out to maximise the fast time solver for the traditional manoeuvres. The studies present mathematical fast time models and simulations to evaluate the benefit of the manoeuvres in highest density airspace in Europe.

This section also contains a study focussing on possible new actions targeting a strategy for 'Workload Balancing' by using dynamic sector reshaping to adapt the airspace to fit to the demand. The paradigm is to segregate airspace around bottlenecks with the underlying rationale that not all bottlenecks are at the same level of magnitude at the same time, and therefore airspace portions can be shifted from a lesser active bottleneck to another active bottleneck resulting in balanced controller workload.

Section 4.4 presents studies that relate to planners that apply optimisation techniques to implement strategies. The strategy is on workload balancing with the use of dynamic airspace in order to specialise and segregate airspace. Two studies are developed that can be distinguished by different levels of granularity of their respective building blocks: One treats optimisation of de-collapsing and collapsing sectors as known in today's Centres; this study explains which steps are necessary and which data to be collected and computed in order to create a successful sector opening schedule, or a plan, for a day. The other study treats fine granular dynamic sectorisation and uses optimisation algorithms for the composition of sectors from atomic building blocks at decision times in the day and creates a plan for the day, where the composition criteria are based on simulated complexity measures.

Section 5 is a short introduction about technical enablers for full automation.

Sections 6 summarises the findings and concludes the thesis.

2. AUTOMATION

The formulation of the thesis in the section above sets the scene to the most challenging environment. This section scopes the concept of full automation in high complexity airspace by applying different viewing angles on the concept e.g. the definition of complexity; the differentiation of complexity levels by airspace complexities; setting the boundaries to cockpit automation and multi sector planning etc.

Further the question arises whether full automation is worthwhile the effort. Therefore a business case is constructed with the help of a qualitative cost-benefit study that compares a do-nothing scenario with three automation levels: low-medium-full.

2.1 Definitions and Scope

2.1.1 Airspace and Traffic Complexity

Throughout this document we will use the term ‘complexity’ and therefore give some explanatory words on the understanding of this term with the objective to give some ideas and lessons learnt from the work with this vocabulary from the last years.

The term may be confusing because it is used as synonym for different things, e.g.:

- ATCO understand complexity as difficult situations that fall outside of their routine and present some challenge. The challenge might be of different origin like e.g. special cognitive difficulty, but also trivialities like non-adherence to procedures, exceptional communications etc. Example: Slow climber through all flight levels at the airspace boundary that will clip the next sector which comes once a day maximum whilst military activity is on. The example illustrates that ATCO definition deals with exceptional cases.
- Flow Managers (FMP[25]) understand complexity as the part of controller workload additional to aircraft counts and which is generated by the coexistence of particular traffic flows in volumes, or by specific airspace conditions like weather or military activity. Example: A sector has a specific capacity *C* unless departure flows *AAAA* and *BBBB* cross at the same time or *MIL* is active. Flow complexity treats nominal cases.

  It is interesting to note that there is no scientific literature and no models for flow complexity.
- The currently agreed (by science) definitions (from science) about complexity define sets of parameters from an analysis of the air situation: number of flights in volumes, number of climbs and descents, number of potential interacting flight pairs etc. The underlying idea is to find *the* direct relation to controller workload. Traffic complexity treats nominal cases.

  The current definitions for traffic complexity are given with the references in the literature reviews figuring in the studies about complexity in this document [4.2, 0].

[25] FMP – Flow Management Position

- Workload models are the most holistic and congruent ones and attempt to capture most of the above by using knowledge of airspace state, airspace procedures and equipment levels and more to model reality as close as possible. The most sophisticated workload models emulate cognitive states of the human. The tools can model nominal and exceptional cases. Usually fast time simulators are used for modelling workload.

Throughout the thesis and if not mentioned explicitly we use ‘complexity’ as one of the above and as synonym for workload, or traffic density.

2.1.2 Automation and Airspace Complexity

ATM is a heterogeneous environment. The possible levels of automation depend on the domain of application i.e. at the airport, the TMA, or en-route. From a top-down view the total automation of the entire ATM system is impossible and cannot be wished because there are many and sometimes contradicting business processes involving necessary human interactions to satisfy the clients, e.g. passengers at airlines, airports, military etc. Further, we will set airport land and air side out of scope because other research deals with it. Furthermore, the terminal control area (TMA) will be scoped out, even though it often contains high-complexity airspace. This is a voluntary decision to downscale the scope, and the remaining part will still be large enough; though, many of the principles that figure in this work are also applicable for the TMA. This leaves us with the en-route ATM system.

The scope is on automation of en-route ATM.

A possible categorisation of automation in ATM can be given by using airspace complexity as discriminator for the aforementioned domains of airports, TMA and en-route. Each domain has different levels of complexity e.g. there are airports with varying complexity, TMAs with varying complexity etc. Also in the en-route domain we can distinguish between different levels of airspace complexity, and these induce different levels of automation. For the purpose of this introduction we will not go into deeper detail of the definition of complexity; instead it will be sufficient to associate high complexity with high traffic load.

Domain	Airspace Complexity	Automation Concepts
En-route	Low	Single frequency reporting
		ACAS[26]
		ADS-B[27] See and Avoid
		Basic Ground Based CD & R[28]
En-route	Medium	Low-Automation **+**
		Airspace Development with P-RNAV[29]
		Improved flight planning
		ASAS[30] / ADS-B
		Advanced Ground Based CD & R

[26] ACAS - Airborne Collision Avoidance System

[27] ADS-B – Automatic Dependent Surveillance

[28] CD&R – Conflict Detection and Resolution

[29] P-RNAV – Precision Area Navigation

[30] ASAS – Airborne Separation Assurance System

		Medium Automation **+**
		Advanced dynamic airspace planning
		Advanced dynamic route planning
		Pretactic and tactic planning
En-route	High	Tactic flights organisations

Table 1: Automation and Airspace Complexity

Table 1 lists possible ATM concepts that would enable automation as a function of airspace complexity.

Low complexity airspace e.g. in remote regions or at night time when airspace is almost empty does not require ATM at all. This can be experienced in operations over large parts of the world where it is sufficient (by practice) to be equipped with ACAS or to make repetitive voice position reporting on the same R/T[31] frequency. ADS-B See and Avoid procedures will increase the safety under these circumstances. Also ground-based solutions could be envisaged here; however, the ground-based resolution advisories require sophisticated CNS[32] infrastructures to be in place together with intelligent functions. Common to all automation measures for low complexity airspace is the assumption that there is a very small risk for clustered problems where it would be difficult to find solutions with the simple means that are provided by the listed ATM concepts.

Medium complexity airspace would require conceptual enablers like improved airspace development that structures the flows in a way that they cannot conflict; improved flight planning functions that would prevent that two aircraft are at the same place at the same time; and air- or ground-based automatic conflict detection and resolution. A good example for airspace development that incorporates 'separation by design' combined with flow constraints is an emergency plan for an ATC centre (e.g. [25]). For such a plan to work without human intervention it could be envisaged to create a contingency layout where flights are separated e.g. through specific flight level allocation schemes; and where there are specific constraints at the entry of the human-out-of-loop airspace like sequencing rules. This could possibly be achieved through very precise flight planning and sophisticated sequencing by the adjacent airspace. Then also ASAS procedures for sequencing and merging could support this concept by applying self-merging, self-sequencing and self-separation before entering the airspace. If airspace can be reserved only for ASAS operations, then eventually even (very) high density but yet low complexity can be tackled like highways. The same function could also be implemented with centralised ground-based systems. Medium level complexity airspace should have sophisticated CNS infrastructures in place that are required for the ground-based solutions. The CD & R algorithms must be at the same level as for ASAS i.e. still low provided that the risk of clustering is still low.

All previous measures for low and medium complexities could be seen as simple local problems with a local solution, where individual aircraft pairs are treated without affecting surrounding flights, where risks of clustering and knock-on effects can be neglected, and where single resolution manoeuvres have no impact on the overall system performance. Higher traffic densities and airspace complexities, however, will no longer permit to treat the problem locally and must in contrary raise it to a higher context; they require some qualities of higher degree than the previous measures. Instead of treating conflict pairs a much higher importance is given to

31 R/T – Radio Telecommunication

32 CNS – Communication, Navigation, Surveillance

conflict clusters with preferably optimal resolutions. In addition, the spatial and temporal horizons are enlarged by treating several hotspots possibly over several sectors. Instead of looking just a few minutes ahead it will have a sufficient time horizon to look ahead for events to come and have the time to react in an orderly way i.e. events are not individually treated but instead collected to work out meta-local plans. Combining several elements into a common problem solution and to plan them over a wider time horizon is called a strategy. It is the goal of strategies to achieve meta-local optimisation regarding flow densities and separation.

The strategy consists of a number of parallel or sequential plans where each plan consists of designated sequences of actions. There will be strategies for dynamic airspace as well as for dynamic flow and flight management. All will lead to a higher level of organisation of the system with the effect on higher levels of traffic organisation.

The scope is on high-complexity airspace.

The scope is on strategies.

The scope is on planning.

2.1.3 Cockpit Automation

Automation of the cockpit is continuing with the current venue of one-man cockpits and UAVs. As long as there is a pilot in the cockpit this has no immediate effect on air traffic control but unmanned cockpits will have impact because communications with the ground will most probably require data link; and at least initially they require reserved airspace. There will be another impacting issue and that is the distributions of plans: It is safe to assume that unmanned cockpits will have more planning intelligence than the simple flight plan or trajectory in order to be able to autonomously end a mission even without guidance from the ground, similar to unmanned spacecraft. This might lead to synchronisation problems with centralised plans from ATC. Nevertheless, we believe that there will be enough time to tackle these issues should they really arise.

Unmanned cockpits are out of scope.

2.1.4 Automation-Level

Automation can be characterised by the degree of which the human is in the loop as a decision maker or not. The steps from the ‘manual’ ATC to full automation are depicted in Figure 3. The non-automatic state is thought of to be a typical modern ATC equipment with sophisticated controller working positions visualising digital air situation pictures and providing intensive support for procedural control, i.e. eventually no strips etc. Once upon a time this was considered as a high degree of automation, now we take it as the baseline for further automation. The first step in automation includes alerts of all kinds that are generated by probes, e.g. STCA, MTCD and other monitoring aids. The second step is with the help of decision support tools that are generated by predictors, like occupancy predictions, workload predictions (WLM[33]), minimal distance prediction (VERA) etc. The following next step is advisories like ACAS, OPTICON[34], CORA, and ERATO. At this step the human is presented with the tactic plan but his or her main task is to acknowledge

[33] WLM – Workload Monitor

[34] OPTICON – Optimal Configurations Tool

or reject the proposal; and then has to implement the tactic plan. E.g. the pilot follows the ACAS resolution advisory by piloting the aircraft; the sector supervisors implement the configuration schedule by giving input into the flight data processing system; the controllers implement the proposed conflict resolution advisory by submitting sequences of clearances to the pilots; and the controllers execute the action plan from a to-do list. The next higher step is by solvers. These systems implement the solutions that are presented, and the only task that is left to the human is to accept or reject the plan and its implementation. There are no examples of implementers neither in operational nor prototype ATC. Implementers are mostly easy to develop and have the supplementary benefit of avoiding human input error. Full automation is then the next logical step by taking the human out of the loop.

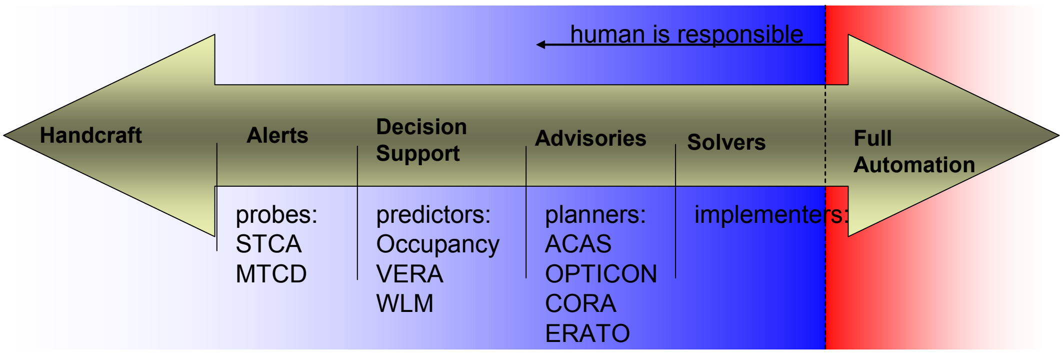

Figure 3: Automation Levels

There are two interesting side effects to the automation transition scheme. First is the question of the ATCO situational awareness, which is increased with visual tools but the more the equipment fulfils complicated functions, the harder it is for the human to understand the proposed behaviour: humans and machines neither share the same skills nor situational awareness. In general it is the human who adapts to the equipment because on one side the technical solution is generally the better one when it comes to highly complicated combinatorial problems beyond human intuition (think of a chess computer), and on the other side it is technically very difficult to programme computers so as to mimic specific ATCOs or other operators of the system and to follow human 'logic' knowing that each controller reacts differently to situations. The second effect of interest which is also linked with situational awareness is the question of responsibility. The more decisions are supported with equipment the smaller the human's responsibility should be which implies that the responsibility must be assumed by the operator of the equipment. In reality, however, it is often supposed that as long as the human takes the final decision it is also him or her who is responsible. This would mean that even when using solvers the controller would be responsible. To assume responsibility the decision must be taken under full consideration of contextual circumstances, which is not possible without situational awareness. This could be called the automation-responsibility paradox.

2.1.5 Look-Ahead Time Scope

In the research for improvements of the ATM system there is a paradigm shift ongoing which integrates asynchronous and synchronous air traffic services ([26][27][28][29][29][31][32][33][34][35]). This consists of a number of operational and technical improvements at the boundaries between the deterministic and the stochastic parts of the ATM system. In simple words it means that flow and capacity management becomes more tactic on one side; and air traffic control becomes more strategic on the other side; with the specific problem of treating uncertainties originating from the look-ahead timeframe up to 2 hours. Figure 4 depicts the imbrications of the different layers and adds some detail in the look-ahead time horizon of up to 2 hours.

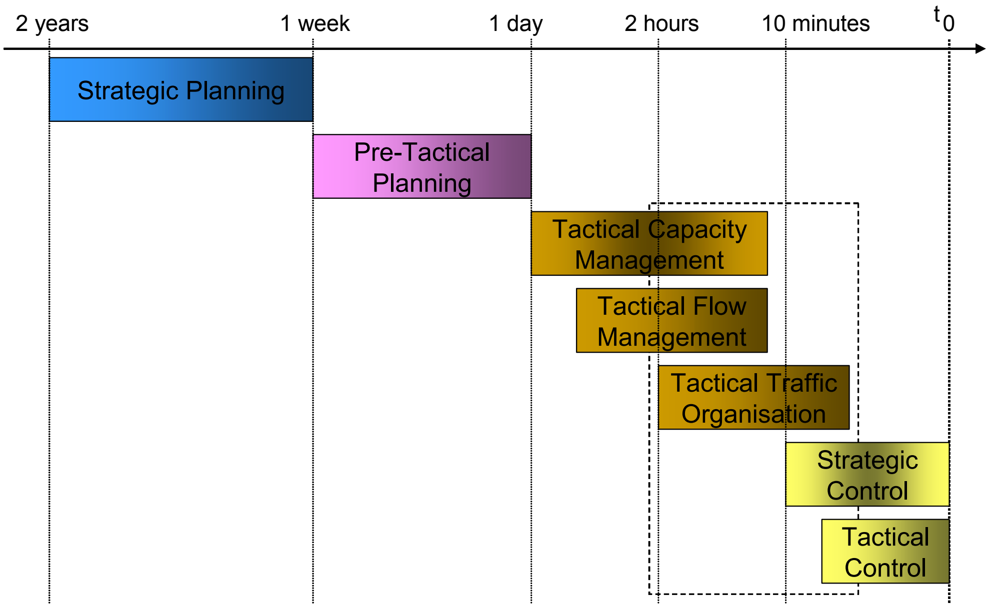

Figure 4: Layered Planning Model

- Strategic planning consists of diverse actions that the different stakeholders in the ATM system may plan and has typically the life-cycle of a business plan. The time span differs depending on the stakeholders e.g. planning of airport extensions or military airspace can take decades, of a new sector may take 2 years, of routes some months, of commercial flights 1 year etc.
- Pre-tactic planning is currently under evolution and is also becoming both more predictive and reactive; e.g. the NOP[35] for a centre is gradually refined as more information like military activations, weather, staff availability, and traffic predictions becomes available. This information is compiled into a first plan of the day with pre-tactic regulations, staffing and sector opening schemes. New tools will soon support this function with what-if simulations to improve the quality of the planning. The feedback from the online system is via statistics of the past weekday, or compilations from a longer time period. The typical output from pre-tactic functions is a plan that contains staff availability, shift schedules, sector configuration schedules, military schedules, airspace use plans for conditional roots etc. and the pre-tactic regulation schedule.
- Tactic Capacity Management (TCM[36]), Tactic Flow Management (TFM[37]) and Tactic Traffic Organisation are three functions treating the centres' operations room for the ongoing day. They all aim at improving and adapting the plan so as to guarantee or increase announced capacity regarding the sum of foreseen and unforeseen constraints. The principles of dynamic aspects of TCM and TFM

[35] NOP – Network Operations Plan

[36] TCM – Tactic Capacity Management

[37] TFM – Tactic Flow Management

have been outlined in the MANTAS[38] Basic Operational Concept [36]. Figure 5 shows the trend for TCM. Full automated planning is the last step of a normal evolution, where we will show in the studies below that the difficulty to develop optimised plans is such that only optimisation tools can solve it so that the role of the human is naturally and gradually diminished.

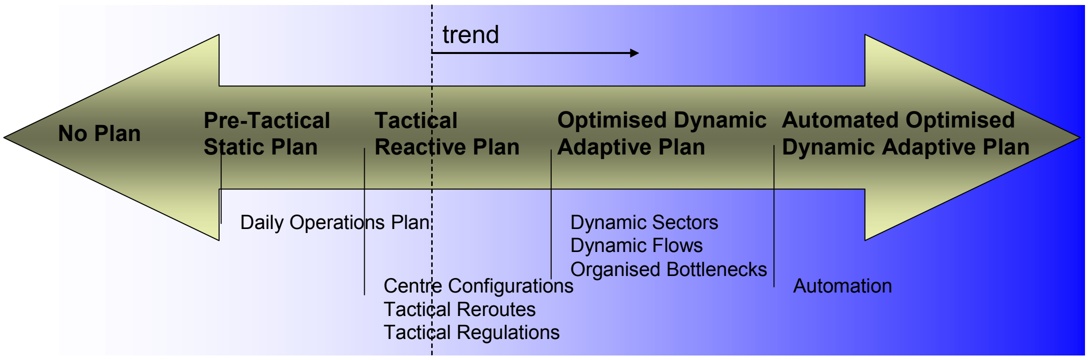

Figure 5: Trend for Tactic Capacity Measures

TCM concerns further refinements of airspace regulations during the day, as well as adaptations to the sector configuration schedule. It targets to fulfil a strategy, e.g. workload balancing, or smart regulation management. TCM is further refined for a more adaptive behaviour with higher dynamics where it dynamically reshapes sector boundaries and optimises sector configurations. The effect on the airspace organisation e.g. is to be composed of fine-grained volumes which can be configured so as to dynamically adapt to the instantaneous demand, and will envelope current traffic flows in an optimal way; under some criteria that fulfil best the strategy. This concept is called Dynamic Sectorisation (DYNSEC[39]).

- TFM reroutes sector flows or flights for capacity-bottleneck avoidance. Flights are rerouted out of critical sectors either by vertical level capping where the flights are kept in lower sectors that are not saturated, or circumnavigated around overloaded sectors. In its dynamic form it dynamically reroutes flows through sectors with a finer granularity of flow control. This concept is called Dynamic Flow Control (DYNFLO[40]). The operational enablers are dynamic air-gates; the technical enabler will be dynamic air-gates optimisation tools.
- Tactic Traffic Organisation is not defined in ATM so far. We will therefore take the liberty to define it here.

  Definition: Tactic Traffic Organisation is an ATM function that plans traffic to fly in an organised and orderly way through airspace that is otherwise overloaded in a predicted tactic look-ahead timeframe of up to 2 hours in order to increase flow-rates and herewith airspace capacities.

  We propose the acronym: OBT[41] – (Tactic) Organisation of Bottleneck Traffic.
- Strategic and Tactic Control are the last two layers and are the usual the separation actions that air traffic controllers apply.

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[38] MANTAS – Maastricht New Tools And Systems project

[39] DYNSEC – Dynamic Sectorisation

[40] DYNFLO – Dynamic Flow Control

[41] OBT – Organisation of Bottleneck Traffic

2.1.6 Differences with Multi Sector Planning

Now that we have defined OBT we should distinguish it from MSP[42]. The initial definitions of MSP [37] emanating from the PHARE project mentioned above are very similar to OBT i.e. an active component in the tactic planning layer that acts on flights to reduce tactic controller workload by smoothing traffic of individual sectors. The avoidance and dissolution of bottlenecks and hotspots is central in the early works. Also it already focussed on sector complexity-monitoring as a triggering event for actions. The actions would then be executed by the MSP providing him with sophisticated 4D trajectory control what-if tools for interactive problem solving.

However, since then the notion of MSP has changed: The task of the traditional planning controller is evolving in an operational environment where sectors shrink more and more. The capability of the planning controller to plan is strongly hampered with the reduced geometrical dimensions of sectors; therefore the role of the MSP is seen as a new old-style planner with look-ahead of 10 minutes, possibly becoming responsible for two or three fixed sectors and eventually suppressing the small-scale planners [38].

In contrary, an actor doing OBT will probably jump from one problem to the next disregarding the sectors; and will have the full toolbox to analyse the current and future situation and then to act on flights at disposal.

The next section will make a rough estimation about the impact on key performance indicators for the aforementioned automation levels as functions of complexity levels, because it will give a main motivation for pursuing the work: The benefit of full-automation will depend on its potential impact on key performance indicators.

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42 MSP – Multi Sector Planning

2.2 (Cost-) Benefit of Automation

The previous sections have categorised automation into domains, concepts, complexity levels, and automation levels. This section will try to elucidate the potential impact of automation. For the comparison a number of key performance indicators are selected: safety, capacity, ATC unit efficiency, economics, environment, feasibility, transition, investment, ROI[43], and jobs per flight. The goal will be to make rough estimates of wins of packages (projects, programmes) along these key performance indicators. For this purpose different scenarios are bundled into packages that can be compared with another and to a baseline.

The baseline for the considerations is a do-nothing scenario against which the different automation packages can be compared. The assumption of the do-nothing option is that ATC for the en-route domain evolves at the usual slow pace and that no quantum leaps are achieved i.e. no revolutionary concepts are implemented in the next 15 years or so. This means e.g. that ATC centres will: increase ATCO[44] workforce for ever smaller sectors, improve airspace design including P-RNAV[45] capabilities, equip with some STCA, MTCD and other probing functions, slowly but gradually equip with CPDLC[46], integrate more sophisticated pre-tactic and tactic capacity processes, and last not least reorganise administrations for higher efficiency. This will already lead to high improvements of the overall ATM system in all key performance areas (but environment).

With that definition of a baseline we now bundle the following automation packages:

- Low-automation package: We could put into that basket one or several ATM concepts that would enable automation in low complexity en-route airspace as shown above. Our low-package will only consist of a distributed concept: ADS-B See and Avoid; ACAS is already part of the baseline. We would not apply basic centralised CD & R here because its benefit is considered too low for the investment.
- Mid-automation packages: The packages are about semi automation, i.e. human-in-the-loop. We bundle three packages, one for the distributed, another one for the centralised approach, and one combining the other. All packages contain the advanced airspace development plus advanced planning functions. The distributed package adds co-operative human-in-the-loop ADS-B/ASAS. The centralised package adds ground-based human-centred CD & R. We show that the latter has advantages regarding investment (Table 2).
- High-automation packages: The packages are about full automation, i.e. human-out-of-loop. There can be three different bundles where the third would be the union of the other. Similar to the mid-packages there is an option to try to achieve full-automation with central or distributed system architecture. I.e. that both mid-packages can be enhanced to evolve to full-automation for the provided functions. In addition the high-packages take the conceptual elements for enhanced automatic planning functions.

[43] ROI – Return on Investment

[44] ATCO – Air Traffic Controller

[45] P-RNAV – Precision Area Navigation

[46] CPDLC – Controller Pilot Data Link Communications

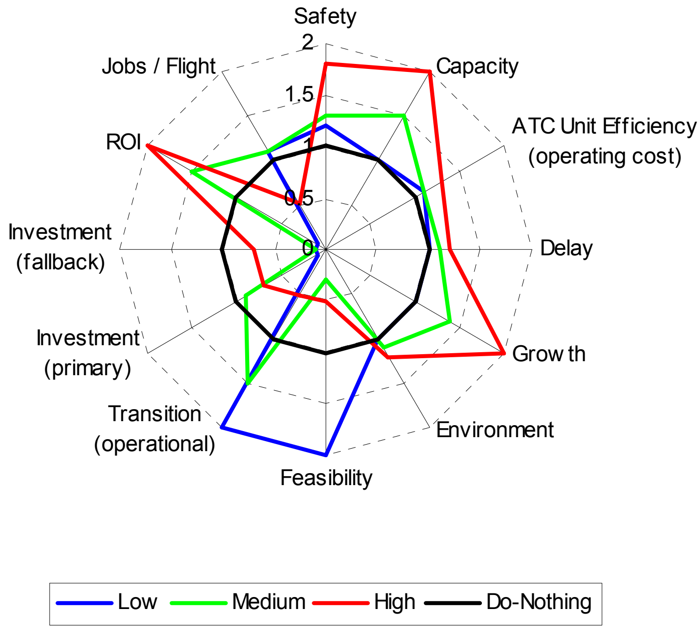


Figure 6: Relative Impact of Automation Levels

Figure 6 depicts the comparison of the automation packages with the baseline. The baseline is set to 1 for all KPI[47]s. All comparisons are qualitative and based on expert opinion i.e. guesses. The rationale for the different values is briefly argued in the following paragraph.

Package Level	KPI	Estimate	Rationale
Low	Safety	+	ACAS part of baseline; See and Avoid will also have negative effects because more complicated than TCAS and interpretation of CDTI[48] can lead to human errors; yet an overall small improvement.
	Capacity	0	Not an issue.
	Unit Cost	+	Eventually permitting lesser night shifts.
	Economics	0	Not an issue.
	Environment	0	Not an issue.
	Feasibility	+++	Solutions do exist.
	Transition	+++	See and avoid very natural for pilots.
	Investment	---	Requires airborne certified equipment and screens.
	ROI	---	High investment, no cost benefit
	Jobs / Flight	+	Equipment manufacturers.
Mid	Safety	++	STCA part of baseline; semi-automated resolution advisories are in general a safety improvement (3rd pair of eyes), but may also disturb controller or pilots' workflow when under stress.
	Capacity	++	Lower overall tactic workload when well implemented.

[47] KPI – Key Performance Indicator

[48] CDTI – Cockpit Display for Traffic Information

	Unit Cost Economics Environment Feasibility Transition Investment ROI Jobs / Flight	0 +(delay) +(growth) + -- + 0 (ground) ---- (air) ++(ground) 0	Lesser ATCOs, more engineers. Small local flight optimisations with optimised solvers. Growth by higher capacities. Small local flight optimisations with optimised solvers. More complicated than full-automation due to interaction with human. Normal difficulty to let the ground system evolve with support tools. Central (ground-based) approach is normal project type; Distributed (airborne) approach very expensive because software-intensive (cost relation line of code by factor 100). Low investment, small and early benefit No true impact on operational workforce; positive for manufacturers.
High	Safety Capacity Unit Cost Economics Environment Feasibility Transition Investment ROI Jobs / Flight	+++ +++++ ++ ++(delay) +++(growth) ++ - -- -(ground) ----(air) ----(fallback) +++(ground) --	Traffic will be better ordered; implementation of the strategy will require monitoring aids also increasing safety (provided system is fail-safe). Full automation of CD & R solves the current en-route bottleneck; planning will further increase capacity with improved flows. Even lesser controllers, even more engineers; very long term investment with no controllers and no engineers. Meta-local flight optimisation. Potential for substantial growth. Meta-local flight optimisation. Solution not proved, but simpler than semi-automation Technical difficulty; humans have to change jobs. Software simpler than semi-automation, but must be proven; Medium investment, very high but later benefit Very long term prediction when system so stable that no additional engineers are required.

Table 2: Qualitative Cost-Benefits

KPIs are often influencing another e.g.

- improved capacity almost always counterbalance safety improvement;
- improved capacity does not only reduce delay but also provides space of growth for the market which creates high potential for huge return on investments;
- improved capacities enable more flights which has negative impact on the environment;
- full-automation increases safety only if systems are safe to fail, which increases investment and operating costs;
- decreased unit operating cost is often contradictory with high employment.

Society gives different weights to the key performance indicators and the weights have been evolving in the last decades, e.g. environment was not seen a problem for ATM until some years ago, and is possibly becoming the largest single constraint in the future. Also the business economics (e.g. cost of delay) and the centre unit operation costs are only part of a complicated socio-economical puzzle, and in general jobs are tried to be preserved and protected. The decision in favour of a semi- or full automated system will rely on the weights that society gives to the different KPIs at a moment in time.

$$value \rightarrow \sum_i \omega_i * KPI_i$$

What happens when the automation systems fail? It can be foreseen that there will be strong requirements for fallback systems when aiming at full automation. There are several options for this:

- Human-centred redundancy means that the automation falls back to the semi-automation system that must then be maintained in some form. This might lead to very high cost.
- Local redundancy in each system means that each system has a redundant fallback of the same type i.e. a centred system would have a second centred system and a distributed system would have a second distributed system.
- Combined redundancy means that a centred system is redundant to the distributed system and vice versa, at least for the tactic cluster resolution. The planning functions are almost impossible to implement in a distributed system that has almost no data link. The advantage of this central/distributed redundancy is that the systems are orthogonal.

Transition management is paramount to the introduction of new concepts and systems. We believe that full-automation will not be introduced in a single revolutionary quantum leap but instead in small transition steps. Full-automation would then be the successor of semi-automation, and the KPIs would have to be adapted in a form that full-automation would not be compared to the current baseline, but to semi-automation. This will lead to different quantifications of costs and benefits.

3. PLANNER-STRATEGY-PLAN-ACTION CONCEPT

3.1 Introduction

This section treats the theoretical part of the thesis on planning under uncertainties. Planning is a psychological process of thinking about the activities required to create a desired goal on some scale and as such is a fundamental property of intelligent behaviour; automated planning is therefore a non-trivial task. That difficulty is further aggravated if the system under consideration is of non deterministic nature as is the case for air traffic, where a view on the system within a look-ahead time horizon of up to 2 hours is inherently incomplete. The incomplete view, also termed partial observability, of the system is caused by the uncertainty of its predicted states like e.g. unknown meteorological conditions, unknown flight delays, unknown airline behaviour, unknown airport and centre capacities, unknown military activities etc. It is therefore useful to conceive a theoretical model which abstracts specificities of planning in Air Traffic Management into a generic planning model. This model is baptised the Planner-Strategy-Plan-Action model.

In the Planner-Strategy-Plan-Action model presented in the following paragraphs the planner is the intelligent function that produces plans. For that purpose it uses optimisation processes to plan for the achievement of a goal with minimal cost. The strength of the model is that we can name the strategies that planners may apply to plan in the 2 hours look-ahead time horizon, because these are different strategies from the fields of tactic capacity measures and tactic traffic control. Strategies use different system components on which they apply a wide variety of different actions. This section enumerates strategies for the mentioned planning time horizon, then lists the system components that strategies act upon, and further identifies a long list of possible actions that each strategy could use in its portfolio of possible actions.

Uncertainty is an intrinsic property of the ATM system and therefore central to the concept of automated planning. Hence, the stochastic part of the system must be understood and modelled, which sets specific constraints for robust planning. A robust plan is stable during its implementation even if some of the underlying assumptions that lead to the plan turn out to be wrong. A plan can also be regarded stable if it only needs some temporary correction and can then be continued to be executed. The planners require a capability to observe uncertainties in the planning time frame and to evaluate the impact on the plan. With bad planners uncertainties translate into unstable plans, where planned actions often change. The next paragraphs attempt to model uncertainty in the planning model.

This theoretic part of the thesis is founded on other literature than the previously listed in the introduction: we found a single book treating automated planning [39], from which we started this theoretical chapter. We also found that planning has a very long history going back to the starting points of game theory and artificial intelligence in the late 1960's, with certainly much more research than the already impressive history of automation in air traffic management. It was impossible for us to treat that literature and hence the presented work bears the risk that similar work may already exist. However, we are certain that no such model exists for air traffic management, and that the relations between a generic model and the application domain are the first of its type.

3.2 Strategies

A strategy[49], χ, is the underlying rationale for a plan[50], Π, and defines a vision, goal or an objective, and a way to achieve it. A planner[51], Γ, uses strategies to create plans. It can be modelled as an optimisation function. Usually multiple strategies exist in parallel and overlap e.g. regulation management is applied in one, workload balancing in all, and some bottleneck avoidance in yet another region. Each strategy leads to at least one plan, which is an ordered list of actions. We could say that the strategy is plans to create a plan.

Definition: A strategy, χ, is the method designed to achieve a particular goal that is applied in the production of a plan.

In all day life humans constantly apply strategies to satisfy a multitude of differing interests, e.g. we all enjoy when children apply visible strategies to hide bad points to minimise negative impact or strive for recognition etc. In politics there are different parties (strategies) that pretend to serve the same goal. In informatics a strategy is a synonym for an algorithm. In ATM there are a number of tactic strategies that can be applied in order to optimise the operations of the day. The following paragraphs list the most important ones.

3.2.1 Tactic Regulation Management

Airspace capacities are modified during the day, often as an effect of manpower planning, but also unforeseen traffic flows. This is called a regulation of a traffic volume for a time, where the traffic volume is a 1, 2 or 3 dimensional airspace element. In Europe regulations affect the departure schedule of flights which is calculated by the CFMU. Tactically the only measure that CFMU can currently provide is delaying flights so as announced sector capacities are respected. The delay is incumbent for the generating ATC service provider and a key performance indicator for the business, and hence delay is tried to be minimised. Regulation management is the function that minimises delay with smart allocations of regulations.

The trend in regulation management is towards other dynamic measures on CFMU level like reroutes; and finer grained allocations of regulations on centre level.

3.2.2 Shift and Break Planning

Manpower planning can be used for TCM because it will allow a better adaptation of demand and capacity. The function provides ATCOs when they are required. The trend goes already today towards optimisers planning rosters, shifts schedules and break schedules.

3.2.3 Flexible Use of Airspace

Airspace is the most important resource for airborne ATM. In Europe large parts of the airspace are reserved for military users. In the last decades the principles of

[49] χ – Strategy, or set of strategies

[50] Π – Plan, or set of plans

[51] Γ – Planner, or set of planners

FUA[52] have been progressively introduced and today many of the military airspace can be made available for civilian usage with different levels of dynamics. This involves temporary reserved volumes or conditional routes.

The trend is towards lower penalisations for the civilian part by better co-ordinations and fine grained military reservations as well as improved plan-ability of conditional routes.

3.2.4 Workload Balancing

Workload balancing is a frequently used strategy because in general it avoids delay, which is a key performance indicator. The principle of workload balancing is to either redistribute flights over sectors - or sectors over flights. Workload balancing can therefore be obtained by moving sector boundaries, or by tactically rerouting flows or flights.

The power of workload balancing is its very high potential to increase capacity by adapting the workforce there where it is required. The higher the dynamics of airspace and flow management are, the better workload balancing performs and the higher the capacity benefit. The trend goes towards higher dynamics and fine grained traffic volumes.

3.2.5 Traffic De-bunching

Bunching of traffic i.e. instantaneous arrival into the same airspace volume is in general considered very complex and leads to high workload peaks, and herewith to lower capacity. Tactic capacity measures will try to avoid bunching.

Later in this document we will discuss airspace complexity and its analysis as an important element and trigger for OBT, and bunching is an important element.

3.2.6 Miles in Trail

MIT[53] is a tactic capacity measure mainly applied in U.S.A. It consists of sequencing aircraft at entry points of volumes using parameterised times or distances between aircraft. This will allow for smoother flows through sectors, and prepare the flows for easier treatment like flow merging, flow crossing, arrival streams etc.

The trend in MIT goes towards meta-local optimisations of local MIT constraints.

3.2.7 Dynamic Flow Routeing (Air-Gates)

Dynamic Flow Routeing (new proposed acronym DFR[54]) is a strategy to combine or segregate flows for a reduction of workload. Hickson [36] invents the air-gate as an enabler for DFR, and the fence as a special no-go air-gate. Air-gates are 2 or 3 dimensional airspace volumes that guide the flows. Air-gates are dynamic and have a life-span. Air-gates put constraints on flows, e.g. geometrical constraint, flight level allocation schemes, sequencing schemes, MIT schemes etc.

---

[52] FUA - Flexible Use of Airspace

[53] MIT – Miles in Trail

[54] DFR – Dynamic Flow Routeing (proposed)

The possibilities of air-gates have very high potential. In European dense airspace they could be applied for e.g.

- Guiding the flows through or around military airspace when switched on or off;
- Splitting dense flows into parallel streams;
- Preparing merging flows by specific sequencing constraints;
- Building local temporal segregations of airspace like corridors, highways, or laced tubes.

Example:

$$\bigcup ac \in flow(nav_1, nav_2, \Delta t)\begin{cases} g_1(180-240, pair) \wedge g_2(140-200, all), TRA(Lauter) = 1 \\ g_3(<260, RVSM), TRA(Lauter) = 0 \end{cases}$$

3.2.8 Organisation of Bottleneck Traffic

The dynamic organisation of traffic through hotspots was defined above as OBT. OBT creates a plan of clearances that are given to flights that pass through the bottleneck at the same time. Conflicting but also non-conflicting flights may be affected by the plan if this leads to an optimum solution. Organisation in OBT means order, but only if this leads to an improved solution. OBT is always reactive and herewith always dynamic. OBT is a generalisation of the Tactic Cluster Resolution strategy for the longer look-ahead time horizon with higher uncertainties for predicted aircraft positions. OBT has a look-ahead time horizon that is limited by the uncertainties of the predicted trajectories that it treats on one side and the possibly higher performances to the Tactic Cluster Resolution on the other.

3.2.9 Tactic Cluster Resolution

Tactic Cluster Resolution thrives at the tactic resolution of conflicts in an optimised way. We have largely discussed this strategy in the introduction of this document. Tactic Cluster Resolution is a specialisation of OBT for the short look-ahead time horizon with lower uncertainties for predicted aircraft positions.

3.3 Plans

Planning is the intelligent function [39] done by planners, Γ, that compiles the strategies, χ, into artefacts called plans, Π. A Π is a time-sequence of actions[55], *a*, on a system[56], Σ. Plans may be interlinked but should not interfere. There may be several Π executing at the same time. If they act on the same Σ then the planners must co-ordinate in order not to create plans with contradicting actions. Plans can be combined. Several Π may be proposed and a selection made for implementation. The best overall plan is selected as the one that satisfies best the common current objective function. With this philosophy we consider planning to be an optimisation function. A strategy χ is then an optimisation function including cost[57] functions, c, and constraints. The decision of the planner is to select the best actions at the best times.

[55] *a* - Action

[56] Σ – System, or sub-system

[57] *c* – Cost function, sometimes called objective function

The difficulty will be to handle the complexity of the overall system. A first approach would be to devise Σ into smaller sub-systems to generate one Π per sub-system, which is then combined into an overall Π. This will work well if the sub-systems hardly overlap i.e. are not connected. In our case and more specifically for tactic capacity measures there are several possibilities to devise Σ into smaller parts, e.g. to produce one Π per strategy; or per look-ahead window. Yet the system is connected, and the combined plans will produce lesser optimisation than a single Π for the entire Σ. At the current state of affairs we will be glad if we can produce optimal plans for sub-systems.

What happens if the plan turns out to be wrong? Ability to recover is an important property of Π; will the rest of the plan have to be corrected; or can some smaller corrective measures be applied and afterwards the plan can recover? We will show in sections below that a plan becomes vulnerable due to uncertainties on the assumptions of input data, with the result that it is wrong. We will also show below that if the current state of the system does not conform to the predicted states, then the plan is rectified. It is important to understand whether in this case the entire rest of the plan must be corrected or only smaller parts of it. This is the ability to recover[58] (γ). Some Π will target for good recoverability, because re-planning is difficult or even impossible and only small corrections can be made e.g. on-the-day workforce corrections. For other planners γ will not be an important parameter e.g. a tactic cluster conflict resolution tool might re-plan until the very last acceptable moment to wait until lowest uncertainty and achieve highest flight efficiency. This is expressed in the impact parameter[59], Ξ.

3.4 Actions

The Π is composed of actions, *a*. Table 3 lists the strategies with the set of actions that planners can use. Some of the actions do not exist in current operations; some of them are elaborated in detail in this document; and others are to be conceived in the future.

Strategy, χ	Possible Actions	Comment
Tactic Regulation Management	Tactic Regulation	Reduces announced capacity on traffic volumes so that less traffic must be treated, produces delay.
Shifts and Breaks	Shift start/end time	
	Break start/end time	
Flexible Use of Airspace	Military start/end time	Trend is to minimise military airspace usage at full satisfaction of military requirements by better collaborative planning process.
	Dynamic configurations	
	Dynamic sectorisation	Trend is to minimise military airspace per game with smaller traffic volumes that are optimised in the civilian flows.
	Conditional routes	Trend is towards more plan-able conditional routes.
Workload Balancing	Dynamic configurations	Study in section 2.6.
	Dynamic sectorisation	Study in section 2.6, 3.2.
	Team adaptation	A team of ATCOs is composed of differently

[58] γ - Ability of plan to recover from non-conformance

[59] Ξ – Impact of re-planning on cost function

		skilled controllers.
Traffic De-bunching (Miles in Trail)	Speed clearance	Study in section 2.2.
	Sequencing	
	Direct clearance	Study in section 2.5.
	Vertical clearance	Study in section 2.
Dynamic Flow Routeing	Flow splitting	If airspace is available then flows can be split into thinner or specialised streams. A possible specialisation could be to split away flows with high uncertainty on predicted entry times.
	Flow re-routeing	Flow can be re-routed around bottleneck airspace, either horizontally or vertically.
	Dynamic FLAS[60] Dynamic LOA[61]	Requires air-gates, for an adaptive management of flight levels at gates. Could even implement extreme non-standard flight level allocations if not hampering safety.
	Highways	Special cases for flow splitting by reserving airspace to a specialised flow. Only beneficial if flow density of specialisation is high.
	Tubes and rubber bands	
Organisation of Bottleneck Traffic	Flow splitting	
	Flow re-routeing	Flow can be re-routed through bottleneck airspace, either horizontally of vertically.
	Dynamic FLAS	
	Vertical clearance	Study in section 4.
	Temporal vertical clearance	Study in section 4.
	Speed clearance	Study in section 4.
	Direct clearance	Study in section 4.
	Lateral Offset clearance	Study in section 4.
	Path Objects	Special patterns of 3+1D-trajectories.
	3+1-D trajectories	More complicated trajectories can be built by OBT, especially when planning for late manoeuvres.
Tactic Cluster Resolution	Vertical clearance	Study in section 4.
	Temporal vertical clearance	Study in section 4.
	Direct clearance	Study in section 4.
	Lateral Offset clearance	Study in section 4.
	3+1-D trajectories	
	Vector	Study in section 4.
	Speed clearance (ROC[62] / ROD[63])	
	Parallel Offset	Study in section 4.
	Parallel Heading	Study in section 4.

Table 3: Strategy – Actions

60 FLAS – Flight Level Allocation Schemes

61 LOA – Letter of Agreement

62 ROC – Rate of Climb

63 ROD – Rate of Descend

3.5 Planning Stability

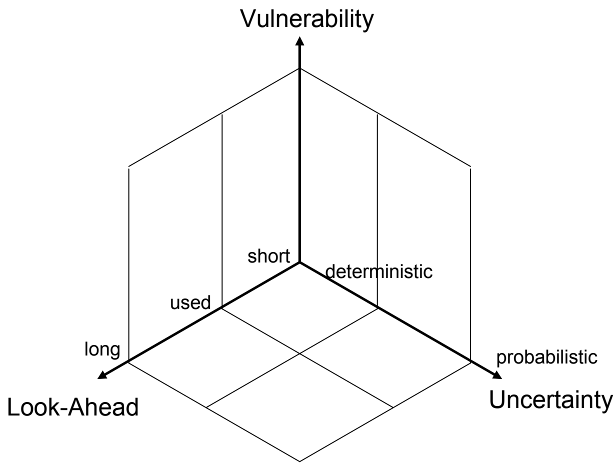


Figure 7: Dimensions of Stability

The effects of improved planning might become counter-productive if the quality of the plans is not high. One key property of plans amongst their ability to solve the problem is their stability[64], ψ: a good plan is executed until its end and does not need rectification - a plan that has to be rectified is a plan that is not performing well anymore. I.e. the implementation of a plan must be observed in order to evaluate its conformance which means that predicted states of the systems must be compared with real states; if the differences between predicted and real states of the system are small then the plan is continued, else it is rectified. The threshold to reinitialise the planning function is another property of the planner for a system. The stability of the plans depends amongst other on the level of uncertainty of the assumptions that have lead to the plan. Each strategy will have a number of assumptions for the predictions of future states that intrinsically have uncertainty. Robustness of plans depends on the vulnerability of actions[65], ϑ_a , with regards to uncertainty. This means that the vulnerability to uncertainty of individual actions influences the stability of the plan.

$$\psi \rightarrow \vartheta_a$$

[64] ψ - Stability of plan

[65] ϑ_a - Vulnerability of action

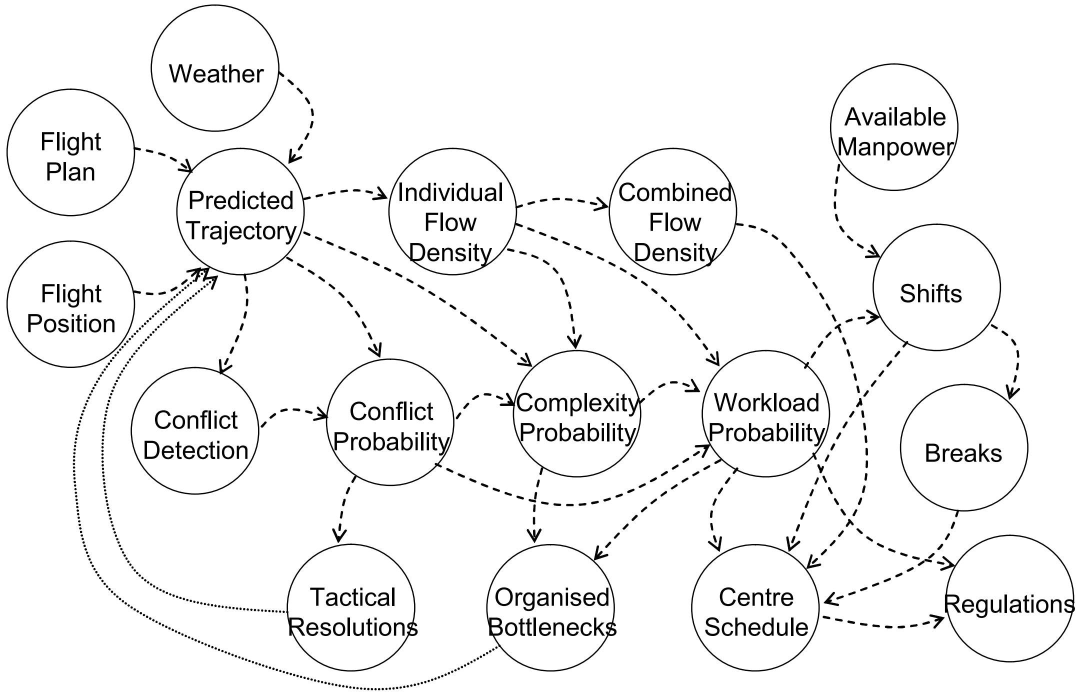


Figure 8: Draft Influence Diagram for Uncertainties

Figure 8 depicts the influences of different components of the system Σ. If Σ was deterministic then all its components would be as well and planning would be easier. Unfortunately it is in the nature of the air transport system to be non-deterministic; yet it is not entirely stochastic because the ATM system controls Σ at each of the above mentioned layered processes, but: flight plans may be delayed; radar tracks not correct; trajectory prediction imprecise e.g. due to weather; manpower planning wrong due to sickness etc. Each component must therefore model the dependency of its input parameters to uncertainty. This can be done with a probabilistic approach. The uncertainties are then modelled with the help of Probability Distribution Functions (PDF[66]) [40]. The input- and output parameters of system components are then in the form of PDF. A Π in contrary must produce deterministic sequences of actions. If the planner observes the system but cannot distinguish between system states[67], *S*, but yet decides for a selection of actions, then the actions are highly vulnerable to uncertainty.

Figure 9 serves for further illustration: Let $t_{\Pi,\omega}$ be the look-ahead time window of a planner. Let $\tau_a \in t_{\Pi,\omega}$ be the time of the planned action. Let $\vartheta_a(t)$ be the vulnerability of an action. Two exemplary influence parameters are shown as probability distributions. The first could e.g. be the prediction of trajectories at a merging point with one flow having higher uncertainties than the other; the second could be the conflict probabilities in an adjacent hotspot with different distributions due to different encounter probabilities. The planner would take this as input. Assume the planner only plans for two actions a_1 and a_2; it would compile the input PDF into vulnerability distributions for the two influence parameters. Each action on its own would have best times regarding vulnerability - but ϑ_a is only one of many parameters to optimise; there are others and possibly more important parameters

66 PDF – Probability Distribution Function

67 S – Set of system states, s - state

that will have impact on the solving process. In the example Π is presented with three actions, from which two are not taken at optimum vulnerability.

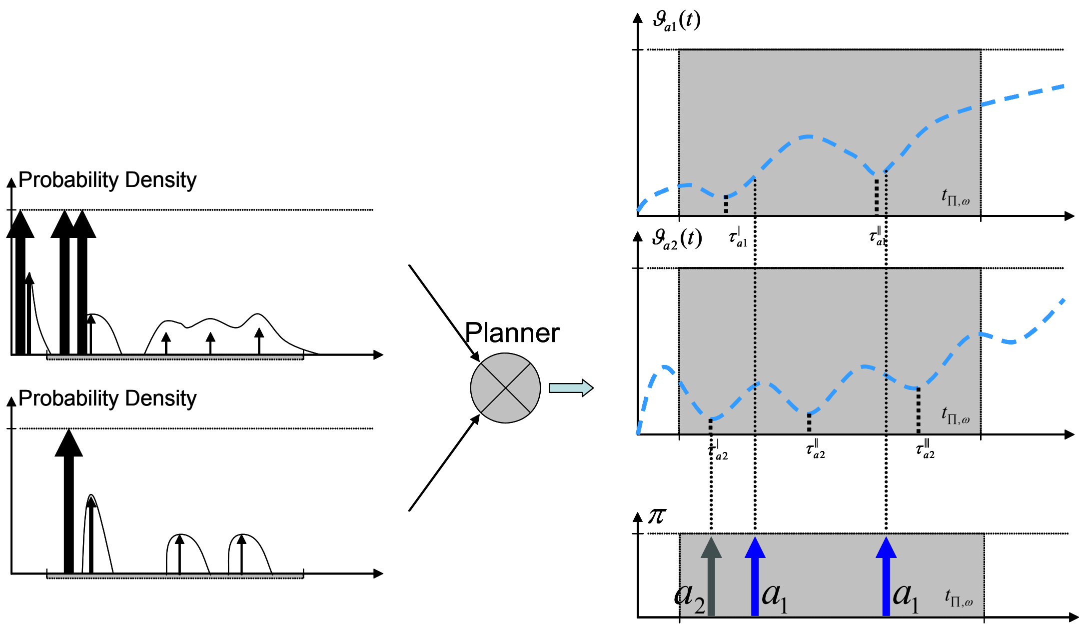


Figure 9: Probability Distribution, Vulnerability, Actions

Some examples to illustrate the vulnerability of actions regarding uncertainty and the impact on the stability of the Π:

1. Let a tactic conflict solver create a Π which contains a sequence of clearances for flights in a sector in a look-ahead time window of 2 to 10 minutes by assuming predicted trajectories. If one of the flows to be separated has high uncertainty in its prediction then the actions planned on flights in that flow will suffer from vulnerability. E.g. an action a_1 ='vector behind' in a plan $\Pi(t_1)$ that is issued at time t_1 may turn out to become a 'vector in front' if the plan was strictly executed, and this would rather aggravate a separation problem which was supposed to be solved by the action. Therefore the Π will have to be rectified. If it had chosen a vertical clearance instead, the Π would have stayed stable, but perhaps less well performing regarding other performance parameters in the optimisation function. I.e. that the action 'vertical manoeuvre' is less vulnerable than the action 'horizontal vector'. It also illustrates that the uncertainty of a trajectory has made an action vulnerable and a plan unstable; we say the action is vulnerable.

2. The changes of centre's sector-configurations are set in a schedule i.e. a Π that is executed over the day. The actions in the plan are scheduled de-collapsing and collapsing times of sectors. Assume that the schedule only depends on predicted traffic and herewith only on predicted sector load. The plan will be stable as long as the predicted sector loads conform to the real situation. The predicted sector loads depend on predicted flow densities and not on predicted individual trajectories. I.e. a sector may be constantly loaded if an entry flow is at a steady flow rate. E.g. changes of orders of individual aircraft i.e. wrong trajectory predictions between planned time and executed time do not affect the plan. This illustrates that the configuration schedule is not vulnerable to wrong predictions of trajectories in dense flows. However, Π will be sensitive to changing flow densities. Stability of configuration schedules is in general given

for high loads that are characterised by high and constant entry flows; whereas low stability is given at low load.

3. Pre-tactic planning refines the shifts and roster for the next two weeks to come. It is based on the centre's assumed predicted air traffic and predicted available workforce. Based on these two assumptions the Π is constructed: Ideally the predicted traffic leads to a shift schedule and a break schedule. Actions of the shift schedule are start- and end times of shifts, respectively of breaks. The predicted shift schedule leads to a configuration schedule i.e. actions for sector de-collapsing and collapsing times. The configuration schedule leads to manpower requirements that the roster has to satisfy. A stable shift plan is a plan that does not change even if traffic or workforce changes, and that is yet very well performing i.e. is very efficient. In contrary, an action with high uncertainty like planning for a person which is still sick will lead to a high vulnerability of the action and possibly to an unstable plan.

Table 4 lists the actions, the look-ahead time in which the planners will typically use an action, the main influence parameters of the action, and three qualitative statements which will help to classify the actions and the worthiness at planning:

1. Nominal $\vartheta_a(t)$ may be a complicated computation based on the planners input influence parameters, (---) means very bad and (+++) no vulnerability.
2. Recover-ability, (---) means very bad and (+++) very good recover-ability.
3. Impact Ξ, (---) means very bad and (+++) no impact on the total value of the plan.

Possible Actions	Look-Ahead Window $t_{\Pi,\omega}$	Influence Parameters	Nominal $\vartheta_a(t)$	Recover-ability γ	Impact Ξ
Tactic Regulation	10h ↔ 2h	. centre schedule . workload prob.	(--)	(--)	(--)
Shift start/end time	10h ↔ 2h	. manpower . workload prob.	(---)	(+)	(-)
Break start/end time	10h ↔ 30min	. manpower . workload prob.	(-)	(--)	(--)
Military start/end time	10h ↔ 30min	. military plan	(+++)	(--)	(--)
Conditional routes	10h ↔ 15min	. military plan . indiv. flow prob.	(++)	(+)	(+)
Dynamic configurations	10h ↔ 5min	. combined flow prob. . workload prob.	(++)	(+)	(+)
Highways	10h ↔ 30min	. combined flow prob. . indiv. flow prob. . workload prob.	(+)	(--)	(---)
Tubes and rubber bands	10h ↔ 30min		(+)	(--)	(--)
Dynamic sectorisation	30 ↔ 5min		(+++)	(+)	(+++)
Flow splitting	2h ↔ 5min		(+++)	(+)	(+++)
Flow re-routeing	2h ↔ 5min		(++)	(+)	(++)
Sequencing	30 ↔ 10min		(+++)	(++)	(+++)
Dynamic FLAS	2h ↔ 5min	. conflict prob. . indiv. flow prob. . workload prob. . complexity prob.	(-)	(--)	(---)

Direct clearance	30 ↔ 5min	. conflict prob. . indiv. flow prob. . trajectory prob.	(++)	(--)	(-)
Tactic Speed clearance	30 ↔ 10min		(++)	(+)	(++)
Vertical clearance	30 ↔ 2min		(-)	(--)	(-)
Lateral Offset clearance	30 ↔ 2min		(++)	(+)	(++)
Path Objects	30 ↔ 5min		(---)↔(+++)	(---)↔(+++)	(---)↔(+++)
Temporal vertical clearance	10 ↔ 2min	. conflict prob. . trajectory prob.	(++)	(-)	(--)
3+1-D trajectories	10 ↔ 5min		(-)↔(+)	(-)↔(+)	(-)↔(+)
Path Objects	10 ↔ 5min		(-)↔(+)	(-)↔(+)	(-)↔(+)
Vector	10 ↔ 2min		(-)	(-)	(--)
Speed clearance (ROC / ROD)	10 ↔ 2min		(--)	(--)	(--)
Parallel Offset	10 ↔ 2min		(+)	(+)	(-)
Parallel Heading	10 ↔ 2min		(-)	(-)	(--)

Table 4: Vulnerability of Actions

We stated above to consider planning as an optimisation function. The optimisation will in general strive for long stability of Π i.e. stability is an optimisation criterion. There are different ways to model stability for the optimisation; one would be to add it as criterion into the cost function, another one to set up constraints that penalise the usage of actions with high vulnerability etc. If stability is modelled in the cost function then it will be weighted against other optimisation criteria; if it is modelled with constraints then the effect of stability will depend on thresholds for the constraints.

3.6 Planners

Planners are the intelligent functions that implement strategies and create plans. Some common properties of planners can be abstracted out.

3.6.1 Triggers for Planning

The triggers for planning depend on the planner, Γ, and the strategy, χ. Yet there are a number of parameters that are common to plans and that can be discussed.

The update rate will define the rate at which the plan is created in the absence of other stimuli. The update rate is a property of Γ.

Non-conformance between planned and actual Σ is a trigger for planners. Non-conformance depends on the thresholds for capacities[68], κ, which is a property of the influence parameter, Ξ. Consider a tactic cluster solver. One of its χ might be to solve conflicts in low-complexity airspace as late as possible with a reduced set of tactic actions like vectors and temporary vertical clearances.

Adjacent planners may retrigger Γ e.g. when some criteria of solvability cannot be fulfilled. E.g. consider a tactic cluster solver that is confronted with a situation of very low solvability, possibly due to some very high uncertainty of some trajectories. This could trigger an OBT-planner that would implement some strategy to reduce uncertainty.

68 κ – Capacity Threshold

3.6.2 Solvability

Solvability[69], Ω, is the ability of the planner to produce a plan for a strategy. We will give it two meanings; one for the level to which constraints must be relaxed in order to obtain a Π; and one for the dependency of the solver on the uncertainty of influencing parameters, PDF(Ξ).

Example for the relaxation case: A conflict solver is unable to find a solution with the constraints that the strategy imposes, but it finds a solution by relaxation of e.g. a speed-envelope, or a vector magnitude, or the number of flight level changes etc. These relaxations can be weighted and set as a parameter of the plan; or could influence the cost of Π. Relaxation of constraints is possibly an implicit function of the solver.

Example for PDF(Ξ): A conflict solver needs to resolve a conflict with low probability, because one of the involved trajectories has a very wide PDF. The solver might then iterate through a set of discrete entry times that lead to conflict probability. The ability of the solver for resolution of conflict at each entry time is then an indicator on solvability. Figure 10 gives an illustration of this case: Aircraft 1 has and equal PDF, aircraft two is deterministic. Some entry times lead to probable conflicts. The solver iterates through all possible entry times and outputs whether it finds a solution. Solvability is then the sum those iterations leading to resolutions devised by the total number of iterations. This example also illustrates that the evolution of the cost of the solving function is an interesting parameter for the planner, which might produce constraints on other planners. E.g. in our case the conflict solver might send no-go entry time constraints to Γ e.g. for an OBT strategy.

t_{ac2}	Solving	Cost
τ_1	OK	100
τ_2	NOK	00
τ_n	OK	10

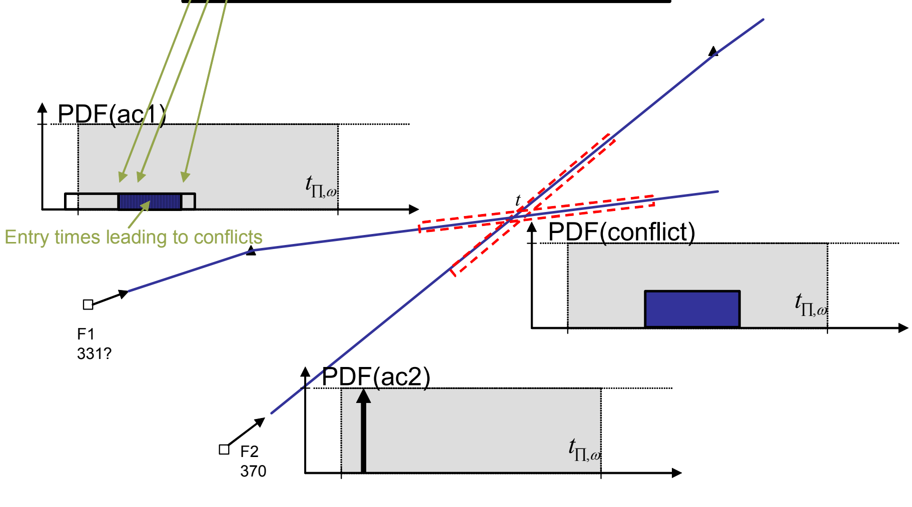


Figure 10: Solvability

69 Ω - Solvability

3.6.3 Thresholds and Capacities

We have stated above (Figure 8) that the planner depends on the influence parameter, Ξ. This is a convenient abstraction for very complicated constructs!, e.g. the precision of aircraft state vectors is ongoing research and under development since decades, as well as the accuracy of trajectory prediction; uncertainty of trajectory prediction is an own branch of research in ATM; conflict probabilities has lead to a (limited) number of publication in the last two decades; airspace complexity and workload are two own branches of research in ATM and their probabilities have not been investigated to our knowledge; there is not much published work yet on manpower management, shifts, breaks and rosters, nor on their probabilities; individual or combined flow densities and their predictions are an own branch of research in ATM; and there is almost no work on individual or combined flow probability etc.

Yet there are a number of discrete capacity-thresholds, κ, which are used by planners, Γ. When the system is under some uncertainty then the thresholds can also be called probability levels. Table 5 lists some examples. Reaching the threshold will in general produce an event that will retrigger Γ because the plan, Π, is not conform anymore. The reception of an event from a threshold that was fired can become important e.g. in the planner's selection of a χ.

Ξ	Γ **or** χ **or** a	κ
Trajectory Prediction	Workload Balancing	Traffic Monitoring Value, i.e. number of flights is sector
Trajectory Prediction	Conflict Solver	Nr of instantaneous conflict pairs
Trajectory Prediction	Conflict Cluster Solver	Nr of trajectories in conflict transitive closure
Trajectory Prediction	OBT	Nr of trajectories in volume of interest
Individual Flow Density	Dynamic Flow Rerouting	Flow density threshold
Individual Flow Density	Flow splitting	Flow density threshold
Individual Flow Density	Miles in Trail	Flow density threshold
Individual Flow Density	Dynamic LOA	Flow density threshold
Individual Flow Density	OBT	Flow density threshold
Combined Flow Density	Dynamic FLAS	Flow intersection threshold
Combined Flow Density	Dynamic Flow Routeing	Flow intersection threshold
Combined Flow Density	OBT	Flow intersection threshold
Conflict Probability	Conflict Solver	Single conflict probability threshold
Conflict Probability	Conflict Cluster Solver	Transitive closure conflict probability threshold
Conflict Probability	OBT	Bottleneck conflict probability threshold
Conflict Probability	Workload Balancing	Combined conflict probability threshold
Complexity Probability	OBT	Bottleneck complexity threshold
Complexity Probability	Workload Balancing	Sector complexity threshold
Workload Probability	OBT	Bottleneck workload threshold
Workload Probability	Workload Balancing	Sector workload threshold

Table 5: Capacity Thresholds

3.6.4 Instances of Planners

How many Γ are required and how do they relate to χ, Σ and Π? The sections above have already implicitly treated this issue but we want it to be clear: There is no strict relation! The aim will rather be to reduce complexity of Σ in a way that Σ can be modelled. If it can be modelled then there is a chance to attain solvability, Ω. Ω is a combination of both a property of a strategy, and the ability of a solver; in other terms: to find a solution one needs a good solver, a decent strategy, and a limited system scope.

The breakdown of Σ e.g. in the layered planning processes is one approach to devise Σ and to group χ; the taxonomy of influence parameters another etc. It will only be with the implementation of planners that software architectures will crystallise.

3.6.5 Meta-Planner and Meta-Strategy

If there are several Γ working on different χ then there is a requirement for higher-level planners, we will call them meta-planners[70], ŕ. The first task of a ŕ is to produce the overall Π based on the output form the different Γ. Another task of ŕ is to revisit and possibly revise strategies. There could be various ways to revise strategies, and in general this is a field of research in AI[71]. So far we have not expanded on this difficult approach; instead we are looking for comparison of costs of Π and select for the most efficient combinations of plans. Implicitly that will be produced by the best strategies; hence an algorithmic revision of strategies is not necessary, nor a meta-strategy[72], χ´. Yet, it will be difficult to hold the assumptions that all strategies are produced at all times so that a ŕ can simply collect, compare and combine plans. Instead the planners will try to reduce computation based on heuristics that observe the states of the planners and their interactions.

3.6.6 Planners treat Uncertainty

When Σ is under high uncertainty, then plans have low stability. There are different meta-strategies for a ŕ to accommodate to uncertain situations:

- Apply a strategy to reduce uncertainties in the scope of the same system. A simple switch could be in favour of a strategy with a set of actions that are less vulnerable to uncertainty, possibly at the penalty of higher costs.

  Example 1: Consider a Γ that applies a strategy for tactic capacity measure with dynamic centre configuration management. At high uncertainty the strategy changes to flow re-routeing e.g. by splitting off flows of high uncertainty, routeing the flows around overloaded area, and merging them back in at uncritical areas with low conflict probability. This solution would have the additional cost of longer flight paths, but would solve the problem.

  Example 2: Consider a Γ that applies a strategy for OBT in a merging area with a limited set of possible actions like lateral offset and speed clearances, which is the first choice; but the solvability is too low due to some uncertainties. Then the strategy would be changed in order to tolerate higher uncertainty on some flights

[70] ŕ – Meta-planner

[71] AI – Artificial Intelligence

[72] χ´ - Meta-strategy

and herewith to allow for lower vulnerability of the used set of actions. This could e.g. be achieved by designing strict path objects on the trajectories that will separate the flights in all cases. The cost would be that the merging might not be completely done, or that the path objects impose some constraint with negative impact on the flight profile.

- Apply a strategy to reduce uncertainties by waiting and pushing the problem into the scope of an adjacent system. The situation is not or only partly solved and handed over to a Γ with shorter look-ahead horizon, the principle of late planning. This will be the nominal case for all situations with low complexity where the solver has knowledge about the maximal capabilities of the subjacent solver.

  Example 1: Consider a Γ that applies a strategy for tactic capacity measure with tactic regulations. The uncertainties are so high that stability of Π becomes critical. Then it might investigate the complexity of the situation and find that a subjacent solver applying e.g. flow-splitting will not be overloaded. Then the Γ does nothing or signals this to the tactic flow solver.

  Example 2: Consider a Γ that applies a strategy for OBT in a merging area and the solvability is too low due to some uncertainties. Then it might investigate the complexity of the situation and find that for all probable entries the maximum threshold of a cluster conflict solver will not be reached. Then the Γ does nothing or signals this to the cluster solver.

- Apply a strategy to reduce uncertainties in the scope of a bigger system. The situation is not or only partly solved and handed over to a Γ with higher capabilities to bring down uncertainties

  Example: Consider a Γ that applies a strategy for cluster conflict solving. The situation is not solvable for some entry conditions of trajectories. This is reported back to the next higher solver, which applies OBT strategies. The OBT solver could then set some fixed constraints on the selected trajectories e.g. a sequencing action, or an RTA[73].

3.7 Summary: Strategy, Planner, Plans, Actions

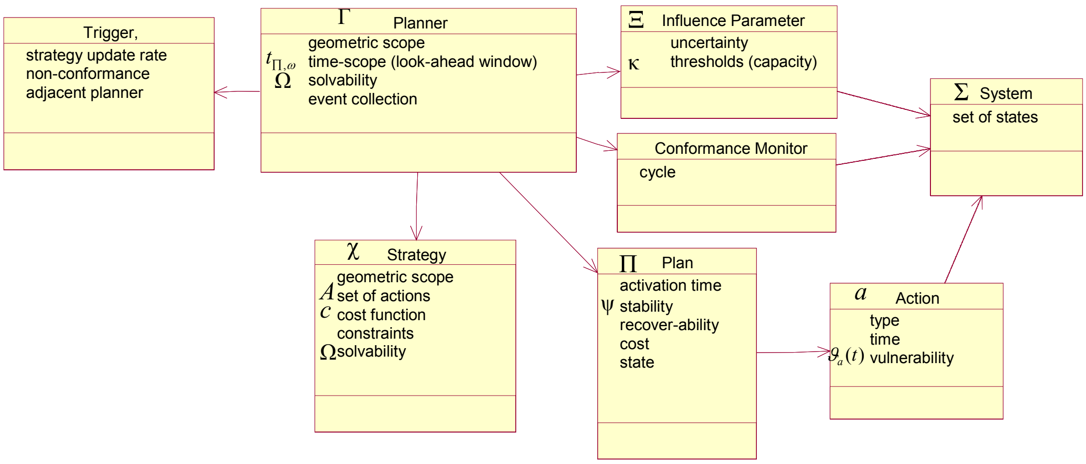


Figure 11: Draft Composition for Planning

[73] RTA – Requested Time At

Figure 11 gives an overview in a pseudo UML[74] class diagram for the relations between Γ, χ, Π and *a*. This very high level of abstraction hides away the extreme complexity of the system.

This finishes our descriptions of the operational concept of full-automation. The following paragraphs treat some main points of the technical enablers for full-automation.

[74] UML – Unified Modelling Language

4. STUDIES

4.1 Overview

This section comprises smaller self-containing works on different aspects of the planner-strategy-plan-action concept grouped into a section on complexity, another on tactic planning actions, and the last on planners. The following overview of the studies presents the rationale for the studies and shows the work flow during this thesis.

4.1.1 Rationale of Studies

The planner-strategy-plan-action concept has been worked out to a level where it can be broken down into work packages. Essential research questions to be answered are:

- What is the effect of uncertainty of flows, traffic and conflicts on the planning of solvers e.g. for sector configuration management, flow rerouting, or conflict cluster resolutions etc.? For that we need more insight into empirical measures from today's air traffic system combined with the application of mathematics for the descriptions of stochastic functions. This leads to the first packages of work in this study dealing with aircraft conflict measures and conflict densities.
- What is the portfolio of actions that (automated) planners, Γ, dispose in order to achieve efficient and safe flow of traffic in high complexity airspace? For that we conceived a catalogue of possible actions from capacity, flow and traffic management. This leads to work packages dealing with tactic traffic clearances as well as dynamic sectors.
- How do planners, Γ, achieve the task of converting strategies into plans? With the definition of the concept of planners-strategies-plans-actions the process of planning is considered an optimisation task under varying degrees of uncertainty. This leads to work packages dealing with optimisation for planning e.g. configuration management.

The detailed focus of the studies is:

1. Complexity
    1.1. Conflict Measures: The empirical study gives statistical analysis about conflict encounter geometries in European airspace based on flight plans and on radar data, and builds a foundation stone for all following studies treating conflict resolution. It discusses conflict probability using mathematical descriptions of the probabilities; and is hence in the centre of the problem of automated planning under uncertainties.
    1.2. Conflict Densities: The empirical study develops visualisation for conflict clusters, and improves the understanding of encounter geometries in conflict clusters as occurring in real airspace. This allows for a better understanding of bottleneck airspace, which is a major trigger for the conformance monitoring function of a Γ: When a conformance threshold is exceeded then a Γ has to make a new plan.
2. Plan-Actions
    2.1. Tactic Conflict Resolutions: The simulation study gives statistical figures for the quality of the conflict solver in RAMS, and is a necessary baseline for all

other conflict resolution studies based on the RAMS tool. It gives insight in the quality of the RAMS solver, which advantage is to resolve conflicts with a rule base, and to implement a very complete and herewith realistic airspace model.

2.2. Dual Conflict Resolution: This simulation study improves the RAMS conflict solver in that both aircraft can be deviated to solve conflicts. The intention is to find out whether the model reaches 100% solving rate, even without further optimisations. It is a necessary step towards a cluster conflict solver in a realistic airspace model like RAMS.

2.3. Speed Control: Speed control for en-route air traffic control is a conflict resolution strategy with a longer look-ahead time horizon than today's tactic control. The intention is to evaluate its performances regarding conflict resolution; then it could become a useful action for a Γ for Organisation of Bottleneck Traffic, OBT; see Table 3. The simulation study developed the model in the RAMS simulator.

2.4. Lateral Offset: Lateral offset is not used in current ATC in the moment. Similar to speed control we investigate the usefulness of this clearance to become a useful action for a Γ for Organisation of Bottleneck Traffic, OBT; see Table 3. The simulation study developed the model in the RAMS simulator.

2.5. Tactic Direct: Tactic directs are in daily use in today's ATC. Yet we want to investigate the usefulness of this clearance to become a useful action for a Γ for Organisation of Bottleneck Traffic, OBT; see Table 3. The simulation study developed the model in the RAMS simulator.

2.6. Dynamic Sectorisation: This conceptual study develops for the first time airspace partitioning to become a useful action for a Γ for Organisation of Bottleneck Traffic, OBT; see Table 3.

3. Planners

3.1. Optimised Configuration Management: This simulation study works on airspace and is the only Γ developed in this thesis. The task of the Γ is to plan a centre sector configuration. We acquire both new insights on sector saturations and configuration schedules; and know-how on optimisers for planning. Further the study has direct use for airspace planning.

3.2. Dynamic Sectorisation Optimisation: This development study conceives an optimiser for dynamic sectors. It is the implementation of an automation strategy, χ, for workload balancing.

During this thesis a number of studies have been started and have not been continued for various reasons:

4. Conflict Probability Density: The tool development targeted the visualisation of conflict probability densities. An add-on simulator to RAMS was developed for the computing of conflict probabilities on simulated traffic; and a visualisation converted developed for visualisation in ATC Playback. The results were not trusted and the work was not continued.

5. Conditional 3 Dimensional Routes: The modelling was started in RAMS and lead to the development of Conditional 2 Dimensional Routes, usually referred to as Conditional Direct Route[75], CDR. Yet the model was found unreliable and

[75] CDR – Conditional Direct Route

very data intensive in the setup, so that no validation studies were produced. The inclusion of the third dimension did not succeed yet.

6. Conflict Pattern Recognition: The empirical study intended to find conflict patterns in a selected airspace with a typical en-route merging point. At that time the radar data analysis tools were not available yet and we found no concluding results from the simulation of filed flight plans. Since then our tools for analysis also for radar data have evolved and would make this study feasible again.

7. Traffic Flows and Sector Dependency: The empirical study evaluated the connectivity of flows and sectors in an air traffic control centre. It showed the sensitivity of sectors to changes of specific flows. The EEC has conducted parallel studies that are becoming features of the NEVAC tool, and shows very promising results. Our study has been interrupted; yet, the better knowledge of flows and their contributions to the probability of saturation in sectors will be central for full automation.

Some studies are ongoing at the moment of edition of this thesis:

8. Air-Gates: This simulation study evaluates first prototypes of air-gates for χ:Dynamic Flow Routeing, already including implementations for flow -rerouting and -splitting.

9. Flow Rate Probability: This empirical study makes statistics about flow entry rates probability based on radar data, which will lead to other knowledge about overload probabilities, conflict probabilities and herewith workload probabilities. This work will create essential knowledge for the treatment of uncertainties in automated planning.

4.1.2 Work Chronologic Order

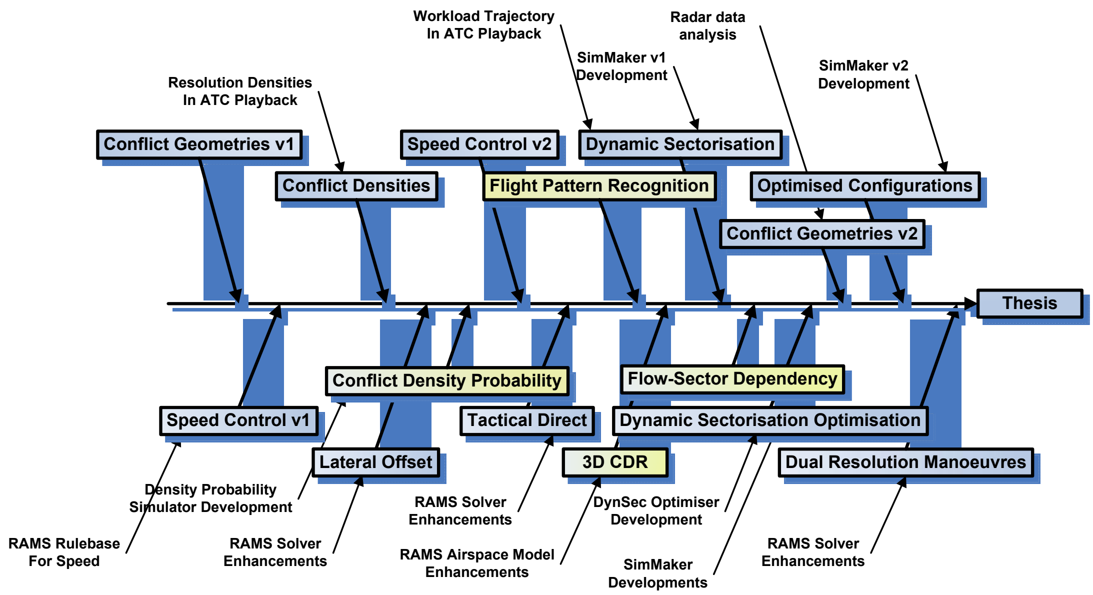


Figure 12: Studies Chronologic Order

Figure 12 depicts the studies chronologic order and the developments that were necessary for the studies. Developments are important to mention because they take a lot of effort, and in the case of changes to tools from outside companies require a longer starting time.

4.2 Complexity Studies

This section covers two studies on complexity with the initial understanding that solving conflicts is a main success factor of automation systems and it would therefore be useful to have a better understanding of conflicts. One work is an empirical analysis of conflicts based on multiple underlying real and simulated data and creates taxonomy of conflicts in Europe. The other work shows with graphical analysis based on simulation that conflicts occur in geographical clusters justifying a new planning strategy baptised ‘Organisation of Bottleneck Traffic’.

4.2.1 Conflict Geometries

4.2.1.1 Objective

The understanding of the nature of aircraft conflict is a prerequisite for successful automation. The approach is to conduct empirical analysis based on fast-time simulation tools that are fed with European traffic data. Part 1 uses European-wide corrected flight plans and part 2 regional radar data. Conflict geometries are counted and classified. The result is discussed using mathematics for conflict probability.

4.2.1.2 Key Literature

Empirics and simulation - [41][43][44], Uncertainties – [45][40][14]; results partly published [46].

4.2.1.3 Modelling and Simulation

Part 1 uses the COCA (Complexity Light Analyser) complexity simulator with corrected flight plan data for all of Europe. The COCA conflict model is an approximation with a pizza-box, and conflicts are counted when boxes overlap inside of a geometric grid. Part 2 uses the RAMS v5.27 simulator with filtered radar plots for the Maastricht upper airspace. RAMS uses circles and ellipses as separation buffers and has a precise conflict detection algorithm.

4.2.1.4 Results

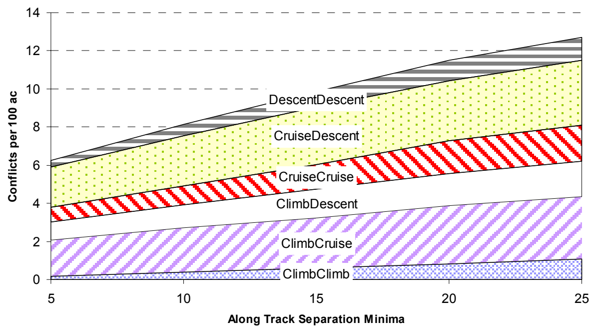


Figure 13: Radar Encounter Geometries

Figure 13 shows the number of different vertical conflicts per 100 aircraft depending on the along track separation minima that are measured with the radar simulation. The cruise-cruise conflict occurs at about 10% only; cruise-climb- and cruise-descent count for about 60%. Conflicting aircraft have the probability p to be in climb, cruise or descent respectively of p(climb)=26%, p(cruise) = 44%, and p(descent) of 30%.

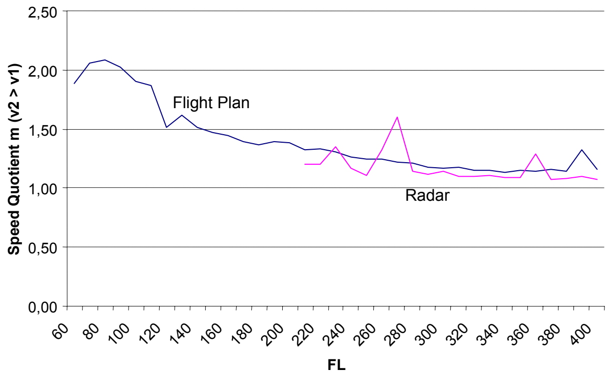


Figure 14: Speed Quotients

Figure 14 shows that encounter speed quotient over the flight levels for both radar and flight plan simulations.

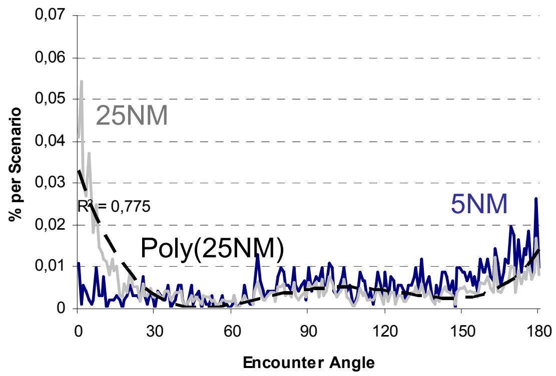


Figure 15: Radar Distribution over Encounter Angles

Figure 15 depicts the distribution of encounter angles in percentages for radar data. There are no conflicts with 5NM along-track separation infringements as can be expected from radar data, with increasing separation minima the along-track and merging conflict counts increases because of aircraft often getting close when sequenced and merged.

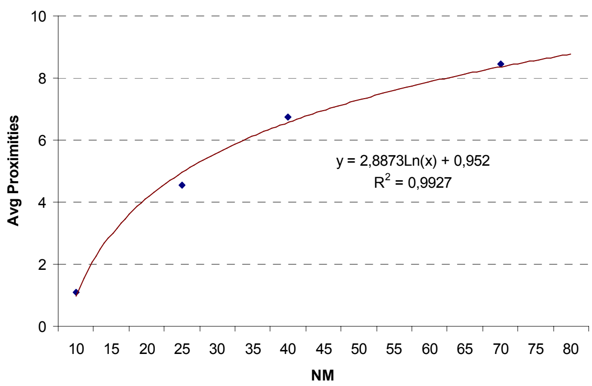


Figure 16: Flight Plan Avg. Proximities

Figure 16 counts aircraft proximities at conflict, which is one of the often used parameters for complexity. In average there is 1 other aircraft in 10NM range, 5 within 25NM etc. The logarithmic trend seems to fit well.

4.2.1.5 Discussion

Irvine [45] finds a relation of encounter angle Θ and quotient of speeds m to describe the variance of the minimal displacement, expressed by a factor γ^2.

$$\gamma^2 = \frac{\left(\frac{1}{m} + m\right)\sin^2\theta}{\left(\frac{1}{m} - 2\cos\theta + m\right)}$$

An operational interpretation of this displacement variance would be that the higher this factor is, the higher the uncertainty of the predicted conflict is and the more buffer airspace is needed. Figure 17 shows an interpretation of the minimal displacement variance based on the measured Θ and m.

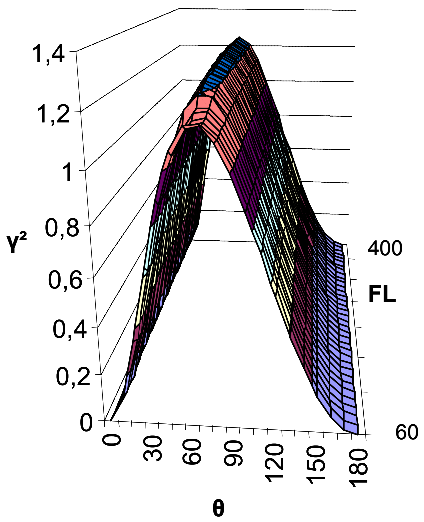


Figure 17: Minimal Displacement Variance

4.2.1.6 Conclusions

Both flight plan and radar data confirm that most conflicts occur when aircraft are either climbing or descending. Most of the academic literature on conflict detection and resolution, however, treats the lateral case (cruise-cruise) and only in exception the vertical cases. It is recommended to treat vertical cases with priority.

The uncertainty of conflict prediction seems to be highest at an angle of about 60 degrees; fortunately the radar measures show that there are relatively small amounts of encounters at this angle, possibly due to the route network architecture.

4.2.2 Conflict Densities

4.2.2.1 Objective

Aircraft in conflict are a key indicator for complexity, and the central problem of air traffic control. In the context of planned traffic organisation the knowledge of conflict areas and conflict clusters are a prerequisite for the development of successful strategies. Therefore it is useful to define refined parameters of conflict cluster analysis; this study treats conflict densities. The discussion targets the analysis of conflict densities with and without conflict resolution using speed clearances, that result from the speed-control investigations (see below).

4.2.2.2 Key Literature

Key publications treat conflict clusters [18] and environmental aircraft [44]. The work is partly published in [47].

4.2.2.3 Modelling

A *conflict* is usually defined as the infringement of protection volumes of two aircraft. The protection volumes may have varying shapes with varying dimensions depending on the applicable rules of the airspace, but are mostly cylinders with aircraft in the centre. Mathematical models normalise these to standard horizontal and vertical separation units, the radius (and not the diameter) presenting one unit. The *Closest Point of Approach* (CPA) is the position of the aircraft having the minimal displacement distance to the other conflicting aircraft. A *Conflict-Volume* is created by the sum of the intersections of the protection cylinders during the conflict duration. A *Conflict Cluster* (CC) is a single graph of aircraft related by concurrent conflicts. ***Conflict Density*** (C-DNS[76]), in contrast, is the sum of conflicts in a time window and airspace volume i.e. sums of pairs of conflicting aircraft that may or may not be represented in one or more cluster graphs. It can be remarked that both CC and CD do not take environmental aircraft into account.

Conflict Densities relate to airspace volumes like sectors, routes, route segments, navpoints or any other kind of volume. Sometimes conflicts are visualised with only one point, either conflict start or CPA; or for the duration of conflict. This leads to C_{SECTOR}-DNS, C_{ROUTE}-DNS, $C_{NAVPOINT}$-DNS, C_{CPA}-DNS, C_{TRAIL}-DNS :

Figure 18 depicts an example of the different conflict densities in two dimensions only, where the circles around the aircraft symbolise the protection circle. A is position of aircraft at time *to*, D''' position of D at *t3*. A is in conflict with B during $\Delta t_{AB} = t1 - to$. B is in conflict with C at time *to*. D is in conflict with E during $\Delta t_{DE} = t3 - t2$. A or B are not supposed to be in conflict with D or E.

76 C-DNS = Conflict Density

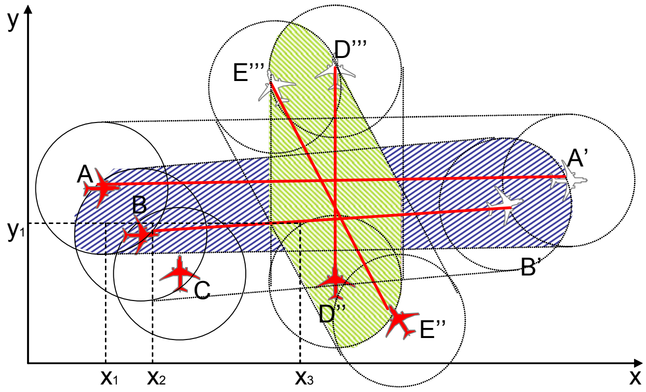


Figure 18: Conflict Densities

At time *to* aircraft A and B as well as B and C are in conflict, therefore A, B and C builds a conflict cluster in space. All aircraft A, B, C, D, E build a conflict cluster in space and time for the time interval $\Delta t = t4\text{-}to$. The CPA Densities are C_{CPA}-DNS(x1, y1, Δt) =2 and C_{CPA}-DNS(x2, y1, Δt) =3. The Conflict-Trail Densities are C_{TRAIL}-DNS(x2, y1, Δt) =1 and C_{TRAIL} -DNS(x3, y1, Δt) =2. Further suppose that A and B share the same leg of a route in their respective flight plans and the conflict occurs on that route leg, then C_{ROUTE}-DNS(route) =2, because the conflict between A and B will count for two CPA occurrences, one for each aircraft.

Resolution Density (RD) is similar to conflict density and relates the density of conflict resolution types to airspace elements. Conflict resolution types are specified with the manoeuvres that are applied on conflicting flights. Again, it does not apply to environmental aircraft. This leads to similar definitions: RD_{CPA} , RD_{TRAIL} etc.

4.2.2.4 Simulation

Fast time simulation data is visualised and analysed; the visualisation tool {ATC Playback} is extended for conflict trails and resolution densities.

4.2.2.5 Results

Conflict- and Resolution Density can be visualised with a geographical viewer. Figure 19 shows an example of C_{Trail}-DNS and C_{CPA}-DNS for the identical situation. C_{CPA}-DNS has shown to be very useful for the visualisation of hot-spots; however, it can be misleading because the significant trigger is the conflict-start and not so much the CPA. There C_{Trail}-DNS helps, by loosing the notion of CPAs.

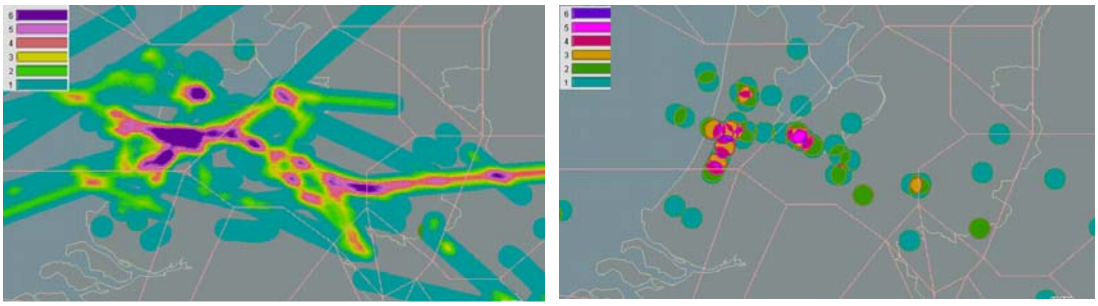


Figure 19: C_{Trail}-DNS (left) and C_{CPA}-DNS, same situation

Figure 20 depicts an example of conflict and resolution densities along the time axes. The sample is normalised to the maximum occurred conflicts in a time interval. The resolution rates for this specific case (speed-control only) vary very much between time intervals and have been integrated over the hour.

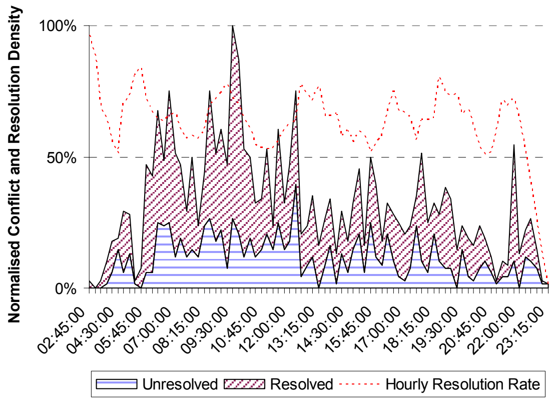


Figure 20: Normalised Conflict Density (1800 samples)

4.2.2.6 Discussion

Solvability: The ability of conflict solvers e.g. from fast-time simulation or online predictors, can serve as a complexity indicator, because there are situations with many conflicts and high resolution rates, and others with relatively low conflict rates and low resolution rates. I.e. there are complex and less complex traffic situations depending on the flows. If for instance the solver explores the six degrees of freedoms for each aircraft in the conflict encounter, then it will still not resolve all conflicts, and then the resolution rate will give a very good indication of the complexity of the situation. Usually solvers scan the conflict area with deviated trajectories. During this scanning solvers detect other environmental aircraft that lead to follow-on conflicts and hinder a simple resolution. A valid complexity indicator can then be derived integrating solvability, number of trial trajectories, and hindering environmental proximities, which is more significant than the simple counts of proximities.

4.2.2.7 Conclusions

Both Conflict Density and Resolution Density are very useful in the analysis of the traffic. The visualisation of resolution densities can help in the analysis of fast time simulation output. Different resolution manoeuvres can be analysed not only in their ability to resolve a problem, but also in their specific geometries. Especially the visualisation of conflict-trail densities has proved to be useful for the understanding of problem hotspots.

4.3 Plan-Actions Studies

This section presents studies that treat actions that a strategy such as 'Organisation of Bottleneck Traffic' could possibly apply if the objective is to manoeuvre traffic in a time horizon of 5 to 30 minutes. Tactic clearances can hardly be used in this planning horizon and herewith also tactic solvers are not useful; instead, other actions must be evaluated that could be used for planning solvers – yet we are still acting on individual deterministic aircraft and not on stochastic flows. The candidate actions are speed control, lateral offset, and tactic direct-to. In order to compare these with the performance of currently used clearances there are two studies carried out to maximise the fast time solver for the traditional manoeuvres. The studies present mathematical fast time models and simulations to evaluate the benefit of the manoeuvres in highest density airspace in Europe.

This section also contains a study focussing on possible new actions targeting a strategy for 'Workload Balancing' by using dynamic sector reshaping to adapt the airspace to fit to the demand. The paradigm is to segregate airspace around bottlenecks with the underlying rationale that not all bottlenecks are at the same level of magnitude at the same time, and therefore airspace portions can be shifted from a lesser active bottleneck to another active bottleneck resulting in balanced controller workload.

4.3.1 Tactic Resolution

4.3.1.1 Objective

The performance of tactic conflict resolution manoeuvres are investigated in order to create a comparison baseline for the following tactic resolution manoeuvres. Investigated are vectors and vertical offset manoeuvres.

4.3.1.2 Key Literature

The literature review was treated in the introduction of this document (see 1.1).

4.3.1.3 Modelling

The RAMS conflict solver was used for the study. Its engine is trajectory oriented and resolves conflicts under application of constraints more than the flight profiles: sectors, special use airspace, changing separation minima, LoA[77] constraints etc. This is a major difference in comparison to many and unfortunately also academic studies, in that it resolves in a wider context. Figure 21 shows a RAMS screen with the majority of manoeuvres that are available.

The RAMS solver works numerically and works on two levels (Figure 22):

1. A rule system reads a set of rules that are programmed by the RAMS user. In its simple forms it investigates the conflict, its geometry and its context like the aircraft performance, flight phase, proximity to boundaries, speeds etc.
2. Its engine uses brute force to find the solution that the rule system chooses.

[77] LoA – Letter of Agreement

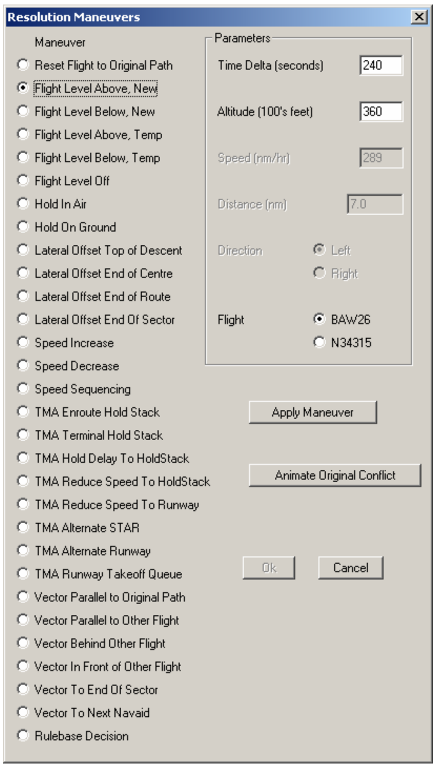


Figure 21: RAMS set of manoeuvres

This study targets to find the potential of the solver to resolve conflicts. Therefore its rules are very simple and force it to scan the airspace for solutions disregarding other rules.

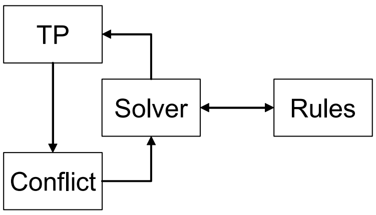


Figure 22: RAMS Conflict Solver

The improvements to the RAMS conflict solver are done in several steps:

Scenario 1: Default factory settings.

Scenario 2: Keep the default rule base but change the conflict resolution parameters in order to maximise resolutions.

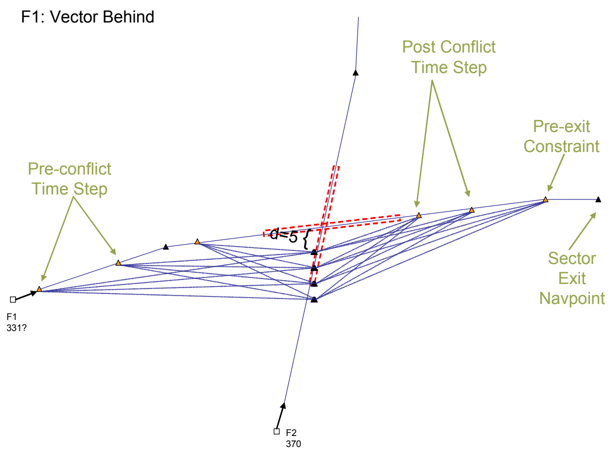
Scenario 3: RAMS with adapted manoeuvre parameters and additional rules.

The manoeuvres that were part of the rule base are listed.

Manoeuvre
HeadingParallel
LateralOffsetTOD { top of descent }
LateralOffsetEOC { end of center }
LateralOffsetEOR { end of route }

LateralOffsetEOS { end of sector }
LevelOff
NewFlightLevelAbove
NewFlightLevelBelow
ParallelOffset
SpeedIncrease
SpeedReduction
TempFlightLevelAbove,
TempFlightLevelBelow,
VectorBehind
VectorInFront
VectorToEOS
VectorToEOC
VectorToNav
VectorToSkipNav

Figure 23 shows examples for the functioning of the solving algorithm. When a conflict is detected then solver uses several constraints for the conflict resolution, which can either be set as simulation defaults, or overwritten by the rule system. In addition the solver considers other constraints from the airspace. The resolution is mathematical, and not numerical, in that all geometries, flight legs, intersections, separation buffers etc use mathematical descriptions.



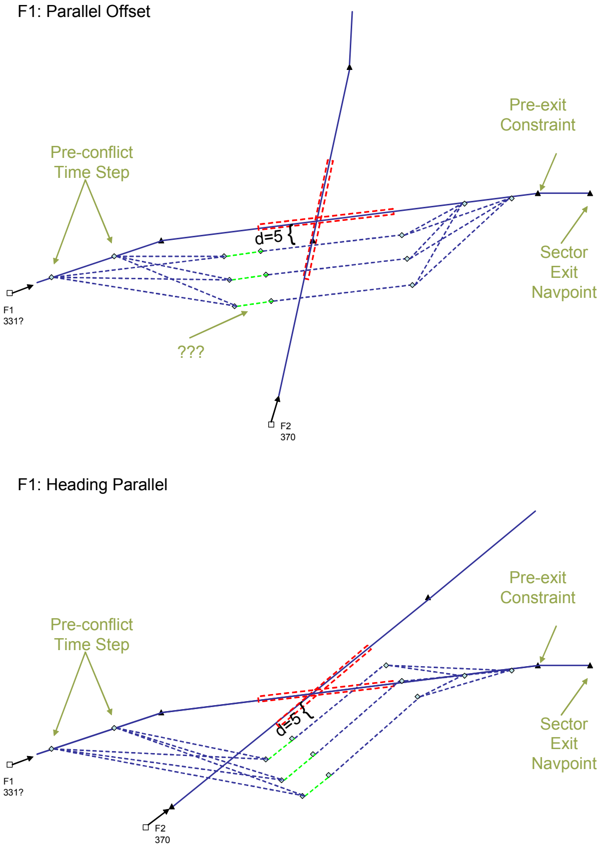


Figure 23: Example for Resolution Algorithms

4.3.1.4 *Simulation*

A setup is used where three airspaces in the core area are investigated: a relative large sector above flight level 345, a small sector in middle airspace (245- 345), and the entire Maastricht UAC with its elementary operational sectors.

4.3.1.5 *Results*

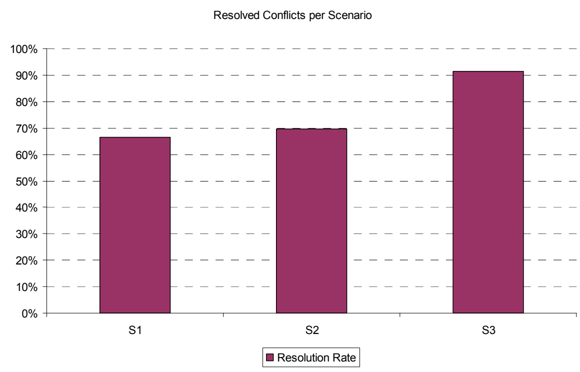


Figure 24: RAMS Solver Resolution Rates

Figure 24 depicts the resolution rates of the three scenarios. It can be seen that the improved rule base solves many more conflicts and attains high resolution rates. It was found that many of the remaining conflicts are due to simulated situations where aircraft enter into a sector whilst already in conflict and where the solver had no possibility to resolve.

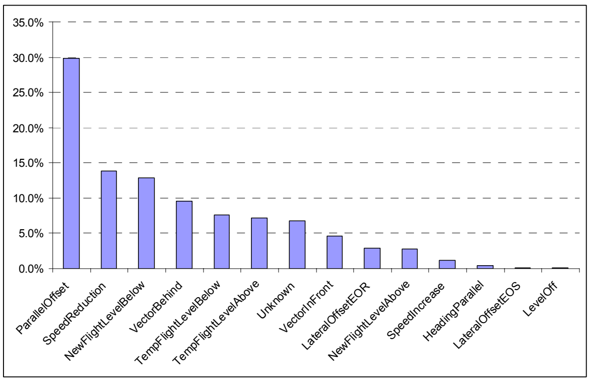


Figure 25: Resolution Distribution by Category

Figure 25 lists the successful manoeuvres. There is a type ‘unknown’ which is logged when a situation occurs where several aircraft are in a conflict cluster and one conflict resolution does also solve another one.

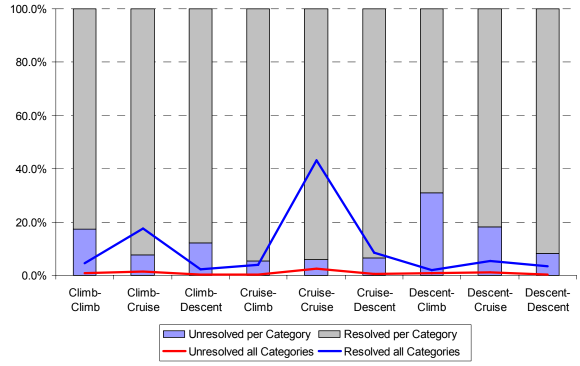


Figure 26: Resolution Rates by Encounter Geometry

Figure 26 shows the resolution distribution over the vertical encounter geometries for scenario 3. It can be seen that the simulations show higher capabilities in solving cruising aircraft, possibly again due to wrong entry conditions.

4.3.1.6 Discussion

The conflict solver in RAMS could be improved, yet, the solver did not solve all conflicts. Analysis showed that aircraft entry conditions mainly lead to unresolved conflicts. Further refinements of the simulation setup were not done.

4.3.1.7 Conclusion

The RAMS conflict solver could be highly improved for tactic manoeuvres from resolution rates at about 70% in the default factory settings to more than 90%. Remaining unresolved conflicts are mostly due to wrong aircraft entry conditions during the simulation.

Additional improvements to the tactic solvers are treated in a study on dual manoeuvres in section 4.3.2.

4.3.2 Dual Resolution Model

4.3.2.1 Objective

The study is a further improvement of the RAMS conflict solver. In the factory version conflicts are solved by navigating one aircraft only (see study section above). This leads to tactic resolution rates of about 70%, and in its improved version to up to 90%. Air traffic controllers, however, achieve to resolve all conflicts I reality. If necessary the air traffic controller vectors both involved or even other contextual aircraft in order to resolve conflicts.

The study introduces a new resolution model to the RAMS simulator that allows for the navigation of both aircraft involved in conflicts. Its objective is to further lower the number of unresolved conflicts so as to approach realistic behaviour.

4.3.2.2 Key Literature

The literature review was treated in the introduction of this document (see 1.1).

4.3.2.3 Modelling and Simulation

The RAMS conflict solver was explained in study section above; the dual conflict resolution adds to the standard solving mechanism the ability to navigate both aircraft (Figure 27). The solver does still use the RAMS rule system.

For the setup of the new part of the rule system which resolved dual conflicts, two air traffic controllers were consulted over several sessions on their typical behaviour. The output was used in the setup. Discussed were about 200 situations with different encounters (angles, vertical profiles, speeds, aircraft types, phase of flight, position in sector etc.). These were further generalised and some thousand combinations generated.

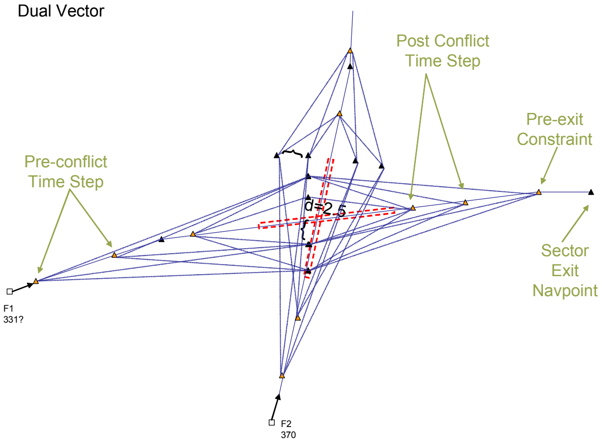


Figure 27: Example for Resolution Algorithms

The programming of the rule system extracts this information and converts it into some rules only, which demonstrates the power of a rule based approach. Also it avoided complicated modifications to the kernel of the solver; instead minor modifications to the solvers interface were sufficient.

By using the rule system as decision making, it is also possible to try different manoeuvres for the two aircraft e.g. one vector and one vertical offset; this however was not used because it leads to additional complexity. I.e. that the dual manoeuvres were always identical: vector & vector, offset & offset etc. Two vertical manoeuvres were not simulated, even though the rule system allows for it, and this might be operationally helpful in extreme cases. Vertical resolutions navigating only one aircraft were enabled.

Manoeuvre
LateralOffsetTODLeft { top of descent }
LateralOffsetTODRight { top of descent }
LateralOffsetEOCLeft { end of center }
LateralOffsetEOCRight { end of center }
LateralOffsetEORLeft { end of route }
LateralOffsetEORRight { end of route }
LateralOffsetEOSLeft { end of sector }
LateralOffsetEOSRight { end of sector }
LevelOff
NewFlightLevelAbove
NewFlightLevelBelow
ParallelOffsetLeft
ParallelOffsetRight
SpeedIncrease
SpeedReduction
TempFlightLevelAbove,
TempFlightLevelBelow,
VectorBehind
VectorInFront

4.3.2.4 *Results*

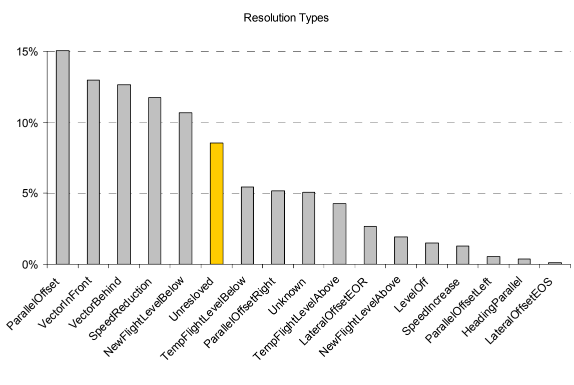


Figure 28: Resolution Distribution

Figure 28 lists the distribution of (dual) manoeuvres that lead to resolutions. The total resolution rate in comparison to the improved single manoeuvre simulations could slightly be improved by a quarter of a percentile, which is not significant.

Figure 29 shows that also the resolutions of different vertical conflict geometries are unchanged in comparison to the study above.

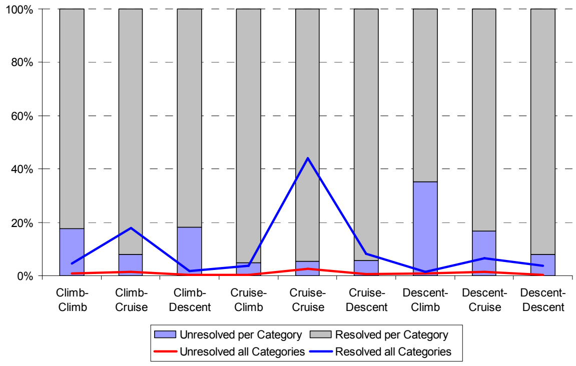


Figure 29: Resolution Rates by Encounter Geometry

4.3.2.5 *Discussion*

The results of this study are that the dual manoeuvre does hardly improve the ability of the solver. This is due to the fact that most of the unsolved conflicts are due to erroneous flight entry conditions into the simulation, where the aircraft are already in (unsolvable) conflict, something that would hopefully never happen in reality.

Possibly the relation of single manoeuvres against dual manoeuvres with 99% of singles is realistic, given that a dual manoeuvre more than doubles controller workload and hence is to be avoided unless really necessary.

4.3.2.6 *Conclusions*

In comparison to study 4.3.1 no significant improvement can be achieved with the inclusion of dual manoeuvres.

Yet the degree of realism of the rule system could be improved because the new setup better reflects true operation. The full value of the new solvers will be seen in larger simulations which will avoid wrong entry conditions. For this study it was found too cumbersome to modify all those cases manually, therefore a final conclusion will be seen in future studies of this type.

Yet, the RAMS solver has been lifted to a level where it could be envisaged for use as an online decision support tool, which is currently under considerations at the Maastricht Upper Area Control Centre. Therefore both studies on tactic conflict resolutions must be considers as very successful.

4.3.3 Tactic Direct

4.3.3.1 Objective

The objective is to evaluate two types of direct-to clearances, one that is given as a tactic controller clearance for conflict avoidance, and the other as a routine planning clearance at sector entry for complexity reduction. Directs as tactic clearances are operational to a great extend and therefore do not present a research area. Figure 30 illustrates this fact with a trajectory density picture for one summer day traffic in 2007. The study serves as comparison material for the more innovative studies on lateral offset and speed control.

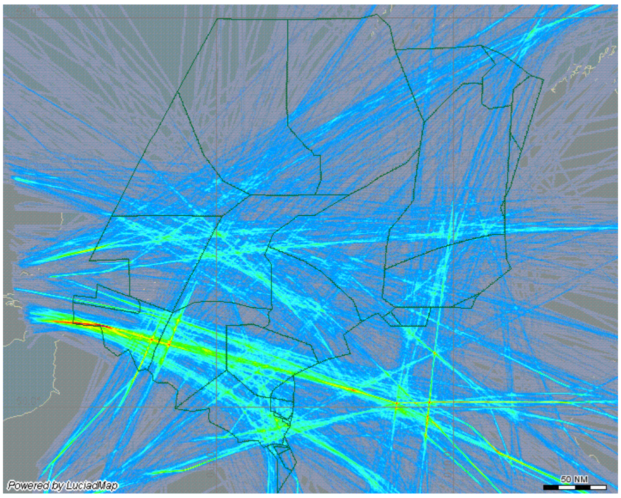


Figure 30: Radar picture for Maastricht (27 June 2007)

The potential of direct clearances depend on the underlying route network structure and contextual situations. If the route network is already direct then a direct clearance has no benefit, and will only be used to put deviated aircraft back on flight plan. If, however, the route structure is not direct for instance due to military zones or tactic reroutes, or when aircraft systematically fly deviated due to some frequent upstream constraints, then the direct-to manoeuvre will have benefit.

4.3.3.2 Key Literature

Directs are no research subject anymore, they have been studied in the Free Route Airspace Programme [48] and some fast time simulations evaluations e.g. [49].

4.3.3.3 Modelling

The direct-to clearance has not been modelled in a dynamic simulator like RAMS before; instead simulators are set with traffic flowing on direct routes, which is much simpler to model. This study implements dynamic models for direct-to clearances, because the specific objective is to study the dynamic behaviour and not the static direct-routes.

Two clearances are implemented:

- The tactic direct is a clearance for conflict avoidance. Its trigger is conflict detection. The RAMS rule system evaluates the situation and if convenient uses the direct-to resolution manoeuvre. This can be a direct clearance to the end of the sector or of the centre.

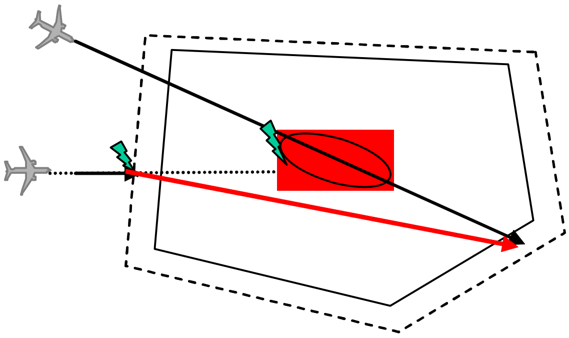


Figure 31: Direct-to Example

- Tactic direct is a routine clearance at sector entry to proceed direct to a specific point: a downstream navigation point, or the end of the sector, or the centre. The implemented model allows per sector controller to set rules depending on the flows to which aircraft belong, and to combine it with a number of parameters from the aircraft context. E.g. an aircraft departing from a specific airport and having a specific weight could be directed to navigation point AAA, and all other ones departing from the same airport and belonging to other classes to the end of the centre.

Both direct clearances take account of special use airspace like military activation. If activation occurs and the rules would normally apply, but the aircraft would cross the activated zones, then no direct clearance is used.

Special attention was given to climbing and descending aircraft and their intersection points with airspace boundaries; special problems occur in the model if the intermediate navigation points that are shortcut by the direct clearance contain level constraints.

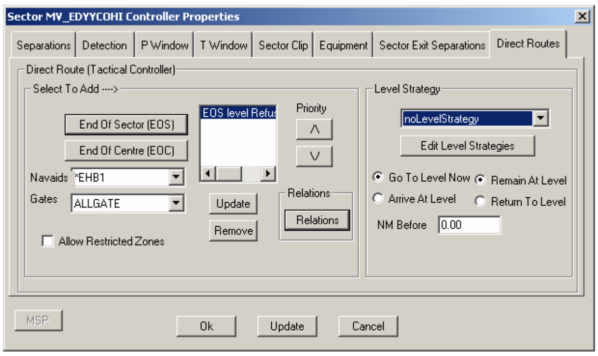


Figure 32: Direct-to Simulation Setup

Figure 32 shows the setup page in the RAMS simulator that was added for the modelling of the direct-to function. This permits per controller to set the direct-to either to the end of the sector, end of the centre, or to downstream navigation points, or to air-gates. (The new air-gate function is not part of this study.) Figure 33 shows that the direct-to function can be set as a relation, which means that it will be triggered only if specific contextual events are true; in the example it is connected to a flight-count in the sector.

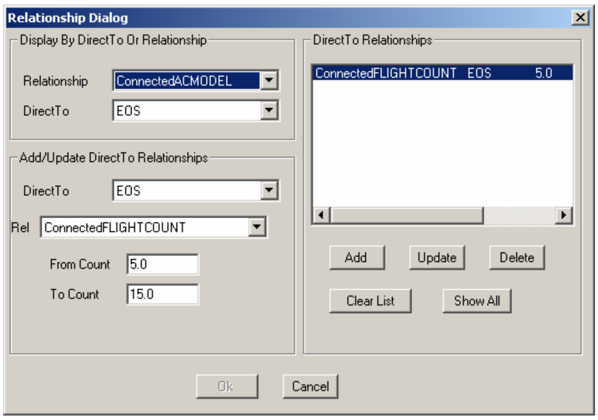


Figure 33: Conditional Relations

4.3.3.4 Simulation

This study uses simulations with several settings for traffic, airspace and controller model. The setup is the same as used in the studies described in sections 2 and 2.2.

4.3.3.5 Results

Figure 34 shows the result of the direct-to simulations. The potential of a direct is a measure that relates the length of the flight plan to the length of the direct in the centre, and was estimated based on manual measures on a map.

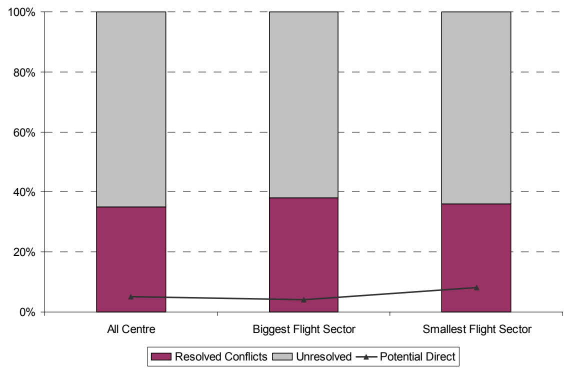


Figure 34: Resolutions with Direct-to

The resolution rates are around 35% of conflicts; a relation with the size of the sector can not be proved, nor with the ability of the flight plans of the sector to be directed. Common sense would have expected that the more flight plans in a sector are curved e.g. due to circumnavigation of military airspace, the higher is the potential to resolve conflicts with the direct-to manoeuvre.

The number of conflict decreases with the application of direct routes. Figure 35 show that the conflict density also decreases, which leads to lower complexities due to lesser conflict clusters.

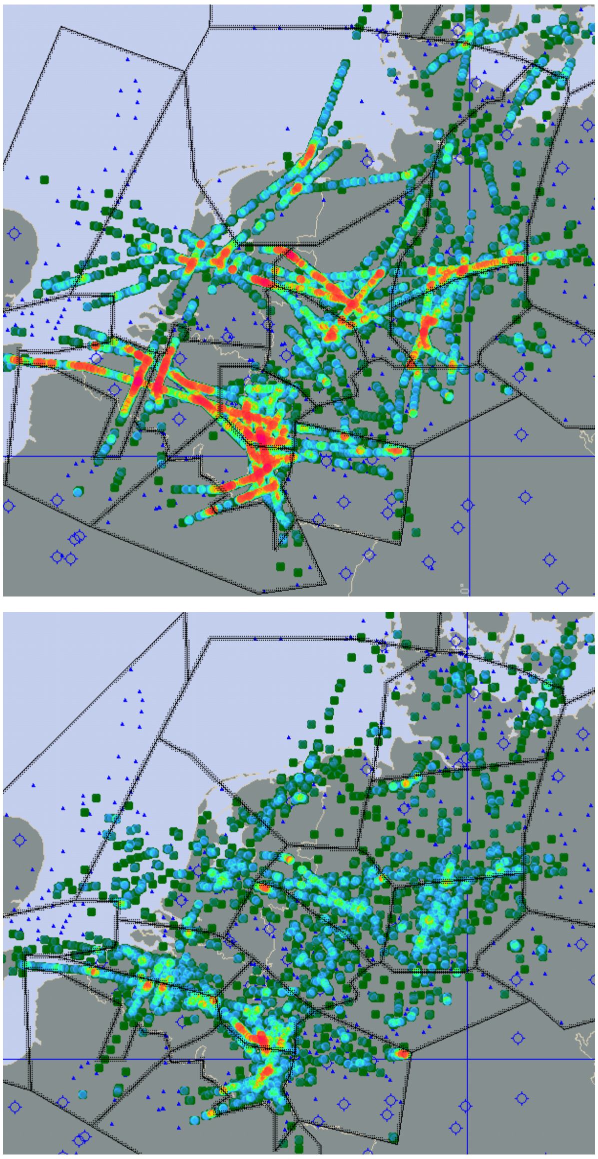


Figure 35: Conflict Density in Fixed Route Network (above) and Direct Route Network.

4.3.3.6 Discussion

The potential of direct clearances depends highly on the underlying airspace. First and foremost, the airspace route network must allow using shortcuts and must be non-direct, which is often the case with military areas. In U.S.A. circumnavigation around weather areas could also be regarded as big areas that create curbed routes. In Europe, when military areas are deactivated and when Flexible Use of Airspace[78] is applied, then civilian traffic that was filed around the military areas can be sent direct. In this context it is worthwhile to note that Conditional Direct Routes[79] may help to structure frequently happening directs, but its meaning is rather the tunnelling of selected flows with FUA procedures.

Another delimiter of directs is the airspace sectorisation. Only those sectors which are either big enough or at the entry of the centre profit from directs, others which

[78] FUA – Flexible Use of Airspace

[79] CDR – Conditional Direct Route (type 2 and 3 cannot be filed)

are close to LoA[80] agreements at the centre exit will not profit, unless LoA can be adapted.

Directs may also solve problems in one area but create others and possibly stronger problems in adjacent areas. Centres will only profit from directs if guidelines are clearly set and organised. Otherwise even within a centre it might lead to adverse effects like bunching and strong bottlenecks.

Directs are very economic from the airline perspective regarding fuel burn and emissions.

Directs are very welcome for aircraft that have encountered delay and that can win some minutes, which are sometimes crucial for hubs.

Directs bear the risk of desynchronising the network, especially for aircraft which have no delay and are at the start of their flights.

4.3.3.7 Conclusion

This study has focussed on direct-to clearances that are applied as a tactic flow measure in order to reduce conflicts and herewith complexity. The direct-to manoeuvre presents a high gain in flight efficiency in airspace where many flights file flight plans on routes around restricted airspace, and where this airspace becomes available due to flexible use of airspace. By flying direct the flights make a better usage of the available airspace by spreading out the traffic, and herewith lowering complexity, and conflict probability.

For planning purposes the direct-to has a very positive side effect, because trajectory prediction becomes very accurate and herewith all correlated predictions more precise e.g. conflict prediction; complexity prediction or workload prediction etc.

The direct-to manoeuvre is a powerful candidate in the toolbox for the organisation of bottleneck traffic with a tactic time horizon.

[80] LoA – Letter of Agreement

4.3.4 Lateral Offset

4.3.4.1 *Objective*

Strategic Traffic Organisation deviate aircraft away from their initial flight plan to resolve complexity bottlenecks. One of the possible measures to act on the flight is the parallel offset, which seems more appropriate than vectors. Lateral offset is a procedure in air traffic control that sets aircraft on a parallel track along the flight plan. Despite the fact that a high percentage of the flying aircraft fleet is equipped to fly the offset automatically, it is not used in operations. Almost no research has been conducted so far. This study uses a fast-time simulation model modelling different parameters of the offset manoeuvre are like the moment of start of implementation, the offset angle, the offset distance, and the duration of the manoeuvre until its return to the initial flight plan. The main performance metric that is applied is the capability to resolve conflicts and conflict clusters.

4.3.4.2 *Key Literature*

The aircraft capabilities are defined in RTCA ([50], 2000), life trials for a limited number of aircraft (Herndon et al. [51] 2000, [52] 2004). Work published in [53].

4.3.4.3 *Modelling Lateral Offset Resolution*

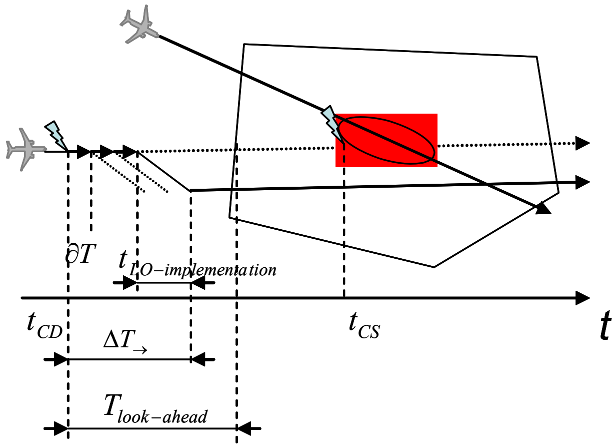
For the simulations in this study, a model for lateral offset has been developed in the RAMS[81] Plus simulator and resulted in its version 5.24. It simulates an operational procedure to offset with a controller specified turn angle/heading:

AT (time) TURN RIGHT/LEFT (heading or number of degrees) OFFSET (distance) REJOIN ROUTE ABEAM (location)

That corresponds to the following parameters:

1. The start time of the manoeuvre is a parameter that is set for the entire simulation setup. The resolution algorithm can either start its search at the position of detection of the conflict, or at the conflict start position. In the first case it will iterate in steps forwards from the detection towards the conflict, in the latter case backwards from the conflict start towards the detection point. The size of the steps can be configured. Let $\Delta T_{\rightarrow}$ and $\Delta T_{\leftarrow}$ be the resolution time window in forward or backward direction, ∂T the iteration time steps in that solution window, the forward iteration start at conflict detection time t_{CD} and the backward iteration start at conflict start time t_{CS}, as depicted in Figure 36.

[81] RAMS – Reorganised ATC Mathematical Simulator



2.

Figure 36: LO time parameters

3. The direction of the offset is set in the resolution rule base and is either to the left or to the right $\mu = (left, right)$. Making it available in the rule base increases the flexibility in comparison to the global simulation setup parameters. This flexibility has not been exploited so far and here the rule base simply iterates left and right side through the different offset distances, starting with the left side.
4. The offset angle α in degrees, $0 < \alpha \leq 45°$, is set for the entire simulation setup. The resolution algorithm starts with a mean value and iterates in increasing steps until a minimal and maximal value. The mean, variation and step size ($\overline{\alpha}$, $\Delta\alpha$, $\alpha_{\Leftrightarrow}$) values can be configured.
5. The LO distance $d_{\amalg}$ in nautical miles is a parameter that is set for the entire simulation setup. The resolution algorithm starts with a minimal value and iterates to a maximum value using steps. The minimum, maximum and step size values can be configured ($d_{\amalg-\min}$, $d_{\amalg-\max}$, $d_{\amalg-\Delta}$).
6. The location of rejoin is set in the rule base. It can be set to rejoin at the end of the route, at sector exit, centre exit, or at top of descent (Υ_{EoS} , Υ_{EoC} , Υ_{EoR} , Υ_{TOD}). Υ_{TOD} should be interpreted as “stay on LO until as late as possible”.

   If left and right offset directions are not programmed in the rule base, then the default algorithm behaves as follows:

   FOR EACH Υ_{EoS} , Υ_{EoC} , Υ_{EoR} , Υ_{TOD} (rule-base driven)
   FOR flight1 AND flight2 (rule-base driven)
       FOR $\Delta T_{\rightarrow}$ OR $\Delta T_{\leftarrow}$
         FOR EACH $d_{\amalg}$
           FOR EACH μ
             FOR EACH α
               TRY new trajectory

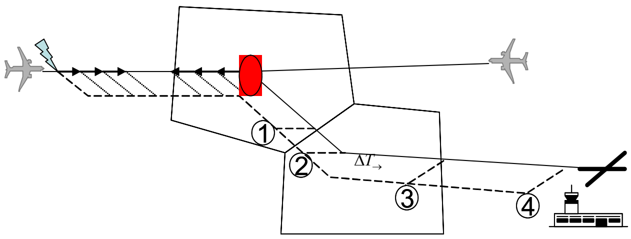


Figure 37: LO parameters

Figure 37 illustrates a conflict between two aircraft in a sector, where the adjacent sector is in the same centre. Then the four rejoin locations are 1. Y_{EoS}, 2. Y_{EoR}, 3. Y_{EoC} and 4. Y_{TOD}.

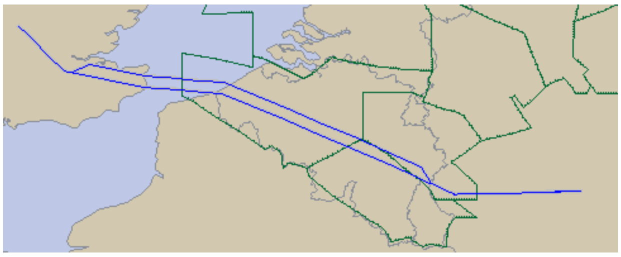


Figure 38: Simulator example trajectory

Figure 38 depicts an example trajectory from one of the simulations with its offset.

4.3.4.4 Simulation

The same simulation setup is used as for the speed control study (see sections 4.3.5). The number of possible combinations of setup parameters is very high and because of the long duration of a single simulation setup only a sensitivity analysis is conducted. All simulations in this study use lateral offset as the sole conflict resolution, no other resolution manoeuvres like vertical offset, speed, horizontal vectors or directs are considered. The objective is to evaluate the potential of lateral offset only and in isolation so that it can be compared to the other manoeuvres and with a special focus on the use for a long term strategic planning like for a multi sector planner.

The controller model imitates the behaviour of an executive Planning Controller (PC) and a traditional Tactic Controller (TC). In contrary to reality, however, the PC in the model does issue clearances and is therefore called an executive PC. The main difference between PC and TC is the look-ahead time when conflicts are detected, which was set to $T_{look-ahead}(PC) = 15\,\text{min}$, and $T_{look-ahead}(TC) = 0\,\text{min}$. I.e. the planner detects conflicts 15 minutes before the aircraft enters the sector, and the radar controller exactly at sector entry.

4.3.4.5 Results

The simulation results show very high resolution rates for Lateral Offset.

The high number of parameters that are to be evaluated leads to an explosion of combinations. The main scenario that was used simulates one day for approximately year 2010 traffic entering the three measured centres Karlsruhe, Maastricht and Reims, with more than 10,000 flights. One run takes about 1.5 days on a 2GHz Pentium, which reduces the number of possibly feasible simulations.

Therefore an exhaustive treatment of all combinations of parameters is practically unfeasible. Instead some scenarios analyse the sensitivity to change of parameters.

4.3.4.5.1 Rejoin Rules

The first set of simulations evaluates the performance of the four rejoin rules and a combination that was found to be optimal.

In this setup the offset angle was set to 30 degrees and the offset distance to start at 5NM and iterate in steps of 2NM until a maximal offset distance of 15NM. In addition the resolution search started at the detection of the conflict, which was set to 15 minutes before sector entry. The traffic sample for the year 2010 corresponds to 200% related to a 1997 baseline, which was already used in previous studies [1]. ($d_{\amalg-\min} = 5NM$, $d_{\amalg-\max} = 15NM$, $d_{\amalg-\Delta} = 2NM$, $\overline{\alpha} = 30°$, $\Delta\alpha = 5°$, $\alpha_{\Leftrightarrow} = 15°$, $T_{CD} \geq 15\min$, $\Delta T_{\rightarrow} \leq 30\min$, $\partial T = 300\sec$)

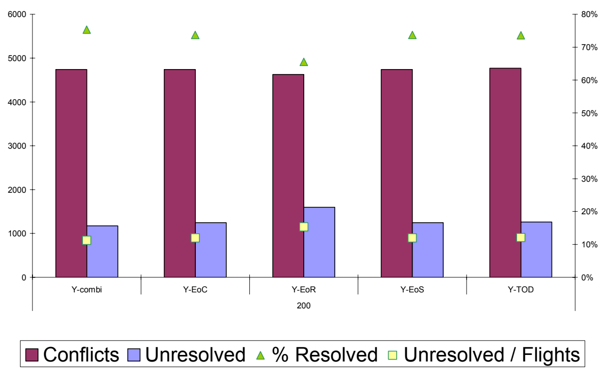


Figure 39: Different rejoin rules.

Figure 39 shows the number of conflicts (mauve column, left scale), the resolution rates P (green triangles, right scale), the absolute number of unresolved conflicts (blue column, left scale), and the number of unresolved conflicts related to the number of flights (yellow rectangles, right scale). The variations that can be observed are very small and all scenarios perform well. The combination of the different rejoin rules performs best with 75% resolution rates and 11% of unresolved conflicts per flight.

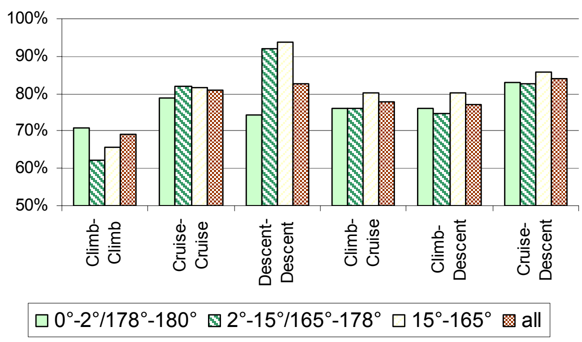


Figure 40: Resolution rates per conflict encounter angles and attitudes $\mathrm{P}(\vartheta,\theta)$.

Figure 40 quantifies the resolution rates depending on the conflict encounter angle $\theta, 0^{\circ} \leq \theta \leq 180^{\circ}$ and the aircraft attitudes ϑ for the combination of rejoin rules, $\mathrm{P}(\vartheta,\theta)$. It shows that in general LO has most difficulties to resolve conflicts where both aircraft are climbing, and resolves best where both aircraft are in descent, or one aircraft in cruise and the other in descent. Dependency on the encounter angle is high for climb-climb and descent-descent encounters, the first having relatively high resolution rates for very small or very high θ, and the latter having absolute high resolution rates wide angles.

It should be noted that the simulated traffic scenario generates a high rate of cruise-type conflicts in comparison to the pan-European study, with 33% of cruise-cruise conflicts (Figure 41) – compared to 18% for the pan-European traffic. This might be due to the higher flight level cut, this study measuring en-route air traffic control centres above flight level 245 compared to flight level 180 for the referenced study.

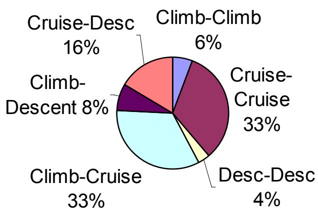


Figure 41: Conflict types in three measured centres Karlsruhe, Maastricht and Reims.

4.3.4.5.2 Offset Angles

The setup for the rejoin rules used a range of offset angles α. Figure 42 shows the distribution of resolutions when the offset angles iterated +/- 15° starting from 30° ($\overline{\alpha} = 30°$, $\Delta\alpha = 5°$, $\alpha_{\Leftrightarrow} = 15°$).

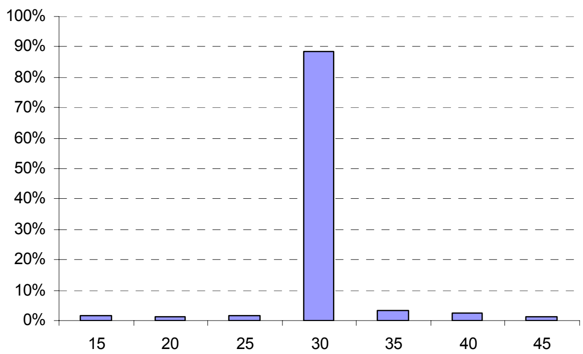


Figure 42: Distribution of resolutions over LO angles.

The offset angle influences the performance of LO manoeuvres to resolve conflicts. This is due to two reasons:

1. Small LO angles need longer implementation times $t_{LO-implementation}$. The smaller the LO angle, the longer the time until the aircraft reaches the offset track, the longer $t_{LO-implementation}$. The time difference between the conflict detection t_{CD} and conflict start t_{CS} times must be bigger than the implementation time. The horizontal approximation by simple geometry is:

$$t_{CD} - t_{CS} \geq t_{LO-implementation} \geq \frac{60 \cdot d_{\amalg}}{\bar{v} \cdot \tan\alpha}$$

, where $\bar{v}$ is the average speed in knots of the aircraft. If $d_{\amalg} = 5NM$, $\bar{v} = 430 knots$ and $\alpha = 10°$, then the value $t_{LO-implementation} \geq 3.9\min$.

2. Small LO angles require more airspace A, with the probability that this airspace is used by other environmental aircraft that may hinder the resolution process. The horizontal approximation by simple geometry[82] is:

$$A = \frac{d_{\amalg}^2}{\tan\alpha}, \quad \frac{A_1}{A_2} = \frac{\tan\alpha_2}{\tan\alpha_1}$$

E.g. 15 degrees occupy almost 4 times the airspace of 45 degrees LO angles.
E.g. 15 degrees occupy almost 4 times the airspace of 45 degrees LO angles.

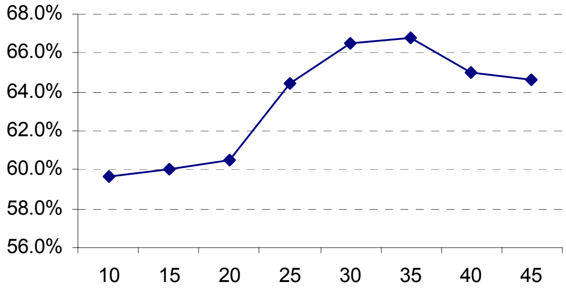


Figure 43: Resolution rates over LO angles.

Figure 43 shows the results from simulations with offset angles set to a single value without iterations around it. The scenarios run 10 to 45 degree offset angles in steps of 5 degrees ($\bar{\alpha} = \{10,15,20,25,30,35,40,45\}°$, $\Delta\alpha = 0°$, $\alpha_{\Leftrightarrow} = 0°$). The return angles are the same, $\beta = \alpha$. An empirical optimum concerning conflict resolutions can be observed at $\alpha = 35°$. The decreasing resolution rates for $\alpha = 40°$ and $\alpha = 45°$ can only be explained with the aircraft performance model that would reject the computation of zig-zagging trajectories.

4.3.4.5.3 Limited Offset Distances

It would be of interest to limit the offset distances to discrete values to emulate closely spaced parallel routes. Three simulations have been set up using offset distances with multiples of 7NM[83], where the resolutions could find one, two or three parallel tracks on each side, depending on the scenario. The offset angle was set to 35 degrees, the rejoin rules were the combination which performed best, and the planning controller implemented the offset manoeuvres starting at conflict detection with the look-ahead of 14 minutes and made every 200 seconds a new iteration.

[82] And other assumptions about usable airspace areas.

[83] 7NM offset distance assumed to correspond to realistic value for parallel tracks in close future RNP.

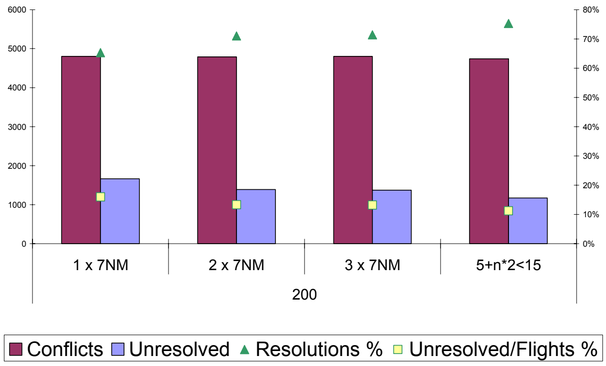


Figure 44: Offset to distinct parallel tracks.

Figure 44 depicts the result of the three simulations and for comparison the scenario that allowed for more parallel tracks between 5 and 15 nautical miles. It can be seen that still very high resolution rates are achieved, but lower than the comparison scenario. There is no difference between two or three parallel tracks with 71% resolution rates and 13% unresolved conflicts per flight. One parallel track performs less well, with 65% resolution rates and 16% unresolved conflicts per flight.

It should be highlighted that the resolution algorithm has no memory whether aircraft have already been put on offset or not, and will always try the left side first. Therefore it happens that the aircraft distribution over the multiple parallel tracks is slightly on the left side, and that more than the one, two or three parallel tracks are used, but only for a small number of aircraft.

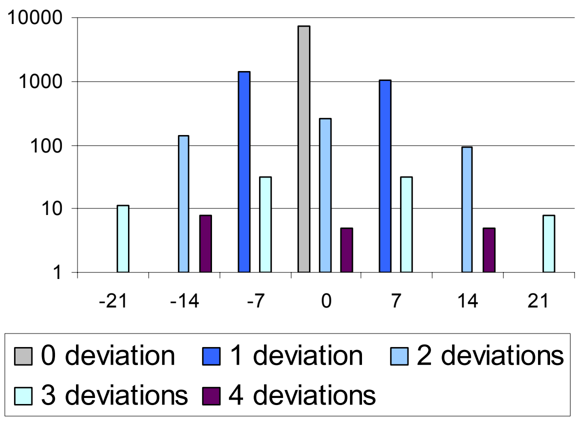


Figure 45: Aircraft distribution *log(N)* over parallel resolutions and number of deviations per aircraft.

Figure 45 indicates how many resolved aircraft have been put on which parallel track (negative = left side) for the scenario that uses only one parallel track for resolutions. 83% of resolved aircraft are deviated by one track of 7NM, 8% by 14NM and less than 1% by 21NM left and right side confounded, and 8% back to the flight plan. A normal distribution seems to apply here. Furthermore, 24% of all aircraft suffer only one, 5% two, 1% three and much less than 1% four deviations.

That means that airspace is dramatically under-utilised in the parallel tracks, given that the percentage of conflicts per flight is the same on each parallel track, and the central track absorbs 75% of the traffic. From this it can be assumed that a more intelligent distribution of the LO to the left and the right would further improve the performance of this manoeuvre.

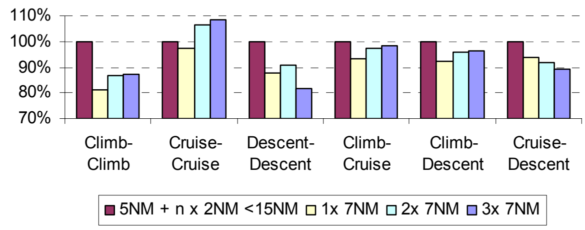


Figure 46: LO resolutions normalised with baseline per encounter attitudes, $\left\|P(\vartheta)\right\|$.

Figure 46 normalises the resolution rates of the three scenarios with distinct LO with the scenario with the 2NM steps, $\left\|P\right\| = \frac{P_n}{P_{baseline}}$. One parallel track performs worse than the baseline, two and three parallel tracks perform better in the cruise-cruise category.

4.3.4.5.4 High Trajectory Uncertainties

All the previous simulations have set a relatively small uncertainty of predicted trajectories, which is emulated with an increased separation buffer using an ellipse of 2 x 7NM long and 2 x 5NM short sides, i.e. minimal separation of $D_{\min,lead} = D_{\min,trail} = 7NM$, $D_{\min,lat} = 5NM$. This compensates for along track uncertainty only. The ellipse is now further stretched for 2 x 10NM, 2 x 20NM and 2 x 30NM long sides. With the same rationale as already applied in the previous study, this corresponds roughly to 0.7%, 1%, 2% and 3% of uncertainty per 10 minutes; or 4.2%, 6%, 12% and 18% per hour. [Recent unpublished studies on trajectory prediction seem to converge towards a value of 1.25% per 10 minutes for existing algorithms of trajectory prediction in the en-route environment in Europe.]

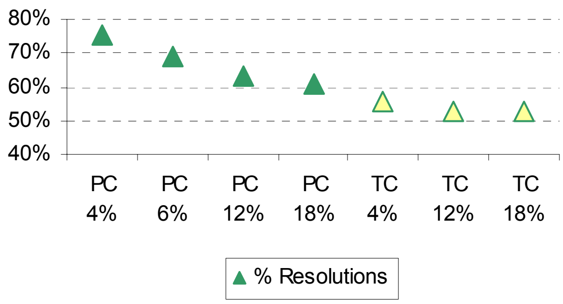


Figure 47: Resolution rate for PC and TC for predicted trajectory uncertainties per hour.

Figure 47 shows the resolution rates depending on the controller and the uncertainty. The PC has in all cases higher resolution rates than the TC, due to the longer implementation window caused by the different look-ahead horizons, as explained above. The LO resolution rates drop with increasing uncertainties, as can be expected. It is noticeable that the resolution rates are high even with unrealistically extreme uncertainty values. The radar controller is less sensitive in proportion to the increase of uncertainty, but has lower resolution rates in absolute values than the planner, due to the reduced resolution spaces by the shorter look-ahead time.

4.3.4.5.5 Conflict Resolution Times

The resolution algorithm searched for solutions within a time window and a search direction, $\Delta T_{\rightarrow}$ and $\Delta T_{\leftarrow}$. The search boundaries fixed the size of ΔT and the step size ∂T the granularity of the search. Figure 48 shows results of some simulations where only the radar controller resolved; the window size varies $\Delta T = (1\min, 5\min, 14\min)$ and both directions are applied with small steps of $\partial T = 30\sec$ for the small windows. A correlation seems to exist between these parameters. The backward search has lower resolution rates, but is hardly sensitive to the window size, whereas the forward search has higher resolution rates but is very sensitive to small windows. It is difficult to explain this effect, and might be due to a bug.

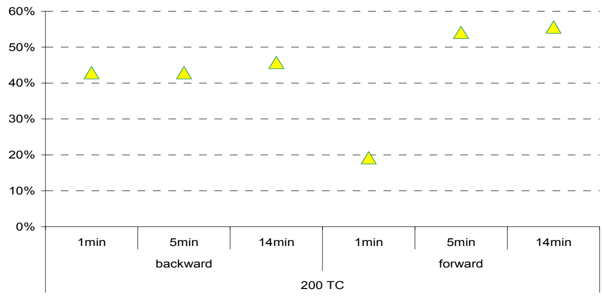


Figure 48: TC resolution rates with changing time parameters

4.3.4.6 Discussion

1. It is very important to improve the syntax of the clearance for the case where one aircraft is issued more than one LO clearance. E.g. the scenario using $d_{II} = n \cdot 7NM$ issued more than one clearance to 7% of flights. If the aircraft is already flying in offset and another offset is issued, then it is unclear whether it is relative to the current trajectory or to its initial flight plan. E.g. if aircraft flies 7NM offset to the left, and the ATCO wants to add 5NM offset to the left, should the new clearance offset to 12-left or 5-left nautical miles? After discussion in the EEC we suggest to use the absolute offset distance all the times.
2. The syntax of the clearance proposed by Herndon et al. also allows for confusion of the offset direction $\mu = (left, right)$. The clearance used in this work is simpler and does not bear this risk.
3. If LO is used very often, then the offset direction μ should be optimised for the flights so that the cost of the manoeuvre is minimised. A simple model could e.g. compute the direction of a sector or centre exit point, or the arrival airport, and put the aircraft in that direction.
4. LO can be used to increase safety of flows by offsetting flights from their plans also when not in conflict. The objective is to organise the configuration of aircraft that are members of the same sequence in order to maximise the time-to-chaos T_{kos}. T_{kos} is a system parameter that indicates when the system would generate conflicts or collisions in the case that no clearances are issued, e.g. at

a total communication failure. Therefore sequence members are put on lateral and vertical offset to increase leading distances.

5. LO leads to lesser workload than vectors because normally it will only be one action for the controller, whereas vectors consist of two actions. The degree of order of LO is high, i.e. the flow or flight plan of the manoeuvred aircraft can easily be recognised by controllers, which also reduces workload.
6. LO together with the traditional vertical manoeuvre and speed-control compose a very powerful toolbox for planning controllers, multi-sector planners or automation systems working on the strategic time horizon of about 15 minutes.
7. The performance of LO is highly insensitive to uncertainties of trajectory predictions, which again makes it very suitable for planning.

4.3.4.7 Conclusions

Lateral Offset is a very powerful action at the disposal of ATC, which is not systematically used today but yet available in almost all aircraft. The study shows very high benefit when used for conflict resolution, with resolution rates around 65%. The study finds a set of suitable parameters for the offset manoeuvre and proposes corrections to the formulation of the clearance. In addition LO has very high potential for use in planning and automation actions, due to its resilience to uncertainties. And finally LO is suitable for increased safety as strategic action.

4.3.5 Speed Control

4.3.5.1 Objective

One of the possible measures to act on the flight is by speed-control. Speed control is one of the measures that air traffic controllers may use in conflict resolution. However, clearances involving speed are almost unused in European upper en-route sector control (<<1%), whereas transfers, level changes, direct routing and vectors are most commonly used.

The objective of this study is to evaluate the potential of speed-control regarding conflict resolutions especially focusing on its use as a planning action suitable for planners, multi-sector planners or automation systems working in this look-ahead time horizon.

4.3.5.2 Key Literature

The published work was the first literature available on the explicit subject of speed-control [54][55], since then the ERASMUS project has picked up [56].

Related are speed-adjustments necessary for AMAN[84], ASAS[85] and MIT[86] procedures, where speed must be adjusting relative to specific moving or fixed points, as well as traditional speed and rate of climb and descent clearances.

4.3.5.3 Modelling

The RAMS[87] PLUS fast-time simulator was used in its version 5.04 and 5.20. No adaptations of the kernel were necessary, only the user defined rule base, which is an expert system emulating the controllers' behaviours, is modified.

4.3.5.4 Simulation Setup

4.3.5.4.1 Conflict Detection

RAMS includes a tool for conflict detection and resolution that influences the performance of the simulator and is briefly described here.

[84] AMAN – Arrival Manager

[85] ASAS – Airborne Separation Assurance System

[86] MIT – Miles In Trail

[87] RAMS - Reorganised ATC Mathematical Simulator

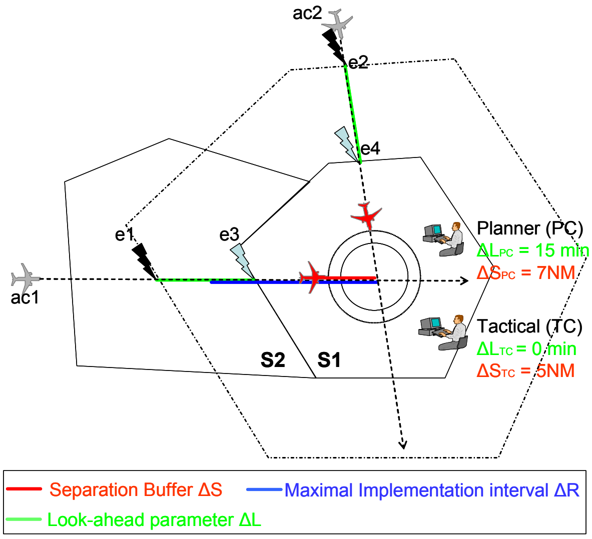


Figure 49: Simulation setup.

Conflict detection is triggered upon sector-entry events. For each aircraft there is one event for sector entry for the planning controller, and one event for the tactic controller, making two events per aircraft per sector entry. The conflict detection is only successful if the other conflicting aircraft is in the "window" of the respective controller. This means that each conflicting aircraft pair can be detected once or twice.

Figure 49 illustrates an example. If aircraft ac1 enters the PC window at time e1, and ac2 at e2, then e1 will not trigger a conflict, because the other aircraft is not yet in the scope of the PC, but e2 will do. Same applies then for the TC with events 3 and 4.

4.3.5.4.2 Resolution Rule Base

RAMS uses a data-driven, rule-base system as a resolution algorithm, which attempts to emulate real controllers' behaviour. The performance of the rule base is entirely dependant on the way it is programmed, and the default rule base coming with the simulator is not running at optimum. Therefore, the rules have been modified for this study. The logic of the rule base for speed resolutions is depicted in Figure 50.

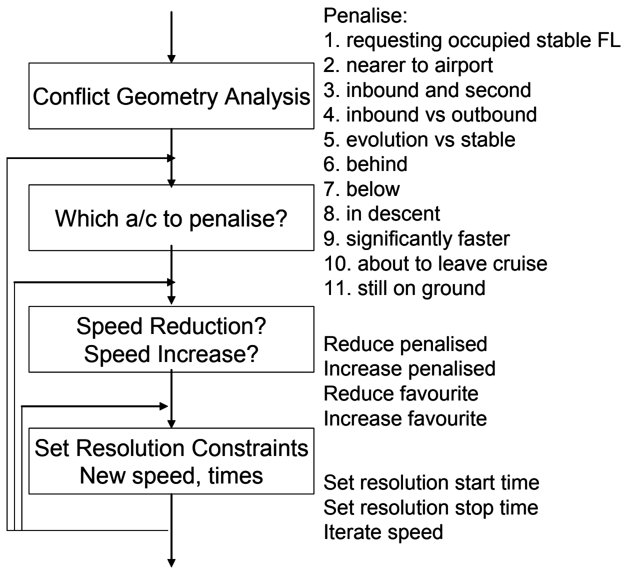


Figure 50: Logic of rule-base for speed manoeuvres.

First, an analysis of the conflict geometry is undertaken with a categorisation of conflicts depending on the angles and attitudes of the aircraft involved. Next the conflict coordination is done, i.e. the aircraft to be penalised is selected. Then the manoeuvre is chosen, and finally additional constraints of the speed manoeuvre are set. The rule base that was created only moves one aircraft, which is very limiting - especially for speed where it would be more logical to increase one aircraft and reduce the other one.

4.3.5.4.3 Uncertainty of Trajectory

Uncertainty in trajectory prediction was approximated with the use of higher separation minima for the Planner. Separation minima ΔS were set to ΔSPC =7NM for the Planner, which corresponds to a compensation buffer of 2NM. The look-ahead for the planner is set to 15 minutes from the sector boundary. The average sector crossing time is 8 minutes and therefore the average time to conflict in the sector is assumed to be 4 minutes, i.e. the total time between detection and conflict is on average 19 minutes. The compensation buffer of 2NM corresponds to 1.47% uncertainty per 19 minutes for an aircraft flying at 430 knots (0.77% per 10 minutes), which is possibly slightly optimistic.

4.3.5.4.4 Aircraft Performance Envelopes

The aircraft performance envelope plays a major role in the ability of the aircraft to speed up or to slow down at the specific flight levels and attitudes where the resolution manoeuvres are applied. Significant improvements have been introduced to use the aircraft performance as given in BADA {BADA [57]} including over 100 aircraft types. 20 aircraft types have precise speed envelopes, and all other types are mapped to a representative category, i.e. heavy, medium or light. Nevertheless, the simulator was set up to allow for speed variances no higher than 15%, even if the performance profile of a specific aircraft type would allow for it.

4.3.5.5 Results

The complete results can be found in the publications mentioned above. To ease readability this document only contains the most striking output. The shown results emanate from a setup where only the planner (PC) is enabled with the sole action of speed-control, the radar controller (TC) is disabled.

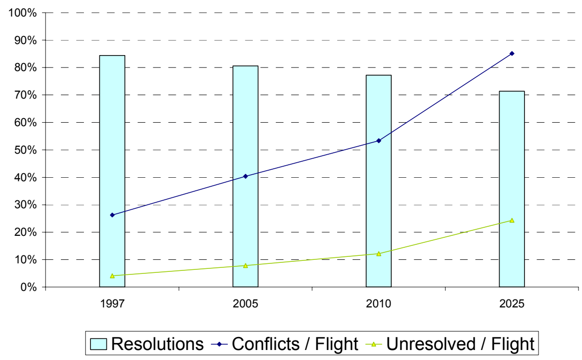


Figure 51: Resolution rates (17503 occurrences)

Figure 51 depicts the resolution rates in four simulations with increasing traffic with the high values even for the tripled traffic rate for the year 2025 in comparison to the peak day of 1997. The conflicts per flight increase non-linearly as well as the resolutions per flight.

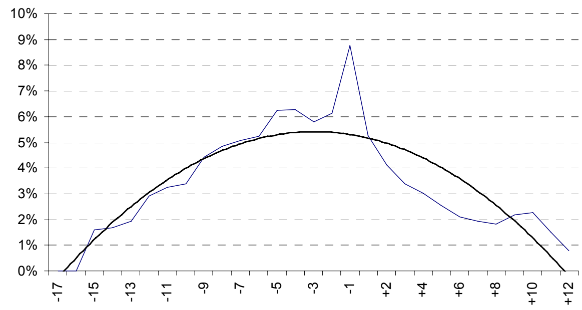


Figure 52: Averaged relative speed changes

Figure 52 shows the averaged relative speed changes for the applied resolution manoeuvres with the trend line. It can be seen that the envelope is set to plus-minus 15% and is not symmetric around zero values, instead more flights are slowed down which is due to aircraft performance and the order of execution of controller rules.

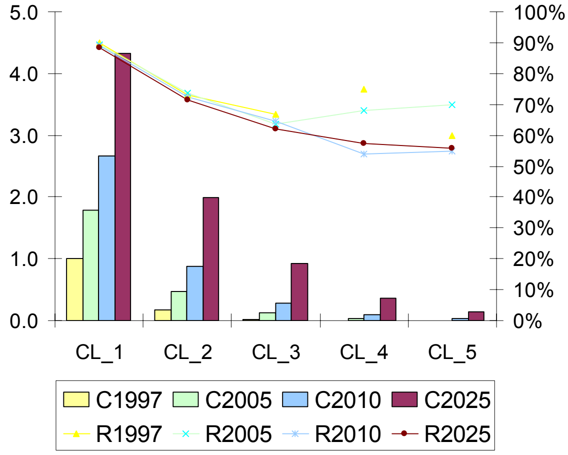


Figure 53: Normalised (954) cluster counts and resolution rates

Figure 53 shows the relation between the size of a conflict cluster, its normalised occurrences with respect to the number of clusters of size 1 in the baseline traffic (954 occurrences = 1.0 on left scale), and the resolution rates (right scale). The cluster is defined as the transitive closure of conflicting aircraft in time and distance. The analysis limited the dimensions of a cluster to +/- 5 flight levels and 8 minutes horizontal time-distance, the first value set arbitrarily, and the latter set to the average sector crossing time of the measured centres. Most clusters are simple conflicts (abscissa value 1) involving two aircraft. The resolution rates are very high for these simple conflicts. The number of conflicts drops exponentially with the cluster size. The resolution rate decreases approximately linearly with the increase of cluster size.

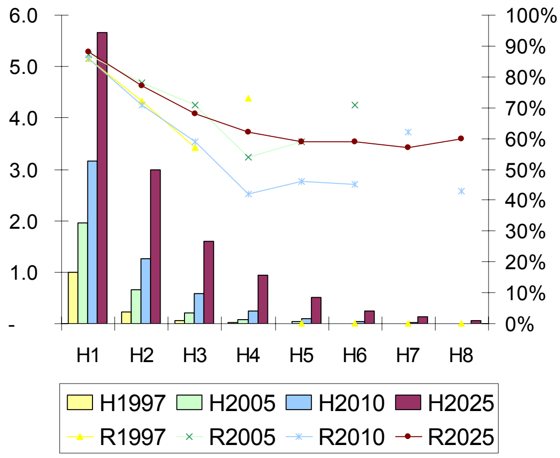


Figure 54: Normalised (1220) hindering aircraft and resolution rates

Another indicator for the complexity of resolution manoeuvres is the number of constraining aircraft per conflict, i.e. how many aircraft were hindering a resolution process of an aircraft in conflict. The resolution algorithm iterates through possible solutions when resolving a conflict. Every iteration tries out a new trajectory. If this trajectory is invalid because another – constraining – aircraft was in the way, then it continues until it exhausts its programmed possibilities. The number of constraining aircraft per search can be counted; however, it seems more significant to show the growth rates as a function of traffic rather than the simple counts.

Figure 54 therefore normalises to the number of conflicts that had no constraining aircraft in the baseline traffic sample. It can be seen that the number of constraining aircraft strongly increases with the traffic density.

4.3.5.6 Discussion

The performance of speed-control is high even for very high traffic forecasts and depends on aircraft performances, available airspace, conflict clustering and other hindering aircraft, varying between 50% and 90% resolution rates.

These resolution rates are achieved using very long look-ahead times of 15 minutes, which gives enough time for manoeuvres with even small speed changes. Speed control can be applied by automation, which has no specific difficulty to compute trajectory predictions in applying speed changes. Humans, in contrast, have difficulty to apply speed manoeuvres due to high errors in (human) trajectory prediction, which is a reason why speed changes are hardly used in today's operation, even in their simplest form (ROC[88], ROD[89]).

4.3.5.7 Conclusions

Speed-control gives high resolution rates, but requires long implementation times in the order of 15 minutes. This makes it very suitable for automation tools in a multi-sector environment, but less usable for humans and is not suited for air traffic control.

[88] ROC – Rate of Climb

[89] ROD – Rate of Descent

4.3.6 Dynamic Sectorisation

4.3.6.1 Introduction Functional Airspace Segregation

Airspace development in Europe is in general a long planning process which takes at least one year for the implementation of small changes up to several years for more complicated changes e.g. for effects beyond sector boundaries. The dynamics of airspace is relatively low once airspace is implemented and in operations. In general it is limited to online de-collapsing and collapsing sectors out of predefined configurations of the centre, but never changes in sector shapes. The future of airspace design and airspace operations, however, is oriented towards a much more dynamic system that adapts airspace capacity with the demand with a finer granularity in space and time. The common denominator of all future concepts in airspace development is to split airspace into functional blocks, to segregate traffic for higher specialisations, and to increase the dynamic behaviour for higher reactivity to demands.

Figure 55 depicts the different levels of dynamic airspace management.

At the 1st and lowest level is static i.e. no configuration management where centres usually swap between one night and one day configuration.

At 2nd level configuration management throughout the day is executed by sector supervisors or other managers and in the best case the transition steps are planned through pre-tactic planning by flow managers. This is current practice in Europe.

At the 3rd level there is optimised managed configuration management where decision support tools based on optimisation heuristics recommend transitions between configurations. This is starting implementation at first ATC centres in Europe.

At the 4th level are optimised dynamic sectors where the building blocks of the operated sectors are fine-grained and sector shapes may evolve by swapping air blocks from one sector to the other. Dynamicity can be high and planning eventually short for an optimal adaptation to demand at a time.

At the 5th level are optimised floating boundaries where sector shapes are no more predefined but are created on-the-fly for the best possible adaptation to traffic.

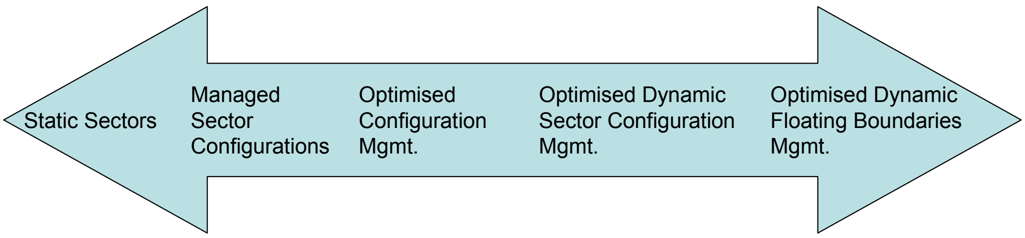


Figure 55: Trend in Airspace Management

Other airspace concepts target at higher specialisation or specific ‘behaviour’ of airspace, like tubes, highways, or 3D routes. Their underlying principle is to design a route network that separates flows and herewith aircraft ‘by design’ in using the 3rd dimension, in the same way as routes do separate flows horizontally in the current route network structure. Tubes can be considered as very high 3-dimensional specialisations that are only linked to flows and that have dynamic boundaries. Highways are 2.5-dimensional specialisations that are only linked to flows and that have static shapes, in general defined as routes and not as sectors. 3D-Routes are a merger of tubes and highways. They are 3-dimensional specialisation linked to flows and to merging and crossing points, but have no or low dynamics. The design of airspace with 3D routes is already applied e.g. for military corridors, and around some major airports where arrival and departure PRNAV[90] routes cross by applying strict flight level allocation schemas (FLAS[91]). A study was started in this thesis to model the 3D routes with the RAMS simulator, and some preliminary results have been achieved. However, the modelling has shown to be very cumbersome and the setup of the simulation very labour- and data- intensive. The study could not produce results at the level of modelling and is not further detailed in this report.

Dynamic airspace management could comprise all above elements when they are useful. At the current stage, however, levels 3 and 4 i.e. optimised managed configuration management and optimised dynamic sectors respectively are considered as implement-able. Therefore the following sections focus on these two conceptual elements only.

4.3.6.2 Objective

Functional airspace segregation is a key function for planning that should create high rates of additional capacity by adapting the airspace to the demand. The trigger function may be complexity and workload prediction; and also traditional traffic forecast for the day. The dynamicity of the airspace adaptation may span from traditional strategic long-term airspace planning several months ahead to very reactive modification in a relatively short look-ahead time of down to 15 minutes, similar to current de-collapsing and collapsing of sectors. The segregated airspace elements may be dynamic sectors and highways, 3D airways, or 4D tubes.

Dynamic sectorisation is a specialisation of functional airspace segregation and the MANTAS project uses a definition from the MANTAS Basic Operational Concept [36]: Dynamic airspace is conceived based on atomic air blocks that are then further regrouped into traffic volumes that serve as operational sectors. Upon change of the traffic demand, the sectors will adapt and change their shapes vertically and horizontally for an optimised efficiency of the individual controller as well as for the controller teams.

Figure 56 illustrates an example of a simple re-sectorisation where some blocks change from one operational sector to another.

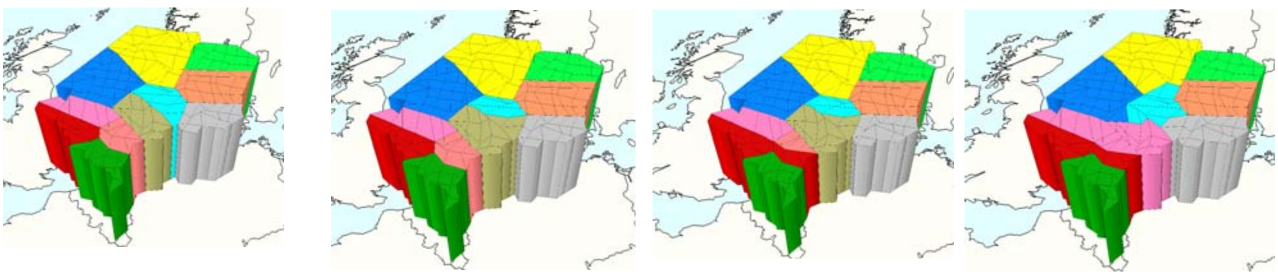


Figure 56: Example Dynamic Sectorisation

[90] PRNAV – Precision Area Navigation

[91] FLAS – Flight Level Allocation Scheme

Workload and complexity prediction is the key-decision support for dynamic sectorisation. Because of the longer prediction horizon of 15 minutes and more, but typically 30 to 45 minutes, the uncertainty of the predicted air situations is still very high; Maastricht e.g. counts approximately 30% of traffic that is still at the airport 15 minutes before entering the airspace, which makes this traffic highly unpredictable. Furthermore this traffic is climbing, which makes the precise trajectory prediction difficult due to level winds. The other traffic, however, is either close to destination or in over-flight, which allows for relative precise predictions. This example illustrates that other than the known mechanisms must be elaborated, possibly based on stochastic processes, which is also part of the project. In this document however only the dynamic sectorisation is further evaluated.

The decision making function for dynamic sectorisation may apply different strategies, e.g. a balance of workload amongst the sectors, or a concentration of overload into one area that would further be regulated to force reroutes and delays for a limited zone, or an adaptation of workload to the sector team etc. In all cases it should create higher capacity and efficiency, and possibly also safety.

The objective is to create a dynamic sectorisation for the Maastricht area. This requires innovation on the airspace design process as well as tool development.

4.3.6.3 Key Literature

There is some high-level documentation available from research ([61][62]). There is existing literature for optimal configurations (e.g.[57][59]), and for airspace design tools ([63][64] and both ([65][67][68])). The MANTAS[92] project has produced some project documentation ([71][72]).

Some of the work is published in [73].

4.3.6.4 Modelling

The approach that is taken in this study is to define the building blocks for dynamic sectorisation first and relatively statically, and then group and combine these atomic air blocks so that at a first level operational sectors are created that can be handled by air traffic controllers, and at a second level the centre configurations are built on the operational sectors. The creation of the atomic air blocks is based on development principles. So far two models are elaborated, the problem-parents-children and the flow-combination models:

- Problem Parents-Children:
- Identify flows;
- Identify problem areas P_n (parents);
- Draw ideal airspace around the problem areas so that the problem could be worked in isolation;
- Intersect the problem parents to get the children $C_m = P_n \cap P_{n+1}$.
- Children can then be assigned to one or the other parent, depending on the traffic. The problem areas may differ in their function and herewith in their shape, e.g. triangular boundaries for merging problems, squares for en-route crossings, circles for LoA treatments etc.
- Flow-combinations:

[92] MANTAS – Maastricht New Tools And Systems

- Identify weight of flows;
- Draw boxes around flows starting with big ones and split intersections;
- Fill unused airspace so that assignment of children leaves many possibilities to create operational feasible operational sectors.

4.3.6.5 Simulation

The validation of the many different combinations was done with fast-time simulation for the problem-parent-children model using RAMS, and necessitated the creation of the SimMaker tool for the automation of the execution and analysis of the many possible scenarios. Both problem-parent-children and flow-combination models were further evaluated by the creation of an airspace optimisation tool.

4.3.6.6 Results

The results are the innovation of the airspace development process itself and also its outcome.

4.3.6.6.1 Problem-Parents-Children

The design process targets a completely new airspace design starting from a blank sheet, based on the principles of dynamic airspace management. The approach to this objective is taken by grouping a number of sector supervisors and air traffic controllers and built a new airspace using a set of tools. Three iterations have been conducted:

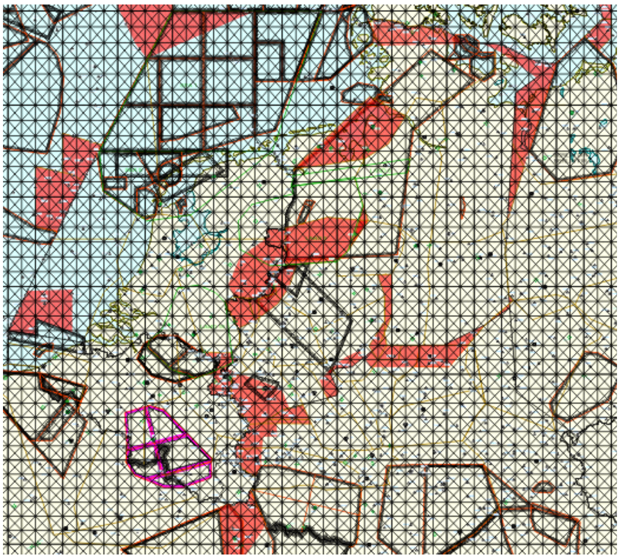


Figure 57: Geometrical grid

Starting point for the from-scratch airspace design is a mathematical grid, as depicted in Figure 57. The geometry of the grid is small triangles, because it allows for straight sector boundaries and for a good approximation to sectors. The length of the sides of the triangles is set using common sense and some examples printed on maps. It must allow for a fine-grained airspace boundary around smaller flows, and must also lead to a number of geometries that can be handled by humans. It is decided not to rotate the axes of the triangles. The grid is then projected on an airspace map lacking any route structures, and only showing military areas. The first task of the operational experts is to identify the gates (sorts of extended navigation points in form of a line) with the entry and exit constraints. This may be arrival and departure gates, or lateral and internal gates.

Next all problem areas are identified, classified and marked on the map, starting from airport problems, transition problems, and over-flight problems. In total 25 problem areas are identified, that are called the 'parents'.

The next step is to mark 2-dimensional boundaries for the atomic air blocks, starting from the parents. When there are clear transition between parents, then a clean line is drawn; however, when the airspace surrounding the parents can be allocated to several parents, then it is subdivided per flow creating little air blocks that are called 'children'. Children in MANTAS can be allocated to one or several parents to form sectors. 36 children air blocks are created. Figure 58 depicts the result of the first iteration for the definition of atomic air blocks, strictly sticking to the mathematical grid.

The following task is to group all the atomic air blocks into sectors. The applied concept permits for an unlimited number of division flight levels (DFL) and for balconies, but not for stairs in the airspace (double balcony). First the expert team is not constrained in the maximum number of sectors and this leads to unrealistically many sectors (26, compared to a maximum of 15 for 2006). Next the number of sectors is reduced to match a more constrained forecast target for the year 2009, around 20 reflecting the sustained traffic growth of 6% per year in the last years.

Several options for DFLs [93] are tested, one option for unique DFLs that are valid for the entire centre, another for changing DFLs per region and adapted to the need, another for no, one, two, or three DFLs etc.

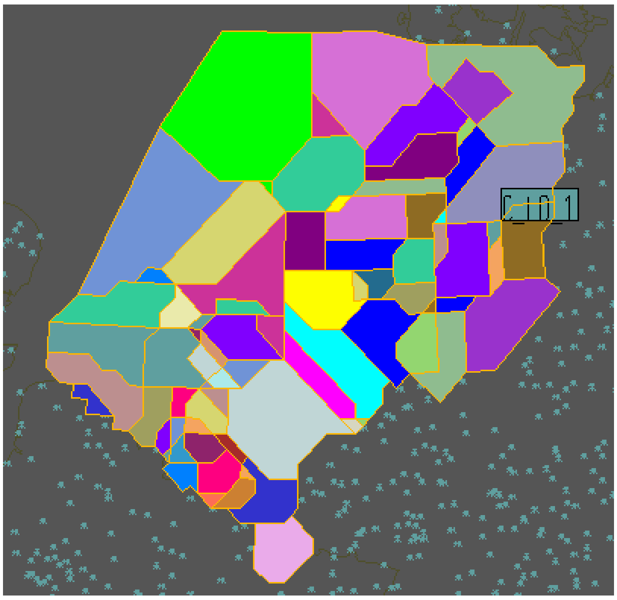


Figure 58: Iteration 1 Problem parents and children

This terminates the first iteration of airspace design. It is now digitized and fed into a fast-time simulation tool (RAMS[94]) that evaluates the theoretical capacities of the production. The traffic for the simulation corresponds to a forecast for 2009 and is either highly rerouted on direct routes, or is strictly kept on the currently filed fixed route network. The results expressed in figures for capacity, occupancy and complexity serve as input for the next design iteration.

[93] (v)DFL – (variable) Division Flight Level

[94] RAMS – Reduced ATC Mathematical Simulator

The second airspace development iteration concentrates on the vertical sectors. The constraints to draw on the grid are relaxed, and lines between all points are admitted; yet no additional points are allowed.

The exercise repeats the steps of creation of atomic air blocks and definition of sector configurations, but the expert team is instructed to think in vertical terms only. Figure 59 shows the resulting atomic air blocks.

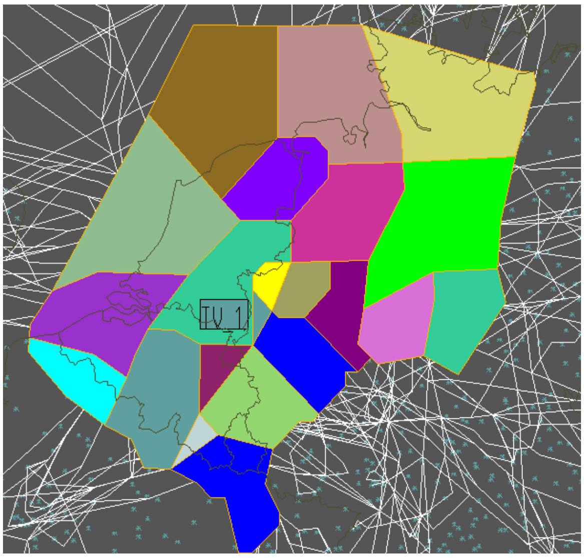


Figure 59: Iteration 2 Vertical Thinking

It can be seen that the total number of parents and children are reduced. A much smaller number of options are created in the horizontal sense. However, the number of vertical possibilities increases in the same proportion, and the second iteration produces a higher number of combinations than the rather horizontal exercise from the first iteration.

The creation of valid sector configurations is very cumbersome and creates frustration amongst the experts, partly due to repetition, but mainly due to the very high complexity of the work (‘Task for a computer’). The simulation tool is not reactive enough for what-if scenarios. This is found to be a major limitation.

Only a limited amount of sector configurations comprised of 2 and 3 layers, respectively 1 or 2 DFLs, is simulated and analyzed regarding theoretical capacity.

In iteration 3 the results from iteration 1 are adapted to those of iteration 2 and both combined, together with boundaries around military areas. The grid is abandoned and some boundaries are adjusted to minimize sector clips and skips.

Figure 60: Iteration 3 Combined Refined Boundaries

That leads to new boundaries on both vertical and horizontal layers. Figure 60 shows the horizontal boundaries emanating from this process. It can be noted that new scenarios are created with an intensive use of flow restrictions and flight level allocations reminding of microscopic channels or tubes for part of the airspace that is already considered ‘optimal’ or ‘atomic’ i.e. the Brussels sectors.

Further a limited airspace is chosen for the MANTAS real-time simulation nr 4, i.e. that not the entire airspace is considered anymore. The reduced scope makes a human definition of fine-grained sectors possible again. Each unique sector is named and different configurations are elaborated, resulting in a high number of possible sector configurations (50). The configurations vary the number of operational sectors between 3 and 5, plus military sectors. Fast-time simulations run through all of the possible configurations. The results lead to an expert selection and in some cases also to modifications of viable configurations, bringing their total number down to 40 for the selected airspace.

In a last step the experts define a transition matrix of allowed centre schedules. The rationale is that not every sector configuration may transit to another one, the allowed transitions are defined with a state chart. Therefore transitions may require passing via predefined sequences in order to achieve the wanted configuration; a strategy for sector configuration schedules is required. Once again this task is found too complex and too dynamic for humans, especially if it is to be executed on-the-fly in operations.

This concludes the step of the airspace development process. The results are used for the further real-time simulation. The next section describes the tools that have accompanied the process in more detail.

4.3.6.6.2 Flow-Combination

The airspace development for the flow-combination model is far simpler, because new tools become available in between the elaboration of the two models. The new air blocks can be painted directly over the flows, which result from a parallel study (FAB).

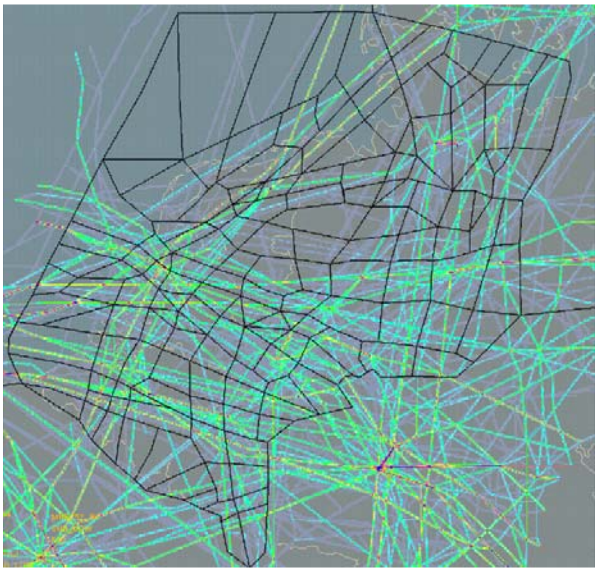


Figure 61: Flow-combination model

Figure 61 depicts the result from the flow-combination model. The number of atomic air blocks increases due to the high number of crossing flows, which leads to many intersections and herewith many children; and also from the filling of unused areas into small children that build feasible airspace when allocated to one or the other adjacent grouping.

4.3.6.6.3 Operational Sector Configurations

A further step is to define the operational sectors and their configurations. The dynamic airspace model leads to very high numbers of different configurations that combine the many operational sectors. Some variations of the configurations differ from simple swaps of children to completely different layouts e.g. due to different numbers of operational sectors in a configuration. Therefore the transition between configurations becomes more of an issue than the current de-collapsing and collapsing of sectors. It is found that some transitions are easy and others forbidden (traumatic). Some transitions require intermediate configurations. Table 6 shows an example state-transition table for three configurations and their possible transitions. Dynamic sectorisation in a centre like Maastricht will have hundreds of possible configurations.

From \ To	C_1	C_2	C_n
C_1	-	OK	OK
C_2	OK	-	Via C_1
C_n	Traumatic	OK	-

Table 6: Example Configuration State Table

4.3.6.7 Discussion

The problem-parents-children approach leads to operational meaningful volumes, which are further divided when shared between problem areas. If many problem parents are close, then the initial meaning of the parent gets lost, and herewith the main value of this approach. Then the combinatorial logic to create operational sectors becomes very difficult to solve for humans and machines. It is relatively difficult to automate that approach due to the operational expert knowledge that decides on design issues.

The flow-combination approach leads to higher numbers of atomic air blocks in dense airspace, with an exponential explosion of possible combinations for the creation of operational sectors and sector configurations. It has the advantage of using less initial operational knowledge of airspace and it is technically feasible to automate that step; further the analysis of flows is simple and can be done on-the-fly and herewith opens the possibility to automate; however, the combinatorial logic is even difficult to handle by computers.

Atomic air blocks are compound into operational sectors, operational sectors are compound into centre configurations. With dynamic sectorisation the number of constructions of operational sectors is very high because of the high number of combinations of atomic air blocks; and the number of possible configurations also very high. This leads to the difficulty for humans to find reasonable operational sectors and especially configurations. The combinatorial logic is too high for humans and requires tool support.

4.3.6.8 Conclusions

Two approaches for dynamic sectorisation are developed: one compiling operational knowledge into a problem-parents-children model; the other analysing flows and their combinations. Both lead to high numbers of atomic air blocks, which are further compound into operational sectors and centre configurations. Attention must be given to transitions between configurations because the shapes of sectors may differ very much.

The airspace design is highly depending on traffic demand and traffic flow, which is a permanently changing process. Therefore the airspace design must be kept dynamic as a whole and must be quickly reactive for change. Instead of a static airspace layout, a floating airspace baseline is created. The challenge of operations is to create systems (people, procedures, equipment) that have the same reactivity.

The combinatory logic of creating sectors from air blocks and configurations from sectors and taking into account constraints like shapes and division flight levels and their dynamics is beyond the limit of human capabilities. A mathematical optimisation tool is required to support this process.

It is of highest usefulness to iterate through the airspace design process by applying capacity-simulations. The simulation time is a critical factor during the design process. It would be ideal to have what-if scenarios during the design itself. This is not feasible with today’s simulators and requires further developments.

4.4 Planners Studies

This section presents studies that relate to planners that apply optimisation techniques to implement strategies. The strategy is on workload balancing with the use of dynamic airspace in order to specialise and segregate airspace. Two studies are developed that can be distinguished by different levels of granularity of their respective building blocks: One treats optimisation of de-collapsing and collapsing sectors as known in today's Centres; this study explains which steps are necessary and which data to be collected and computed in order to create a successful sector opening schedule, or a plan, for a day. The other study treats fine granular dynamic sectorisation and uses optimisation algorithms for the composition of sectors from atomic building blocks at decision times in the day and creates a plan for the day, where the composition criteria are based on simulated complexity measures.

4.4.1 Optimised Configuration Management

4.4.1.1 Introduction

ATC centres in Europe adapt the centre sector configuration to the traffic demand by dynamic configuration management that de-collapses and collapses sectors. The decision for transition between configurations is taken by some operational managers e.g. sector supervisors and in the best cases planned through pre-tactic planning functions by flow managers. Now new decision support tools are introduced (e.g. OPTICON by CFMU) that give advise for best transitions between configurations. ATC centres start using it.

4.4.1.2 Objective

The objective of this study is an improved analysis of airspace using a configuration optimisation tool. It is found useful to elaborate on optimised configuration management despite its advanced state regarding implementation for several reasons:

- The implementation of online-configuration optimisers is tool centric with a risk of rejection. It is necessary to have better operational knowledge.
- It builds a foundation on which optimised dynamic sectorisation can be built.
- It is found extremely useful to answer questions from the airspace design process because of its ability to quantify usefulness of new or current sector configurations.
- For automated planning it is very useful because it presents one of the first optimisation functions that are used for planning purposes.

4.4.1.3 Key Literature

The literature can be split into two parts, one for configuration optimisation, and one for configuration analysis. Configuration optimisers have been developed in the past years and are nowadays available: ICO from Experimental Centre [58], SAAM-Optimiser from EUROCONTROL HQ [no publication], and Airsecoma [product] are off-line optimisers; Opticon from CFMU [59] is integrated in the current deployment of the CHMI and is operational online; and one specificity is the eTLM [60] from AENA that uses workload-based configuration optimiser in a real-time simulation environment.

4.4.1.4 Modelling

4.4.1.4.1 Definitions

An Atomic Airblock is the smallest 3-dimensional traffic volume in airspace.

An Elementary Sector is composed of one or more Atomic Air blocks. In general Elementary Sectors are not overlapping.

An Operational Sector, or simply a Sector, is an airspace volume that is operated by a controller. It consists of one or more collapsed Elementary Sectors. In general Operational Sectors are not overlapping.

A Centre Sector Configuration or simply Configuration is the partitioning of the entire airspace of one centre into Operational Sectors.

A Centre Configuration Schedule (or Sector Opening Scheme) is the time plan for one centre for changing configurations during a day.

4.4.1.4.2 Configuration Optimisation Tool

Central to the study is a configuration optimisation tool. The retained optimiser is from the SAAM tool suite and is explained in more detail in annex 11.4.6 ‘SAAM Configuration Optimiser’. The optimiser works ‘mathematically complete’ and produces all possible combinations in the solution space which might be restricted with constraints. The only hidden constraint found so far is that transitions between sectors cannot have difference in sector-count higher than 2. It was its second use in an operational study and the extended preparation and analysis around it lead to a high validation level.

The environment around the optimiser has been developed in SimMaker for the purpose of this study and is explained in more detail in annex 11.4.4 ‘SimMaker Configuration Optimisation’. One useful development is a simulator for Monte-Carlo simulations with the optimiser, which does sensitivity analysis for input parameters. The generation of the input imply some assumptions and are described in the next paragraph. The different and sometimes new statistics are described in sections below.

4.4.1.4.3 Input to Simulation and Optimisation

The configuration optimiser is fed with sector-overload and sector-configurations information.

Sector-overload is generated on sector-load and capacity information. For this study the sector load was generated based on radar data in and around Maastricht (see Figure 62), and the SAAM tool computed the sector loads by intersecting the traffic with Maastricht airspace. I.e. that a traffic model is consciously used where the entire ATM system has worked on and that includes all weather, regulations, other delays, and controller actions etc.

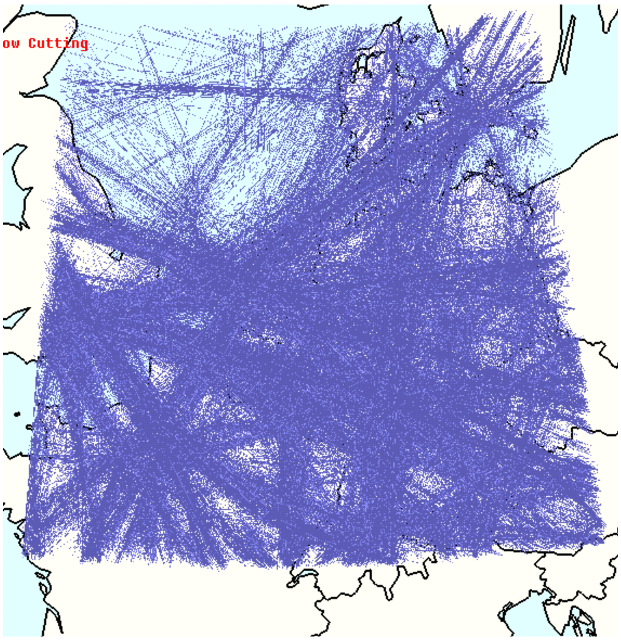


Figure 62: Example for Radar Data Area

That sector entry-exit information leads to sector loads. Then capacity thresholds are applied on the sector load, here we work with a capacity threshold for 60 minutes called the Traffic Monitoring Value (TMV[95]) and another threshold for instantaneous capacity limits (iTMV[96]) with a small 1 to 10 minutes interval, which is set to 10 minutes for this study. From this the Sector Saturation (S[97]) is computed. The SES contains a comparison of the TMV with the Sector Hourly Entry Rate (SHER[98]) that counts the sum of all entries for the next hour. Similarly the ITMV is compared with the occupancy (INST[99]), which is the maximum instantaneous count in the 10 minutes time interval. This leads to information about hourly and instantaneous saturation of the sector. Figure 63 shows the graph where SHER is shown in a blue line until it is saturated and turns to orange; and INST is shown in green bars until it is saturated and turns read. It also shows the average flight time through the sector, which is not further used. It can be seen that the shown sector is relatively big with an average flight time of 18 minutes, but has high occupancy that is saturated beyond iTMV of 21; and is hourly saturated beyond TMV of 63.

[95] TMV – Traffic Monitoring Value

[96] iTMV – Instantaneous TMV

[97] S –Saturation

[98] SHER – Sector Hourly Entry Rate

[99] INST – maximum INSTantaneous occupancy in interval

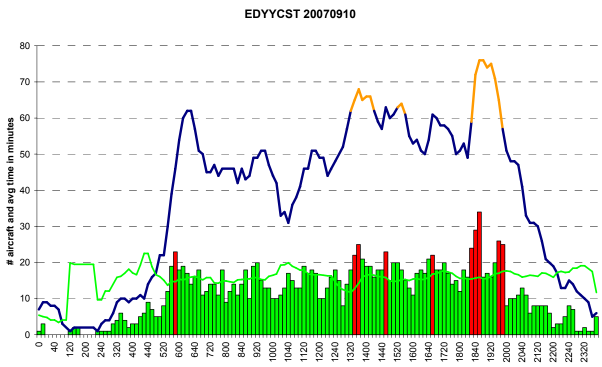


Figure 63: Absolute Traffic Load

The SES are further normalised using their respective TMV in order to allow comparison of sectors, which will become important for the configuration optimiser to evaluate overload (below). This leads to the Relative Sector Saturation (RSS[100]). Figure 64 shows the RSS for the same sector. There are times when SHER or INST or both are in saturation.

Capacity values in the form of TMVs for each Operational Sector (OS) are input to SES as shown above. They are known when existing OS are used in a study; however, when new traffic volumes are investigated then the TMVs must be newly created. If available then the TMV for new volumes can be calculated by detailed capacity fast-time simulations. In the absence of capacity simulations they can also be guessed[101]. Also the Monte-Carlo sensitivity analysis explained below will help on this issue.

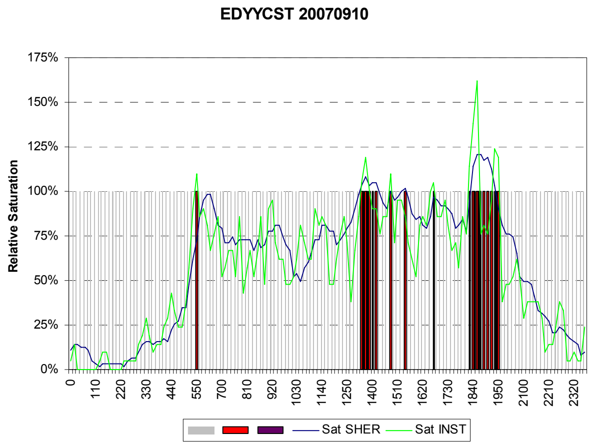


Figure 64: Relative Sector Saturation

The next step is to compute Controller Overload or simply Overload (O[102]). Overload in contrast to saturation is a workload measure and not a traffic measure. The relation between overload and saturation is a matter of interpretation. E.g. tactic capacity management executed by flow managers (FMP[103]) in the operations room

[100] RSS – Relative Sector Saturation

[101] *Note: Guessing capacity for new volumes is found to be a very good exercise for airspace developers, and can be guided using specific criteria.*

[102] O - Overload

[103] FMP – Flow Management Position

using predicted traffic scans the saturations and then decides whether there is a risk to overload the sector team, and as a result does some flow- or airspace measures. Long SHER saturations for example will lead to tactic regulations. Short SHER saturations are tended to be neglected. INST saturations will be interpreted and discussed with the sector team before deciding for a measure. Longer or critical shorter INST saturations lead to tactic traffic measures.

Hence it would be better to work with workload monitors rather than with TMV, even if the TMV is already a complicated compilation of workload and complexity into a single capacity value. This study is conducted with TMVs regardless this fact. Several interpretation methods are used to combine the two saturations and vary TMVs.

Figure 65 shows an example of overload for one day for 91 OS. The overloads are high due to a specific method that lowers the TMVs to emphasize the saturation and herewith the overload effect.

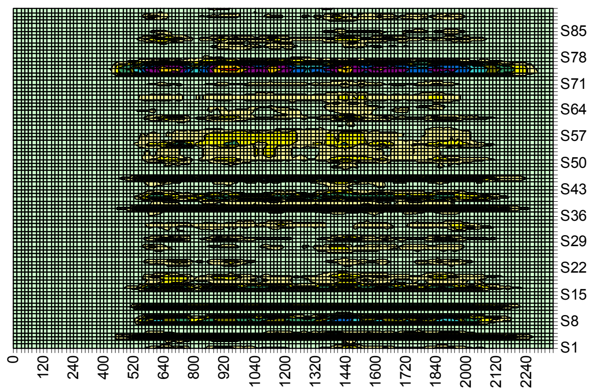


Figure 65: Overload for 91 Operational Sectors

4.4.1.4.4 Configuration Optimisation

The overload for all OS is input to the configuration optimiser together with the definition of all possible configurations. Figure 66 schematises the construction of centre sector configurations. For new traffic volumes all possible combinations that can be realised must be created. Note that in this study one ES has exactly and only one capacity value.

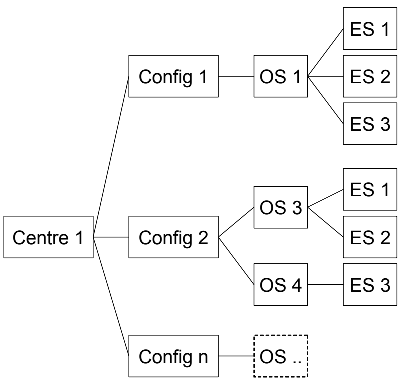


Figure 66: Centre Configurations

The parameters of the configuration optimiser (see 11.4.6) must be set according assumptions and then the optimisation can start.

The results of the configuration optimisation are Centre Configuration Schedules as defined above, together with some optimisation values:

- Cost from the optimiser's internal cost function,
- Sum of saturations of the solution,
- Sum of sector*time intervals,
- Number of configurations.

The overall results can be detailed in the analysis as explained in the next section.

4.4.1.4.5 Optimisation Analysis

(Relative) Configuration Saturation Envelope (CSErel[104]) is a graph with one Relative Sector Saturation (RSS) curve per sector for one configuration. The envelope is the difference between the most and the least saturated sectors for a time, with an average saturation. The value of the standard deviation of saturations is an additional balance indicator about the spread of saturations. Figure 67 shows an example CSE_{rel} for one day.

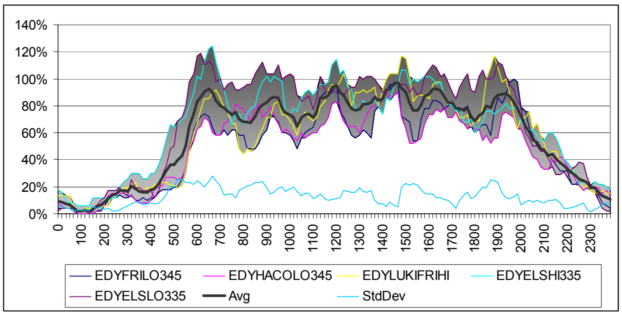


Figure 67: Relative Configuration Saturation Envelope

The Centre Schedule Saturation Envelope[105] ($CSSE_{rel}$) has two scales (see Figure 68), the left side y-axes shows the relative centre schedule saturation envelope, the right y-axes the number of operational sectors (SOT[106]). The SOT is the result from the configuration optimisation tool; it shows the number of open sectors and the different configurations are colour coded. The $CSSE_{rel}$ is composed of the different CSE_{rel} from the selected configurations in the schedule.

The $CSSE_{rel}$ allows for first interpretation of the quality of the output from the configuration optimiser. First and foremost the times of overload are visible together with the configurations that generate it. The size of the envelope together with the standard deviation shows how balanced the chosen configurations are. E.g. if the envelope is big and the standard deviation is high, then the balance of the Operational Sectors of that specific configuration at that time is low, which is in general unwanted; if in addition the configuration runs into saturation, then it can be concluded that the airspace or the flows must be improved, because it was a result of an optimisation. The consequence would be tactic reroutes, or even to improve the airspace design if such phenomena can me measured over longer time periods.

104 CSE_{rel} – Relative Configuration Saturation Envelope

105 CSSE – Centre Schedule Saturation Envelope

106 SOT – Sector Opening Table

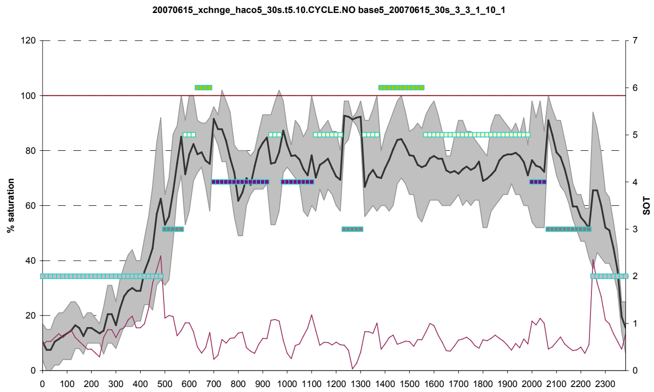


Figure 68: Centre Schedule Saturation Envelope

This last example illustrates how we will further exploit the results of the configuration optimiser. It will give us indicators about usefulness of the airspace: The more specific configurations are selected by the optimiser, the better they are. This in return allows validating the building blocks of the configurations: The more a configuration is used the better its OS, ES and atomic air blocks are. In contrast, configurations that are never used are not useful, and their components are not useful either. An indication of problematic airspace design is if configurations are selected but yet run into saturation. To resolve problems it could be envisaged to reorient flows from the saturated to less saturated sectors if saturation occurs together with imbalance; or if saturation occurs and balance is high that means that the entire configuration is saturated and sector design should be revisited.

Applying this logic the following statistics can be retrieved. The Configuration Duration Distribution (CDD[107]) measures the distribution of durations of configuration over the SOT. A configuration with high share is useful, with low share or no use is useless. Figure 69 is an example output for a real small ATC Unit Airspace with 8 ES combined into 25 OS and 64 configurations. Only 5 configurations are chosen, and the share of one of the SOT = 4 configurations is low. This analysis could decide on usefulness of those that are not or hardly used to discard them from operations, e.g. to reduce cost for controllers' licensing.

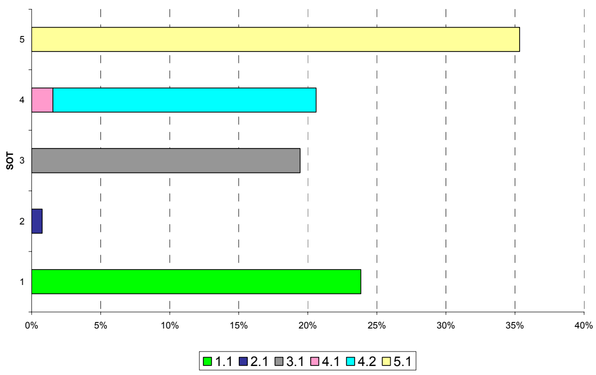


Figure 69: Configuration Duration Distribution

The distributions of durations of activated OS are measured in the same way which leads to the definition of the Sector Duration Distribution (SDD[108]). The more the

107 CDD – Configuration Duration Distribution

108 SDD – Sector Duration Distribution

OS from a configuration are selected the more they are useful. Figure 70 lists the distribution from the same example above and illustrates that only 10 of the 25 OS are used; the others are useless.

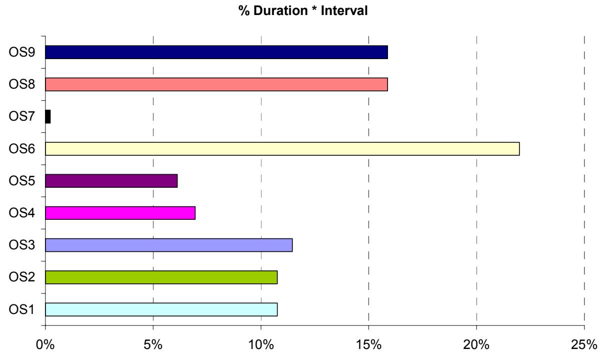


Figure 70: Sector Duration Distribution

The next statistics that are derived from the configuration optimisation are the Bottleneck Operational Sectors (BOS[109]) or bottlenecks. BOS are those sectors that are selected even though in saturation. The unit to quantify the bottleneck is the sum of aircraft and intervals in saturation.

Figure 71 shows the BOS for the same example with same colour coding for configurations as examples before. If sectors are frequently bottlenecks then the operations of the sector should be revisited. Tactic capacity management will rather concentrate on the analysis of short-term bottlenecks.

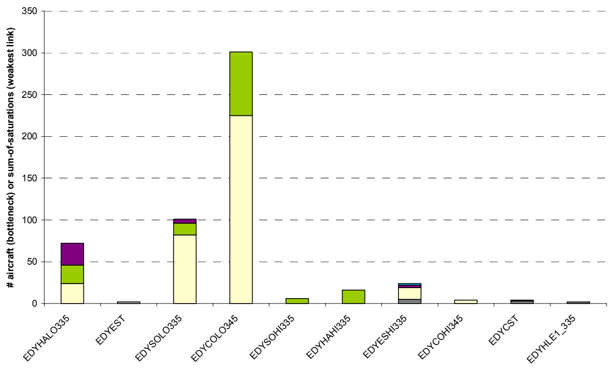


Figure 71: Bottleneck Operational Sectors

Similar to bottlenecks, one is also interested in the sector that is the closest to saturation when selected in configurations, even if it is not saturated. This is called the Weakest Link Sector (WLS[110]) or otherwise (see [77]) called critical sector. The sector which is the weakest link in a configuration is the one that is the closest to its saturation when the configuration is selected. I.e. that at each time interval there is one weakest link, even if it is far from being saturated. The units for measuring the weakest link are based on relative saturation, which is summed up for each interval ($\sum_{interval} S_R$). Figure 72 depicts the weakest link sectors from a run of the optimiser.

[109] BOS – Bottleneck Operational Sector

[110] WLS – Weakest Link Sector

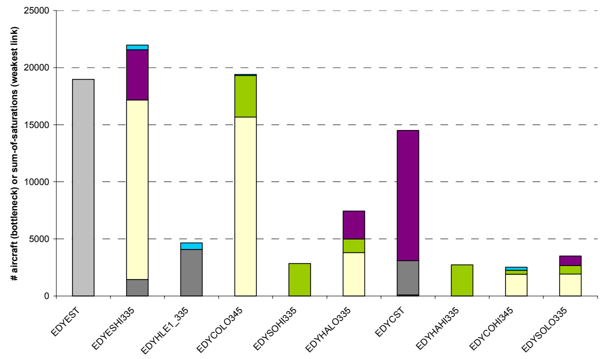


Figure 72: Weakest Link Sectors

Next is considered how the system behaves under peak conditions, which is most useful for capacity improvements. Therefore the previously defined metrics are multiplied with weighting factors. This factor is chosen by convention and is either the relative saturations $\overline{S}_R(t)$ and $\overline{S}_R^{\,2}(t)$ or the Sector Opening $SOT(t)$.

The significance of the WLS is relatively low because there will always be a weakest link even if the configuration is far from being saturated. The Weighted Weakest Link (WWL[111]) multiplies WLS with the average configuration saturation per time interval. A quadratic weight emphasizes the effect: $\sum_{interval}(\overline{S}_R^{\,2}(t) * WLS(t))$.

Further we are interested in the number of transition between specific configurations.

From \ To	1.1	3.1	5.2	4.2	4.1	2.1
1.1		9				1
3.1	8		6	10	2	1
5.2		9		25	1	
4.2		7	26		1	
4.1			3			
2.1		1				

Table 7: Configuration Transition Matrix

4.4.1.4.6 Monte Carlo Simulation

The input to the configuration optimisation depends on numerous assumptions.

- The input parameters of the optimiser must be set (see 11.4.6) where the knowledge of good combinations is limited to a number of manual iterations.
- The heuristics to compute overload vary which leads to a wide range of possible input files.
- The TMV might be guessed and herewith highly affect overload.

Therefore it was deemed useful to develop a tool that evaluates the sensitivity of the process depending on its input parameters. This tool was developed in SimMaker (see 11.4.4). All possible permutations of input parameters are computed and each

[111] WWL – Weighted Weakest Link

combination leads to a scenario for the optimiser. The results from many runs are compared and appropriate settings selected.

4.4.1.4.7 Sensitivity of Optimiser Parameters

The sensitivity analysis for the settings of different parameters of the configuration optimiser runs through various combinations of the settings. One can then select a best scenario by comparing the results that are produced from the optimisations with the different settings. This can be used for further simulations. Figure 73 shows an example of some runs where the optimum input parameters can be found at the minimum of the regression curve.

4.4.1.4.8 Sensitivity of Capacity Parameters

The sensitivity analysis of capacity parameters has a more operational rationale: What impact has a change of a TMV to the overall output? The output of this sensitivity is precious, because it allows statements of which sectors need to be improved by which percentage in order to improve an overall increase in capacity. It also allows finding the next following bottleneck sectors once a bottleneck is resolved; that leads to a sequence of bottlenecks, and that can lead to a management plan for airspace improvements in a centre.

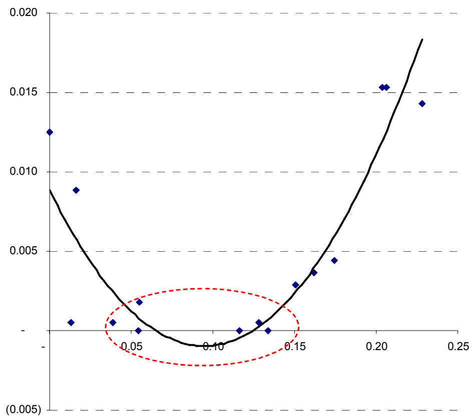


Figure 73: Optimisation of Input Parameters

4.4.1.4.9 Application

The tools and processes as explained above have been developed and refined in a project for a new sector layout touching about 50% of an ATC centre airspace. All statistics have been used. The combined results have highly supported a cost-benefit analysis, and one of the options that could be worked was selected for implementation. The clarity of decision would otherwise not have been possible.

4.4.1.5 Discussion

Configuration management is a planning task that is in the look-ahead time horizon of tactic capacity measures and also in the short look-ahead time of the full-automated planning functions that are subject to this thesis.

It serves as an example of how optimisers can solve a planning task. In this case a mathematical and complete optimisation is applied running on the Cplex engine. The model for this is fairly simple.

To treat uncertainty is of paramount importance for robust planning. Table 7 could be the empirical foundation for Markov decision processes, so as to create a probabilistic configuration optimiser. This optimiser would then in addition to the current processing also include the probability transition scheme from recordings.

Further the sensitivity analysis for capacity parameters shows how varying uncertain input parameters influence the output of planning together with some key performance parameters of capacity management.

Regarding uncertainty, it would be of interest to investigate the stability of the plan regarding the uncertainty of the flows. For this we lack the foundation for the description of uncertainties of flows.

4.4.1.6 Conclusions

The presented innovative process for airspace design has proved utility during an airspace project. It has produced the most important key performance parameters to support management decision for further steps in the implementation process. In this case it was in favour of a new sector layout.

The new process has many advantages, by:

- improving the quality of airspace development;
- shortening the development cycle of new airspace layouts;
- showing the network effect in the airspace of consideration so that the focus can be set on airspaces that do need improvements;
- giving various insights to the sector behaviour with the new statistics and graphical presentations; and
- indicating the sequence of problem sectors that will occur once current bottlenecks are improved.

The study is a necessary first step towards the use of optimisers for automated planning. It would be most useful to investigate the behaviour of the planner regarding uncertainty of traffic flows.

4.4.2 Dynamic Sectorisation Optimisation

4.4.2.1 Introduction

Dynamic Sectorisation is an airspace concept that aims at improved capacity-demand balancing by a fine grained adaptation of operational sectors to the actual demand. It is enabled by an innovative process where operational sectors are composed of many small sized atomic air blocks. The composition of operational sectors from the atomic air blocks follows optimisation strategies, in general by trying to balance workload between operational sectors. The previous study has found that this composition process is very cumbersome and erroneous when done by humans. This study presents of a tool development which implements algorithmic optimisation techniques for dynamic sectorisation, as well as results from its validation.

4.4.2.2 Objective

The objective of this study is to develop and validate an airspace optimisation tool for dynamic sectorisation. The optimisation process receives as input the airspace volume that is parcelled into atomic air blocks, as well as a number of statistics about the traffic that flows through the air blocks. The optimiser computes best solutions through combination and variations of the different statistics by applying a cost function including geometrical, complexity and workload parameters. The result of the optimisation process is the combination of atomic air blocks into operational sectors that are further combined into sector configurations.

4.4.2.3 Key Literature

Parts of the work are published in a diploma thesis.

The majority of related literature treats the route network, ARN[112], as baseline for optimisation and not a predefined airspace partition. Then the problem can be approached by using evolutionary algorithms from stochastic optimization [65]. Heuristic search techniques which are based upon principles of natural selection are used to create optimised sectorisations by partitioning the transportation network graph into K balanced sectors for which the induced quantitative workload is minimized. Sectors must be designed as Voronoi cells and respect safety and minimum stay time constraints.

Another approach based on the ARN [67] with a constraint programming formulation using efficient heuristic procedures. The main heuristic is inspired from the notion of gain of the Kernighan/Lin algorithm for graph partitioning. To find optimal solutions for larger instances of the problem a good initial solution is necessary which then is re-optimised locally.

The airspace is looked at from a different angle by covering the airspace with a high-resolution hexagonal grid tied to a rectangular grid, on which a workload-optimised sectorisation shall be composed. This problem is solved by partitioning the airspace based on the Equalized Traffic Mass principle [68]. The total aircraft count is assigned to each combined grid cell by using a Traffic Mass metric. These traffic amounts are balanced for all sectors so that busy centres are smaller in size than centres with sparser traffic.

[112] ARN – Airspace Route Network

A proximate problem is the centre configuration problem which aims at combining the elementary sectors of an air traffic control centre into optimised sector configurations. Tree search methods are applied for evaluating the set of all possible configurations [67]. A branch-and-bound algorithm is used to avoid exploring every branch of the tree. Each node represents one configuration and is evaluated with the difference of actual workload and maximum capacity. The corresponding leaf is stored if it is better than previous nodes and cut off otherwise. To maintain reasonable computation time this exhaustive technique is only practicable for small Air Traffic Control Centres and thus a low number of elementary sectors.

The objective of balancing and reducing costs can be found as well in the closely related problem of planning and optimising the airspace route network. Both, airspace sectorisation and route network optimisation influence another. Hence the concept of automated route network design which builds up a Voronoi structure based on traffic density is complementing the process of airspace design and sectorisation.

4.4.2.4 Modelling

4.4.2.4.1 Airspace

The optimisation is based on an existing partitioning of the airspace, called a floating baseline. This is the output of a design process equivalent to the previous study above. It is floating because of the dynamics of the flows and therefore constantly changing adaptations of the layout to flows; and it is a baseline because it serves as an airspace model for the finding of operational sectors.

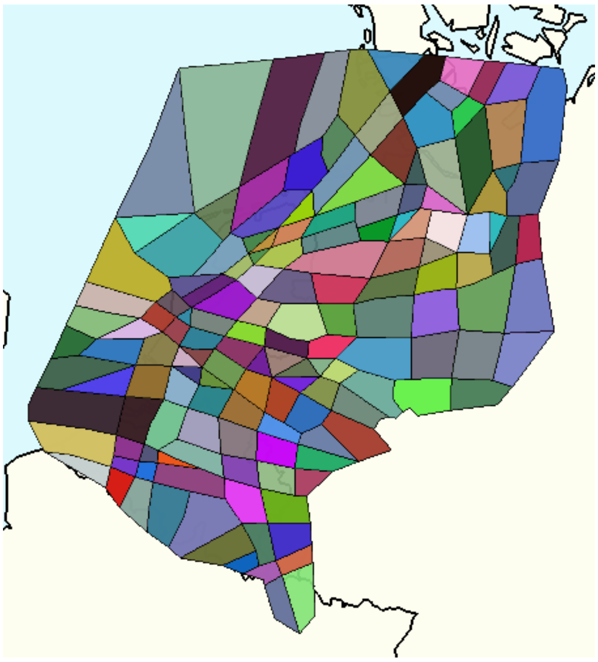


Figure 74: Example Layout

Figure 74 and Figure 75 show an example floating baseline. Division Flight Levels[113] (DFL) specify the different heights where the airspace is partitioned into a

[113] DFL – Division Flight Level

complete slice (z-axes). The resulting layers are called flight layers. The smallest partition is called an atomic air block.

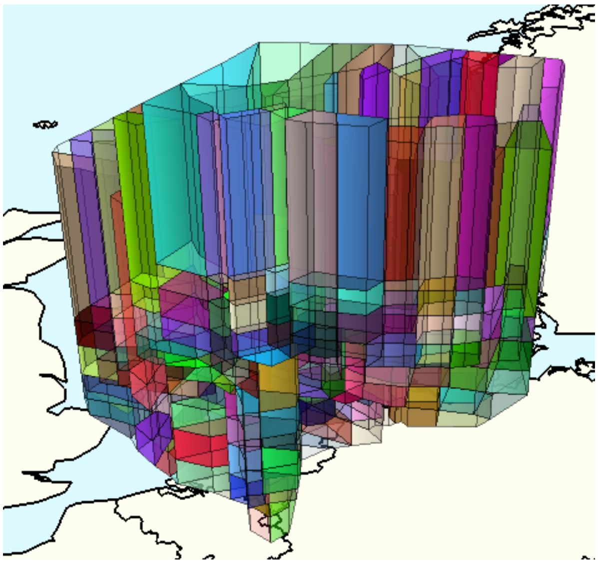


Figure 75: Vertical Partitioning

The airspace partitioning can be described as a graph, where each air block is a vertex and neighbouring air blocks are connected with edges. The resulting graph

G(V,E) with V={air blocks}, E={neighbour relationships between V}

is called graph of the airspace. An airspace element is connected if its graph is connected; it is solid if it is connected and its outline has no holes; a solid airspace element is compact if it contains all air blocks enclosed by its outline.

4.4.2.4.2 Data Structures

The most important data objects are: air block; operational sector; airspace partition; and sectorisation.

4.4.2.4.3 Constraints

- An operational sector must be connected, solid and compact;
- An operational sector has a minimal height;
- An operational sector must be as quadratic as possible;
- The target number of operational sectors
- Military sectors;

4.4.2.4.4 Cost Penalty

The optimisation works with penalties in the cost function. Penalties are given for different complexity parameters:

- Entry-, exit-, conflict- and occupancy rates against some threshold, with quadratic weightings.
- Mixity is a complexity measure for the uniformity of vertical movements in the sector. Because of its dependence of entries and exits it will have a lower weight with linear trend.

- Conflict encounter geometries get different linear penalties. The RAMS conflict categories for same, opposite directions, small angles, perpendicular angles are used, without distinguishing between diverging or converging encounters.

4.4.2.4.5 Cost Function

The cost function which is applied to the optimisation algorithms is composed as follows:

Cost = entries + mixity entries + exits + mixity exits + conflict value + sum of penalties on thresholds

4.4.2.4.6 Data

The data comes from three different models, e.g. designing the airspace is done in ATC Playback and SAAM, simulation data is from RAMS.

4.4.2.5 *Complete Enumeration*

The smaller airspace partitioning in this study contains 324 air blocks, which have to be grouped into 16 operational sectors. The number of possibilities to distribute the air blocks in the sectors can be calculated with the Stirling number of the second kind:

$$S(324,16) = 6.52 * 10^{376}.$$

The second partitioning with 462 air blocks extends this to $9.61 * 10^{542}$. Even by making additional assumptions like connectivity seems impossible to sufficiently reduce the amount of sectorisations so that a mathematically complete optimisation could work. We therefore chose for an algorithmic local optimisation approach.

4.4.2.6 *Algorithms*

We will present two algorithms which produce the best results so far. Both have in common to start with a given sectorisation, because we wanted to allow for evolutions from the current sectorisations. Also it is generally believed that the existing sectors and their configurations are close to optimum due to the constant improvement process.

4.4.2.6.1 Rearrange

- Iteration

While the termination condition is not fulfilled the algorithm iterates the following main structure. A start sector is selected and consecutively merged with each of its neighbour. For each of these merged sectors all possible compact splits into two are generated. If the merged sector itself is compact there is a huge amount of generated splits. There is at most one split when it is not compact. After all neighbours have been considered all generated sectors not matching all constraints are eliminated. Finally the best split is chosen from the remaining sectors. The start sector and the corresponding neighbour are replaced by these new sectors and the sectorisation data is refreshed.

- Step 1: Chose Start Sector

Let S be the current sectorisation and n = |S| the number of sectors. Let L be a list of the all sectors in S sorted by costs and beginning with the cheapest sector. L(i), i 2 {1, . . . , n} is the sector at position i in the list. L(i) is returned as start sector. The index i is a global parameter and determined based on whether an improvement has been achieved or not. If the start sector was rearranged in the previous iteration i is set to n. In this case the sectorisation has changed and the sorted list is updated. In the opposite case it is set to i − 1. Because the sectorisation has not changed the list does not need to be updated.

- Step 2: Check Type of Neighbourhood

For the chosen start sector the type of neighbourhood is determined for all neighbours. If we examine the airspace from the profile view there are six possibilities how two neighbouring sectors can be positioned next to each other. Figure 76 depicts the six possibilities of neighbourhood can be summarised into three types.

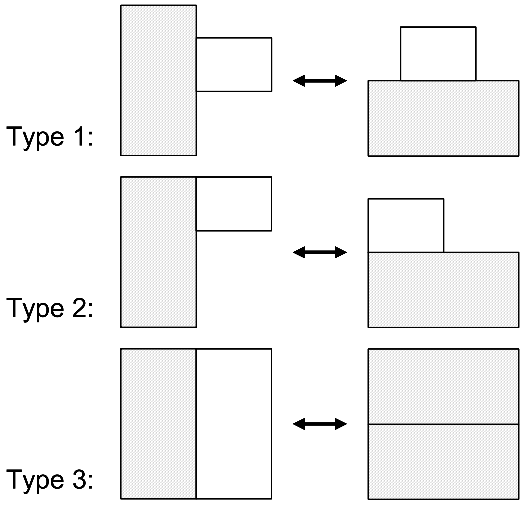


Figure 76: Possibilities in Profile View

- Type 1: Side by side: Neither the upper border nor the lower border coincide. On top of each other: No side of the polygonal outline coincides.
- Type 2 (L-form): Side by side: Either lower border or upper border coincide. On top of each other: At least one and not all sides of the polygonal outline coincide.
- Type 3: Side by side: Lower and upper border coincide.

- Step 3: Generate Sector Splits

The algorithm is called Rearrange Algorithm because it rearranges the air blocks contained in two neighbouring sectors into two new sectors. This is actually done by a merge and a split operation. Firstly the two sectors are merged to a single sector. With it the problem is reduced to finding the best split for this sector. On account of the assumption that there are at any time only compact sectors in the sectorisation the resulting sectors from the split must have the same attribute.

For the three types of neighbourhood there are different approaches for splitting: In the first case there is no possible rearrangement apart from the original pair of sectors. The second type allows only one possible rearrangement. The "side by side" pair of sectors can be rearranged into the "on top of each other" pair and vice versa. Type three provides a huge amount of rearrangement possibilities because splitting the joint outline by one continuous cut or splitting by Division Flight Level (DFL) always results into compact sectors.

For the last case one possibility is to divide the sector by a split at a DFL. If the sector consists of k flight layers there are $k - 1$ possibilities of such a split. There are not many but they are important to consider none the less. It is possible that a split at a different DFL leads to a successful separation of traffic flows which will reduce costs substantially.

The other possibility is to split the outline of the merged sector into all pairs of compact sectors by means of the 2-Partition-Algorithm described below.

- Step 4: Check Constraints

Here every pair of sectors in the list produced by the previous method is verified if it matches the given constraints. If one sector does not match all constraints the complete pair is removed from the list.

- Step 5: Choosing Best Split

In the remaining list all pairs of sectors match every single constraint. This function is running through the list trying to find a pair with better costs than the original pair. The condition is that the costs of both sectors must be below a threshold.

In the beginning the threshold equals the costs of the start sector. If a pair satisfying this condition is found the threshold is set to the maximum of their costs. At the end of the list, the function has either found a pair and the index determining the start sector is set $n = |os|, os \in S$ or no improvement could be made and the index is set to *index = index − 1*.

- Repeat these iteration steps until the termination condition is fulfilled.

4.4.2.6.2 Start Condition (Sub of Rearrange)

It may not be possible to achieve an improvement by rearranging the most expensive sector with its neighbours. In this case other expensive sectors are selected as start sector. This choice has two advantages. Firstly also the costs of sectors in the mid-field of the cost range are balanced and reduced. Secondly these rearrangements in other parts of the sectorisation can make room for the most expensive sector to be then rearranged. The detailed procedure of choosing the sector to be rearranged and termination is described as follows.

At program start i is set to n and therefore the first sector to start with is the most expensive one, *L(i)* with *i = n*. At the end of each iteration the algorithm verifies if an improvement has been achieved by rearranging the start sector with one of its neighbours *L(j), j 2 {1, . . . , i − 1}*. If the costs of both resulting sectors lie below the costs of *L(i)* the algorithm assess the iteration as an improvement and resets *i = n*. In the next iteration the algorithm will start with the most expensive sector. Keep in mind that two sectors have been replaced and the order of the list might have changed. *L(i)* from the last iteration may not be the identical sector *L(i)* of the current iteration.

If no improvement has been achieved no sectors have been replaced and the algorithm sets *i = i − 1*. In this case the next most expensive sector from the sorted list is picked as start sector.

4.4.2.6.3 2-Partition (Sub of Rearrange)

Looking at the outline we realise that we only need to find all splits in two dimensions, or with other words of one layer. If we want an air block to be contained in the first or second sector all air blocks lying below and above must be in the same sector because of the compactness assumption. Therefore it suffices to find a split of the floating baseline to this layer.

The number of air blocks in one layer often exceeds 30 air blocks because the sector to be split has been built from two sectors. This means there are regularly one billion combinations to be generated and checked for constraints which are too much to be processed in an acceptable runtime. This approach to completely enumerate all combinations has one obvious disadvantage. In most cases the generated sectors are not connected. We have developed an algorithm that generates only splits of two sectors that are both connected. The size of the output is finally small enough to be processed by the means of home resources.

4.4.2.6.4 Functionality of 2-Partition

For theoretical purposes we will consider the graph of one layer of the sector to be split. Because the sector is compact this graph is connected.

- Preconditions

Given a connected Graph *G = (V,E)*. Let A_G be the set of articulation points of *G*. Choose an arbitrary vertex $v \in V \setminus A_G$ and set W = {v}.

The 2-Partition-Algorithm requires a database, *DB*, to store sets of vertices.

- Input

set of vertices $W \subseteq V$; if $W \equiv V \rightarrow STOP$.

$\forall w \in W$ and $\forall$ neighbour vertices *nv* of *w*, $nv \notin W$ check if:

- Case 1

$nv \notin A_{G-W}$ check if $W \cup \{nv\}$ is contained in *DB*. If not, store *W* in *DB* and call 2-Partition-Algorithm(*W*).

- Case 2

$nv \in A_{G-W}$, *nv* dissipates *G - W* into components.

Let *C* be the set of their vertex sets exclusive of *nv*.

$\forall C' \in C$ check if $W := W \cup \{nv\} \cup \bigcup_{C \in C \setminus C'} C$ is contained in *DB*. If not, store *W* in *DB* and call 2-Partition-Algorithm(*W*).

4.4.2.6.5 Split'N'Merge

The Split'N'Merge Algorithm is a variation of the Rearrange Algorithm which was originally intended to be an extension only but which produces very good results in isolation. Although the main goal is to balance the costs of the sectorisation all efforts instantly become useless if the algorithm does not succeed in reducing the costs of the most expensive sectors. When applying the Rearrange Algorithm this phenomenon may occur if expensive sectors are clustered together. Because of the little cost difference between neighbours the resulting sectorisation usually has one or two sectors with costs no better than in the initial configuration. If the most overloaded sectors are preserved the results are naturally not satisfying. We had to think of a fall back solution for these cases. Instead of merging two expensive sectors and trying to find a possibly non-existing better split we split only the most expensive sector and merge two cheap sectors.

The direct application of this idea to the initial sectorisation produced such good results that we implemented it as a stand-alone algorithm. This also allows us to pre-process the initial configuration to eliminate the most expensive sectors before deploying the Rearrange Algorithm to further reduce and balance out costs.

- Iteration

Given are an initial configuration of operational sectors and a set of constraints. Iterations consist of one split and one merge operation in this order. When we split the sector with the maximum costs first we give the algorithm the possibility to consider one of the two resulting smaller sectors in the following merge operation. The algorithm terminates when there is no pair of neighbouring sectors which can be merged to a sector with lower costs than the sector which has been split in this iteration. Otherwise the newly merged sector will be the start sector in the previous iteration

- Step 1: Split

As mentioned in the introduction the Split'N'Merge Algorithm was developed after the Rearrange Algorithm which already provides a very good function to split a sector. The split method of the Split'N'Merge Algorithm resorts to this functionality which is described in detail above.

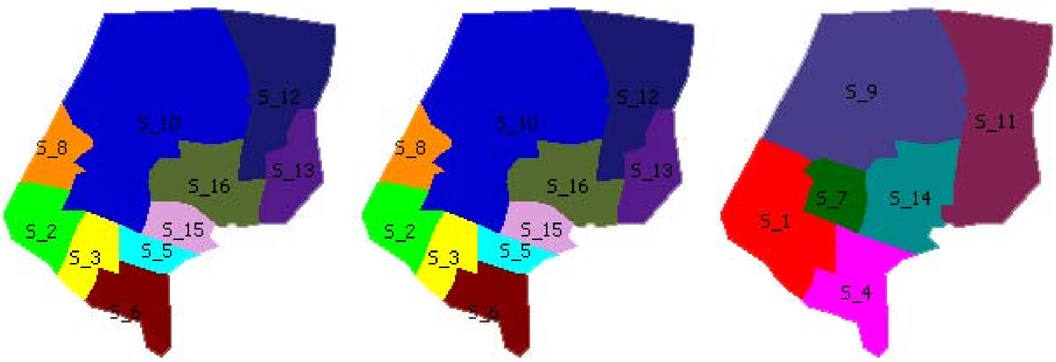
- Step 2: Merge

The algorithm considers all pairs of neighbours which are compact when merged. Of these the pair is selected which has the lowest costs as merged sector and lies below the costs of the sector that was split in this iteration.

4.4.2.7 Results

4.4.2.7.1 Rearrange Algorithm

The Rearrange Algorithm produces operational useful results. Their quality depends on several factors, e.g. the partitioning of the airspace and the starting configuration. If a sector shall be rearranged with its neighbours it is desired that they are compact when merged (neighbourhood type 3). Only in this case enough splits into two compact sectors are generated so that a real improvement can be found. Throughout all tests it has seldom occurred that a rearrangement of type of neighbourhood 2 has been selected for it only offers one possible split. In order to produce good results it is very important for the Rearrange Algorithm that sectors and as many neighbouring pairs of sectors as possible are compact. For an initial sector configuration where no sector fulfils this condition probably no improvement will be achieved.



Rearrange Algorithm Starting Time: 8:00:00 Look Ahead: 60 min

	Start Data:	Result data:	Start Config:		Result Config:		Entries:	Exits:	Conflicts:	Complexity:
Average Costs:	137.0	143.0	S_7:	38	S_3:	87	30	33	19	19 %
Minimal Costs:	38	87	S_1:	48	S_4:	89	38	37	8	19 %
Maximal Costs:	306	189	S_15:	70	S_7:	118	35	34	45	14 %
Total Costs:	2198	2283	S_8:	70	S_9:	124	38	32	50	15 %
			S_3:	87	S_8:	125	50	50	19	15 %
			S_4:	89	S_1:	130	50	51	26	9 %
			S_6:	90	S_5:	137	50	46	28	33 %
			S_12:	98	S_14:	139	55	63	12	18 %
			S_2:	111	S_6:	147	52	58	26	25 %
			S_14:	144	S_2:	151	64	51	18	38 %
			S_11:	165	S_15:	160	56	52	36	35 %
			S_5:	202	S_11:	165	57	53	48	15 %
			S_9:	207	S_16:	169	60	57	42	20 %
			S_10:	231	S_12:	174	56	65	38	30 %
			S_16:	242	S_10:	179	50	68	49	25 %
			S_13:	306	S_13:	189	60	61	53	30 %

Figure 77: Results for Rearrange Algorithm

Although the Rearrange Algorithm is only rearranging locally a large part of the sectorisation is examined in each iteration. If for instance sector S_10 in Figure 77 is selected as start sector at least 25 percent of the airspace is considered in the rearrange process. Still it can be a problem if the most expensive sector is only surrounded by just as expensive sectors. In these rare cases it is usually not possible to achieve a significant cost reduction. Even if through the rearrangement of other sectors first it might be possible to further reduce the maximum costs the resulting sectorisation is often not acceptable. A typical result of this problem is that the most expensive sector cannot be rearranged at all and has 50 % higher costs than the second most expensive sector. To avoid this phenomenon it is reasonable to slightly modify the initial sectorisation.

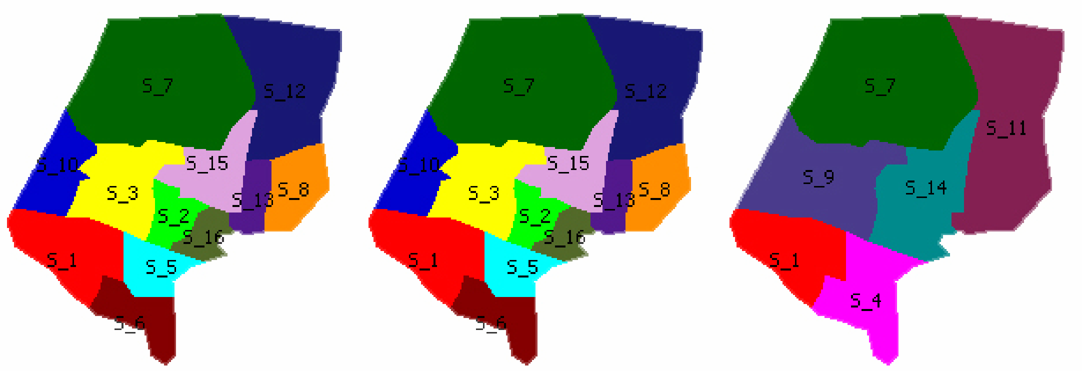
As mentioned before the new floating baseline is responsible for a balance around a much lower average than before. The only disadvantage is that the 2-Partition-Algorithm cannot be used if too many air blocks per layer have to be rearranged. In this case the fall-back solution to composes these air blocks to two sectors is applied which does produce very good results. Still the 2-Partition-Algorithm is not only able to find good results but even the best choice. On the other hand the 2-Partition-Algorithm cannot compete if we consider the relation between runtime and the quality of the output for more than 32 air blocks per layer.

4.4.2.7.2 Split'N'Merge Algorithm

The Split'N'Merge Algorithm was not constructed to achieve a good cost balance but to break down the most expensive sectors. If the initial sector configuration is not already well-balanced this objective is always fulfilled. In each iteration the most expensive operational sector is split usually leaving both resulting sectors in the mid-field of the cost range. In the second part of the iteration of all neighbouring pairs of sectors the pair is merged which will contribute the least costs to the current sectorisation. This pair often consists of two sectors in the cost range below average cost. This way not only the maximum costs are reduced but also the minimal cost are raised. Obviously this can only continue as long as there are pairs of cheap sectors which can be merged. In general one can say that there have to be two neighbouring cheap sectors to reduce the costs of one expensive sector. While the split of a compact sector always results in two compact sectors a merge is only allowed if the merged sector is compact. This shows that the Split'N'Merge Algorithm is dependent on the initial sector configuration and consequently also on the sectorisation produced after each iteration. Figure 78 shows that split and merge operations often change the sectorisation in a way that no cheap sectors can be merged to a compact sector anymore which is additionally quadratic enough to pass the constraints check.

Also because of this fact the Split'N'Merge Algorithm seldom needs more than four iterations. In each iteration one merge operation with negligible runtime and one split operation is performed. The split-function of the Rearrange Algorithm can almost always apply the 2-Partition-Algorithm as only one sector has to be split instead of two merged sectors. Because of the low number of air blocks per layer the runtime is low and consecutively the runtime of the whole algorithm.

Through the combination of speed and the quality of its results the Split'N'Merge Algorithm is predestined to get a quick overview on how much room for optimization is available. In most cases a further reduction of the maximum costs is not possible. To achieve a balance that also considers sectors with costs around average the original idea to combine the Split'N'Merge Algorithm with the Rearrange Algorithm shall be pursued.



Split and Merge Algorithm Starting Time: 8:00:00 Look Ahead: 60 min

	Start Data:	Result data:
Average Costs:	137.0	146.0
Minimal Costs:	38	70
Maximal Costs:	306	207
Total Costs:	2198	2336

Start Config:		Result Config:		Entries:	Exits:	Conflicts:	Complexity:
S_7:	38	S_15:	70	35	30	0	21 %
S_1:	48	S_4:	89	38	37	8	19 %
S_15:	70	S_6:	90	39	37	7	24 %
S_8:	70	S_7:	91	34	28	28	6 %
S_3:	87	S_12:	98	37	44	6	32 %
S_4:	89	S_3:	144	43	66	27	17 %
S_6:	90	S_14:	144	55	63	17	18 %
S_12:	98	S_10:	151	61	60	19	23 %
S_2:	111	S_2:	157	58	53	31	33 %
S_14:	144	S_11:	165	57	53	48	15 %
S_11:	165	S_1:	171	66	56	38	22 %
S_5:	202	S_13:	182	52	61	60	19 %
S_9:	207	S_16:	184	71	70	19	40 %
S_10:	231	S_8:	191	62	61	53	29 %
S_16:	242	S_5:	202	67	71	47	30 %
S_13:	306	S_9:	207	48	43	110	16 %

Figure 78: Results of Split'N'Merge Algorithm

Algorithm	Avg	Min	Max	Total	Balance
Initial Sectorisation	137	38	306	2198	bad
Rearrange Algorithm	143	87	189	2283	quite good
Split 'N' Merge Alg.	146	70	207	2336	good

Table 8: Compared Cost Results

4.4.2.8 Discussion

A final validation is missing at this stage; however, first operational feedback is very encouraging. The validation process should run through fast- and real-time simulations before one can make real statements of the correctness of the optimisation approach.

The algorithms all produce much better results than the existing sector configurations in Maastricht (Table 8).

The optimisation algorithms are based on predefined airspace partitions, which are designed on specific flows for a day. When the flows change e.g. due to military activations, then the partitioning is not well adapted to the traffic demand and the optimisations will produce operationally poor results. This could be overcome with a set of airspace partitions which are optimised in parallel. However, it would still be preferable to conceive another way of producing atomic air blocks. However, our experience has shown that there is a lot of operational expertise in drawing these boundaries, and that it will be challenging to conceive algorithms.

Dynamic sectorisation as presented here is a very useful tactic capacity measure. Concerning further automation it has several advantages:

The changes to sector configurations can take effect with a very short look-ahead time horizon because of its very fine granularity, which will have the effect that moving sector boundaries will have limited impact on the sectors. I.e. that a planner, Γ, disposes of a tool that can be used at very late planning stages.

Dynamic sectorisation can only be achieved with optimisation tools, because the computing of good combinations is beyond human capabilities.

4.4.2.9 Conclusions

The study investigates on an innovative approach to dynamic sectorisation by the use of algorithmic optimisers that recombine atomic air blocks into operational sectors.

A number of algorithms have been developed and evaluated from which the most powerful have been presented here. All algorithms treat a sophisticated cost function and work with operational meaningful constraints, where controller workload has been modelled through various variables from the domain of airspace complexity like entry- and exit counts, entry- and exit vertical attitude of flights, vertical mix of flights in volumes, and a wide range of conflict classifications. In addition the results were constrained to deliver rectangular sector shapes for a good visualisation on typical controller working positions.

The heuristics of two presented algorithms is based on merging and splitting an initially existing configuration: the first by iteratively merging the two most expensive sectors and splitting them again into two sectors; the latter by splitting the most expensive sector into two and combining the least expensive neighbouring sectors into one. Both heuristics produce operationally useful improvement when compared to the initial (operational) configuration.

First operational feedback is very encouraging; however, further validation is still ongoing.

5. TECHNICAL ENABLERS

To achieve full-automation of ATM will require intensive work on the development of equipment. A big part of the ATM system will evolve on the long path towards full-automation, e.g. introduction of new semi-automated planner functions, semi-automated separation advisory functions, controller working positions etc. In this document we cannot cover all the necessary components that the full-automated system and its transition will require; instead we give a brief introduction of what we believe are key technologies: ATM models and fast time simulators, optimisation techniques for planning, and data link.

5.1 ATM Models and Fast-Time Simulators

The models for the ATM system must be improved. Key to success will be the prediction of the future states of Σ. Uncertainty must then be tackled, on one side by making the overall ATM system more deterministic e.g. through more information exchanges, which is a main focus of current big research projects on both sides of the Atlantic; on the other side the inclusion of uncertainty as an intrinsic part of ATM must improve through better empirical measures and mathematical formulations of probabilities of tracks, trajectories, flows, conflicts, complexities, workloads, man-power availability etc.

Fast time simulations will play a major role in the prediction of the system. Tools that are today used for research or strategic studies will find their way into the online system for improved numerical predictions. It will be paramount to increase realism even of the current best numerical models.

At the same time the simulation models should be simplified to allow for faster optimisation techniques.

5.2 Optimisation Techniques for Planning

In sections above we stated that automated planning is conceived as an optimisation, where Γ and ŕ implement χ or χ' by applying optimisation reasoning for their decision making process. Existing optimisation techniques in literature e.g. for cluster solving, or first online systems are still basic. Significant effort will be needed for a better modelling of the optimisation domains. Special attention will be given to optimisation under uncertainty. It is encouraging that the research in mathematics has achieved a sufficient degree of maturity and that optimisation solvers do exist nowadays and will certainly still improve in the coming years; so that one can be quite optimistic that increasingly more highly complex and hard problems can be solved.

5.3 Data Link

An ideal medium for exchange of clearances to the aircraft would be 4D-trajectory exchange using e.g. satellite connections like in PHARE. The actions of a Π would then be delivered to the aircraft by compiling them into 4D-trajectories. The 4D solution is advantageous also for easier conformance monitoring.

Closer to reality would be to use CPDLC. An automation system can then deliver CPDLC messages to the aircraft [41]; possibly by informing the cockpit that there is no human but a machine issuing the commands. The actions of a Π would then be converted into clearances and sent to the aircraft. The conformance monitor is then more difficult to achieve in comparison to 4D due to the loser closing of the air-ground loop.

There are currently no attempts to implement 4D-trajectory control; and the progress of CPDLC implementation is at a slow pace due to the high investments that are needed in the aircraft. In a hypothetical envisaged time frame for the implementation of full-automation one could at least assume that CPDLC will be fully available; and possibly even 4D-trajectory exchange. However, many of the issues that we mentioned in this text are not strictly related to full- but can also serve in semi-automation; and especially those elements at a tactic look-ahead planning horizon could start to be implemented in the medium term. Then these automated processes need to communicate to aircraft in the absence of data link. In the next paragraph we conceive a link using the current R/T[114] and which sends delayed synthetic voice clearances.

Synthetic voice is very easy to produce and has constant high quality. When a Π is active for implementation then the actions are compiled into clearances. In a first implementation this would be today's used clearances; but in the future could be extended for specific procedures like for ASAS or path objects. Synthetic voice is then generated from the clearances; then the ground equipment identifies the frequency that the aircraft is on; and then transmits on the frequency.

If the controller uses the frequency at the same time the automation system uses it, then the controller should have first access to the channel. In this case the ground-telecommunications system delays the transmission of the synthetic string, waits for the controller to release the microphone, and then sends the clearance. If the controller continues to issue clearances whilst the automation system occupies the channel, then his or her voice clearances are buffered, the synthetic voice stream is interrupted appropriately, and the controller's buffered clearances are sent etc. This access protocol is similar to the Ethernet with an additional higher priority for the controller, plus controlled pre-emption rights. The controller can listen to the frequency and feel when the own clearances get through. Priority should always be on the controller's clearances, because the automation system is supposed to give orders of tactic nature that can wait for some seconds until the controller pauses. In addition, an intelligent automation system should evaluate the workload situation of the controller so as not to issue clearances if the controller is already very loaded.

[114] R/T – Radio Telephony

Table 9 lists some advantages and disadvantages of delayed synthetic voice:

Value	Feature
(+++)	Enables an automation system to communicate to aircraft.
(+)	Makes the radar controller be aware of decisions of the automation system.
(+++)	Creates a very good signal on the R/T channel.
(+++)	Speaks international English and no local slang.
(+++)	Very cheap.
(+)	Pilots are aware about originator of clearance (automatic or human), at least as long as synthetic voice still sounds synthetic.
(-----)	Pilot talk-back is not possible anymore.
(---)	Is boring or nerving to listen to for pilots and radar controller and leads to fatigue.
(--)	Interrupts the radar controller workflow.
(---)	Increases radar controller workflow if he or she must verify the read-back (close loop).

Table 9: Pros and Cons for Delayed Synthetic Voice

That finalises the brief overview of key technologies for full-automation. The previous sections have given an overview of the operational and technical concept of full-automation. The next section treats different studies that have been conducted in the scope of this thesis.

6. CONCLUSIONS

6.1 Achievements

This section contains the strong points of the thesis on the theoretic and operational levels.

6.1.1 Theoretic Level

- Scope of Thesis

  The approach of this work is by a concept of automated planning that combines many elements to a holistic tactic capacity, flow and traffic management system. That contrasts to previous work that is mainly only targeting on conflict resolution.

- Planner-Strategy-Plan-Action Model

  A generic definition framework for planning under uncertainties is conceived at an abstraction level which makes it applicable for all planning domains. Its strength is its conciseness. It is explained with many examples and listings from the air traffic management domain. These links and lists are the other main achievement, because it helps the application domain to better understand itself. In addition some of the listed items from the application domain are highly innovative and are believed having high potential.

6.1.2 Operational Level

- Cost-Benefit Analysis

  The qualitative cost-benefit analysis compares different automation levels against a do-nothing scenario. The outcome is astonishingly positive regarding full-automation - but we still believe that full-automation will only come if all societal parameters are in its favour.

- Tactic Manoeuvres
  - It was shown with fast time simulation that speed control for en-route airspace is a very effective measure for aircraft separation. This was the first study in the world evaluating the usefulness of speed control.
  - It was shown with fast time simulation that lateral offset for en-route airspace is a very effective measure for aircraft separation, with an additional quality of being relatively robust regarding uncertainties in trajectory prediction. This was the first fast-time study in the world evaluating the usefulness of lateral offset.
  - It was shown with fast time simulation that tactic directs have a relatively poor ability to solve conflicts, but highly decrease airspace complexity and have other positive properties like e.g. fuel and emission savings.
- Dynamic Airspace
  - We presented a fully validated study on dynamic configuration management based on a numerical optimisation tool. The analysis lead to further higher level optimisations of the centre level network effects. This study is a necessary step towards the newer strategies of dynamic

sectorisation. It also allowed gaining experience in the programming of mathematical optimisers, which are of paramount importance for all further automated planning tasks.

- A study on how-to-design dynamic sectors built on small atomic air blocks showed that different strategies for airspace partitioning can be applied. Here we investigated partitioning for problem volumes called parents-children; and a flow-oriented partitioning. Tools were developed to accompany this new way of airspace development.
- The development of an optimisation tool for the composition of operational sectors and configurations from small granular atomic air blocks showed that optimisers can lead to airspace layouts with much better properties than the current sector layouts. Beyond the direct operational benefit of the application of this tool, we have gained useful knowledge in algorithmic optimisation and considerations about solvability of hard problems.

6.2 Lessons Learnt

6.2.1 Robust Optimisation

We have recognised the importance of robust planning and learnt that just-planning is not enough, even if it is already difficult enough. This has lead to the formulation of the planner-strategy-plan-action model. Future studies must aim for the inclusion of uncertainties and production of stable plans from the beginning. We are currently experiencing that this multiplies the difficulty of optimisations and leads to very computing intensive solutions.

6.2.2 Conflict Solvers

One of the strong points in this thesis turned out to become counterproductive: we choose the RAMS fast-time simulator as tool because it includes a powerful solver based on an expert system and a complete model of the airspace. Initially we achieved many changes to the mathematical simulator very fast and highly productive like e.g. for speed-control and lateral offset studies. In addition the verification of the work becomes easily feasible.

However, the more the (resolution) models became sophisticated the more tedious their implementation was. Finally modelling became so difficult that we failed to implement a number of ideas that we initially had for this work.

This failure can be interpreted in different ways: either the modelling is too ambitious and too little investment was made; or it is impossible to conceive this models with one person only; or the modus to work with an external company is wrong and it would be better to create ones own software.

6.3 Outlook

6.3.1 Fusion of Pre-tactic and Tactic Planning

In current operations the pre-tact planning is very basic and tactic planning almost not existing. In the coming years both will be developed and go through evolutionary processes.

Pre-tact planning has the difficulty to treat high uncertainties and must therefore use a model as worked out in this thesis, or it will fail. It will apply complexity-reduction techniques like rerouting of flows e.g. with the management of dynamic air gates and it will produce workload balancing with improved planning for dynamic sectorisation. Pre-tact planning also treats the manpower planning chain. All pre-tactic planning will be highly automated from the beginning because the processes treat very high data quantities to simulate or optimise, which is beyond human capabilities.

Tactic planning will start with online workload analysis and prediction for improved planning of workload balancing using sector configuration management. This will foster the use of fine grained dynamic airspace. Further it will apply speed control, lateral offset and direct-to to tunnel more aircraft close to the bottleneck. Tactic planning will include filtering functions that will reduce controller workload by filtering away standard situations. Tactic planning will also be highly automated but still keeps the human in the loop, because it will be closer to safety-critical functions; yet the amount of data to be treated will be such that humans will appreciate the support by tools, which they will have to trust.

The two sides will only fusion from the moment when common plans are worked out; but they will already join when it comes to overlaps e.g. in planning breaks, planning a configuration opening scheme, or organising bottleneck traffic etc. When they join it will be the clash of the deterministic and stochastic models, and the fusion of planners will add another challenge to robustness of plans.

Once organisation of bottleneck traffic is applied it will evolve towards higher density management functions which will use different techniques that will more strictly organise aircraft in rosters and patterns to be tunnelled through bottlenecks. That will only be possible with automation systems.

6.3.2 Speed Control and Lateral Offset

Speed control and lateral offset will make their way into operational use because of their excellent properties regarding conflict resolution rates under uncertainty. They will be applied with and without planning; and we foresee that they will be used as normal clearances first and later also by tactic flow managers for improved planning processes.

6.3.3 Uncertainty and Probabilistic Planning Models

For a realistic application of automated planners it will be most critical to tackle uncertainty for robust planning. The easiest examples for robust solvers seems to be the manpower planning chain for shifts, rosters and breaks; but also configuration planners that take probability distributions into account during the solving process. Conflict cluster solvers with robust solutions vis-à-vis uncertainties of trajectories deem also feasible.

6.3.4 Solvers

Fast time simulation models must be simplified or accelerated to allow for shorter computation times in the planning process, which is based on computer-intensive optimisation techniques. A way forward will be simplifications of ATM models e.g. for mathematical optimisations.

Some functions from the fast time solver should be evaluated in online equipment, taking full advantage of last generation trajectory predictors and constraint-based trajectory editors. Automatic conflict solvers have very high resolution rates also in high density airspace but yet are still some years away from operational use.

6.4 Closing

This work is another step towards automation of the air traffic management system; it has not been able to fully validate the thesis nor its anti-thesis but we see the high potential of this work in its first applications.

Parts of this thesis have already been applied like the works on dynamic sectorisation which were used for improved strategic airspace design. Currently we are running a project on pre-tactic planning that includes findings from the Planner-Strategy-Plan-Action model, and treats robustness of plans for shift-, break- and configuration planning by using forecast functions that deal with probability distributions. Operational validation of these functions is currently ongoing.

Almost all functions that are described in this thesis can be seen in isolation without considering automation. This might give some useful insights for readers that are interested in future tactic capacity management tasks only. Yet, many of the new functions can only be achieved with strong tool support for optimisations and simulations which is in general beyond human capability.

Therefore we believe that high or full-automation has become a bit more probable with this thesis. Human-out-of-loop decision tools will very possibly be implemented for ATM planning task, and then it might only be a matter of time until today's ATC tasks will be partially or even fully automated.

7. LIST OF FIGURES

8. LIST OF TABLES

9. REFERENCES

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10. ACRONYMS AND ABBREVIATIONS

γ	Ability of plan to recover from non-conformance
ϑ_a	Vulnerability of action
a	Action
ACAS	Airborne Collision Avoidance System
ADS-B	Automatic Dependent Surveillance
AERA	Automated En-Route Air Traffic Control
AI	Artificial Intelligence
AMAN	Arrival Manager
ARN	Airspace Route Network
ASAS	Airborne Separation Assurance System
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATM	Air Traffic Management
ATO	Actual Time Over
BADA	Aircraft Performance Database
BOS	Bottleneck Operational Sector
c	Cost function, sometimes called objective function
C&FM	Capacity and Flow Management
CD&R	Conflict Detection and Resolution
CDD	Configuration Duration Distribution
CDR	Conditional Direct Route
CDTI	Cockpit Display for Traffic Information
CFMU	EUROCONTROL Central Flow Management Unit
CNS	Communication, Navigation, Surveillance
CORA	Conflict Resolution Assistant (project)
CPDLC	Controller Pilot Data Link Communications
CSE_{rel}	Relative Configuration Saturation Envelope
CSSE	Centre Schedule Saturation Envelope
CTAS	Centre TRACON Automation System
DAG TM	Distributed Air Ground Traffic Management
DFL	Division Flight Level
DFR	Dynamic Flow Routeing (proposed)
DYNFLO	Dynamic Flow Control

DYNSEC	Dynamic Sectorisation
EEC	EUROCONTROL Experimental Centre
ERATO	En-Route Air Traffic Organizer
ETFMS	Enhanced Tactical Flow Management System
FAB	Functional Airspace Blocks
FLAS	Flight Level Allocation Schemes
FMP	Flow Management Position
FMS	Flight Management System
FREER	Free Route Experimental Encounter Resolution
FUA	Flexible Use of Airspace
GA	Genetic Algorithm
HIPS	Highly Interactive Problem Solver
HMI	Human Machine Interface
KPI	Key Performance Indicator
LOA	Letter of Agreement
MANTAS	Maastricht New Tools And Systems
MILP	Mixed Integer Linear Programming
MIT	Miles in Trail
MSP	Multi Sector Planning
MTCD	Medium Term Conflict Detection
MUAC	EUROCONTROL Maastricht Upper Area Control
NOP	Network Operations Plan
O	Overload
OBT	Organisation of Bottleneck Traffic
OLDI	On-Line Data Interchange
OPTICON	Optimal Configurations Tool
PARR	User Request Evaluation Tool, Problem Analysis, Resolution And Ranking
PDF	Probability Distribution Function
PHARE	Programme for Harmonised ATM Research in Europe
P-RNAV	Precision Area Navigation
R/T	Radio Telephony
RAMS	Reduced Mathematical Model Simulator
ROC	Rate of Climb
ROD	Rate of Descent
ROI	Return on Investment
RTA	Requested Time At

S	Set of system states
s	state
SDD	Sector Duration Distribution
SOT	Sector Opening Table
STCA	Short Term Conflict Alert
STO	Strategic Traffic Organisation
SYSCO	System Supported Coordination
TAAM	Total Airspace and Airport Modeller
TCAS	Traffic Alert and Collision Avoidance System
TCM	Tactic Capacity Management
TFM	Tactic Flow Management
TLS	Tactical Load Smoother
TMA	Terminal Control Area
TMV	Traffic Monitoring Value
UAV	Unmanned (uninhabited) Aerial Vehicle
UML	Unified Modelling Language
URET	User Request Evaluation Tool
vDFL	variable Division Flight Level
VERA	Verification of Separation and Resolution Advisory
WLM	Workload Monitor
WLS	Weakest Link Sector
WWL	Weighted Weakest Link
κ	Capacity Threshold
Ξ	Impact of re-planning on cost function
Π	Plan, or set of plans
Σ	System, or sub-system
χ	Strategy, or set of strategies
χ'	Meta-strategy
ψ	Stability of plan
Ω	Solvability
Γ	Planner, or set of planners
$\acute{\Gamma}$	Meta-planner

11. ANNEXES

11.1 Fast Time Simulation

Major parts of this thesis use fast time simulation for the validation of operational concept elements. The validation of operational concepts require to pass many steps to allow final decisions whether it is of some use, and management and investors may take decisions towards the implementation only if at the end of the validation process there is enough information on key performance indicators. Such decisions are usually taken based on return-on-investment[115]. In Air Traffic Management the ROI can be devised into some key performance indicators, which are safety, capacity and economics, to which recently have been added environment and security. Also the technical and operational feasibility should be clarified at stages of decisions to invest; however, as can be seen from the poor pedigree of innovation in ATM in the last decades and considering that there was no lack in ideas for operational and technical change, it can be assumed that there was missing evidence for these key performance indicators. It can be suspected that research has not delivered these indicators.

In comparison to other techniques that are used in the full validation life cycle, fast time simulation has its place in the early lifecycle somewhere in the middle between pure mental or mathematical models that hardly deliver realistic but yet quantifiable results on one side; and the expensive and time consuming real time simulations, life and online trials that generally suffer from quantification due to the small numbers on the other side. Fast time simulation is the tool that allows quantification of key performance indicators already in the very early life cycle of new concepts with a good degree of realism. This performance cannot be met by any other validation tool, and only the online environment will deliver the same amount of exploitable data. Fast time simulation has the following characteristics concerning key performance indicators:

It requires modelling of the operational concept into a simulator. For that the maturity of operational requirements must be lift to a sufficient level. Many questions of operational feasibility can be asked during the modelling phase, which leads to early and mature processes and procedures, as well as early estimation of cost of operational change expressed in transition pain.

It requires modelling of the technical concept to sufficient extend. The technical requirements must be refined to an adequate level so that the technical implementation of products, mostly software, can be achieved. Mathematical models are often turned into numerical models. This leads to the understanding of technical feasibility parameters and cost.

It produces the ultimate results that express the virtue of the new concept through capacity, complexity, and workload figures. Complexity and workload give quantifiable safety statistics. Capacity analysis is a quantifiable output that allows estimation of wins. Capacity-delay analysis is one of the most important business health indicators that can be evaluated.

To use fast time simulation is an art in itself, and the quality of its result is proportional to the quality of the input i.e. the setup of the simulation multiplied with the quality of the model i.e. the simulator. And last not least the results must be

[115] ROI – Return on Investment

analysed. The statistical exploitation of simulation results can become cumbersome due to the high quantity of produced output and requires sound statistical treatment. Therefore the production process can be split into three equal parts: setup, simulator model, analysis. The parts of this thesis that employ fast time simulation have conducted further developments in all three areas. This section describes to some detail the setup and analysis part whereas the previous studies have already elaborated the simulation models.

11.1.1 Simulation Setup

The setup of a fast time simulation is constructed on three pillars: airspace (environment), traffic, and the controller model. The aim is to create a model of the reality so as to reduce the number of assumptions, and the global effort is in general to get as close as possible to reality and to simplify only when the estimated impact on the results can be neglected or can be counterweighted in the analysis.

11.1.2 Environment

The environment in RAMS requires a number of input files for airports names and coordinates, navigation aids names and coordinates, and the airspace sectors. Several air traffic control centres can be used, where each runs over a sector-configuration schedule during the time of simulation, which is usually one day, but can be less and more. Each configuration of each centre fills the entire airspace without holes. The shapes of the configurations change. The sectors are made of one or more sector boundaries, each boundary is defined by its corners. This model allows for simple static constructs e.g. one centre with one configuration with a limited number of sectors and static division flight levels between the sectors, up to very sophisticated constructs with dynamic configurations, and complicated sector boundaries including balconies and variable division flight levels. The RAMS model can be considered complete.

Note: Other fast time tools like SAAM use in addition a route network as the baseline for flight routings. This was not used in the thesis.

Setting up the environment can be done in several ways. Most studies in this thesis use data from the EEC[116] originating from CFMU[117] called DANCE. This data needs conversion into RAMS and SAAM formats, which is carried out using SimMaker (Section 0). SimMaker allows for selection of different configurations and sectors and export into RAMS and SAAM formats. It can be read directly into the tools. Unfortunately the data often contains little errors, because the useful level of detail for DFMU differs from the one in fast time simulation studies. RAMS e.g. does not allow for holes and overlaps. These holes are detected and manually corrected in RAMS. SimMaker can then convert the corrected airspace into SAAM or RAMS again. This process sound simple but demands high operational knowledge of the treated airspace especially for larger airspace like the used 5- and 6-states scenarios.

11.1.3 Traffic

Traffic can originate from flight plan and radar data depending on the requirement of the study. This study uses both, flight plans and radar data from two sources:

[116] EEC - EUROCONTROL Experimental Centre

[117] CFMU – EUROCONTROL Central Flow Management Unit

CFMU-DANCE and MUAC[118]-STANLY. STANLY, which is the Maastricht UAC database for post-analysis, was modified during this thesis to log compatible data to the CFMU formats. However, its scope is only Maastricht and part of the neighbours, but its data granularity is finer for radar data than the CFMU data.

Flight plans are given in two formats: as filed (FTFM), and as flown (CTFM). To correct the filed and produce flown flight plans, the CFMU-ETFMS[119] uses a simple mapping algorithm based on the knowledge of radar plots: If the radar position differs in more than 1000 feet altitude or 10 minutes or 20NM from the flight plan position, then a proximate waypoint is searched and the filed flight plan updated. The ATO[120]s are then corrected for the entire flight plan.

Depending on the requirement of the fast time simulation it may be requested to run traffic models with more or less degree of the flown situation. The use of corrected flight plans and radar data in the simulation has the advantage to model the flight profiles closer to reality; however, the entire ATM system has already acted on these flights when they are recorded and simulations with controller models become imprecise, because conflict detection and resolution will not trigger. Therefore most simulations use FTFM with further corrections:

- Filtering by airspace volumes. The pan European flights are filtered to reduce the number of flights to the area of interest. SimMaker has a powerful filter function for CFMU formats, SAAM and RAMS have very powerful filters.
- Filtering of ghost flight plans. Filed flight plans contain a high number of flights that have never flown, these are filtered out.
- Horizontal correction of the flight profile. This is necessary whenever modifications to the route network are simulated or when e.g. the use of direct flights is simulated, as is the case in Maastricht. SimMaker has the possibly most performing re-router function, this thesis has developed some function for dynamic on-the-fly reroutes to model controller workload in RAMS.
- Vertical correction of the flight profile. Fast time simulation tries to simplify the vertical profile in order to enable the controller model to interact with the flights and herewith produce workload results. Therefore only key parameters of the vertical profile are taken: entry level, requested level, exit level, if wished by sector. SimMaker has a powerful function to impose LoA[121] restrictions on flights.
- FTFM time correction. The filed flight plans departure time is corrected with the time stamp from the corrected flight plan.
- Trimming of the traffic. The traffic originates from CFMU with pan European flight plans. These are trimmed to the area of the simulation. SimMaker can provide this function (RAMS and SAAM as well).
- Flights must be converted from one tool to the other. This function is provided by SimMaker.

[118] MUAC – EUROCONTROL Maastricht Upper Area Control

[119] ETFMS – Enhanced Tactical Flow Management System

[120] ATO – Actual Time Over

[121] LoA – Letter of Agreement

11.1.4 Controller

The air traffic controller workload is modelled by putting weight on specific events that occur when traffic passes through airspace. E.g. centre entry, sector entry, navigation aid crossing, top of climb and descent etc., in conjunction with the origin and destination of flights lead to different tasks by flow. These tasks are given a weight. The weights are either summed up in simple workload analysis, or further treated in cognitive models to emulate human information treatment. The controller model in RAMS is further subdivided into three major components:

- The list of procedural task loads: Traffic is simulated through airspace. This generates a high number of different events that are set into their contexts to produce task load. For a better overview the tasks can be grouped e.g. to internal and external coordination, flight data management, standard R/T[122], conflict search etc. where each category is further refined to represent as close as possible the procedural tasks in sectors. This may lead to lists of hundreds of tasks that are further modified to reflect specific flows or LoA in specific volumes.
- The interpretation of a “conflict” or problem: treating of conflicts is a dynamic task for air traffic controllers. In the simulation model the action that is conducted depends on the parameters of conflict e.g. the separation minima that can be configured to any value. Further the conflict geometry parameters are available for further treatment, i.e. the conflict angle and the aircraft profiles at start, during and at end of conflict. Then the problem resolution and the attributed task load are set as a function of the conflict parameters, and the rule base system of the simulator is triggered.
- A conflict-resolution rule base system. RAMS simulates the controller reactions to problem with a rule base system. The rule base system is an expert system that is fully user configurable. Many parameters from the simulation are available for further analysis of the situation, e.g. distance to arrival airports, distance to sector boundaries and much more. Herewith the rule base can be configured to reflect as close as possible standard controller behaviour. Many of the studies of this thesis use rule base programming for improved resolution rates like speed-control, lateral offset, direct-to clearances, conditional routes, multi manoeuvres etc.

11.2 Simulation Analysis

Fast time simulation produces very high numbers of output data. The simulated traffic, airspace and controllers all produce data that can further be analysed. This can be compared to online capacity analysis as it is conducted in modern operational centres, with additional difficulties emanating from the controller workload model. Analysis of fast time simulation results allows all kind of operational conclusions on workload, occupancies, complexities, and capacities. The analysis in this thesis is based on three models: one traditional capacity model, some complexity metrics, and a simplified workload model for automation systems. This will be explained in the following paragraphs.

The capacity analysis is a model to evaluate capacities of sectors (and not centres). The method has become standard in the past years, where the origin is unknown to the author. It is composed of the following steps:

[122] R/T – Radio Telecommunication

For each sector, compute the number of sliding hourly entries over the sliding hourly workload (Figure 79a). Units for traffic is number of aircraft, for workload it is undefined; however, if the simulator is calibrated to time units for task load, then a working time unit in percentages is useful.

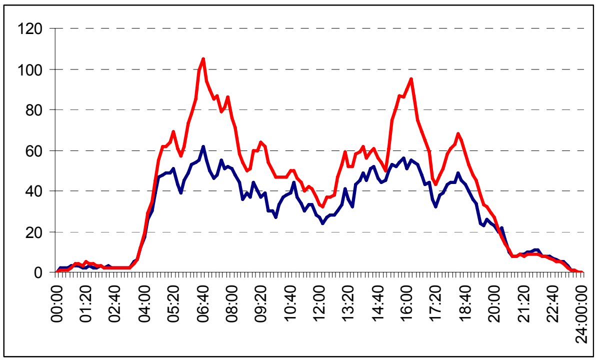
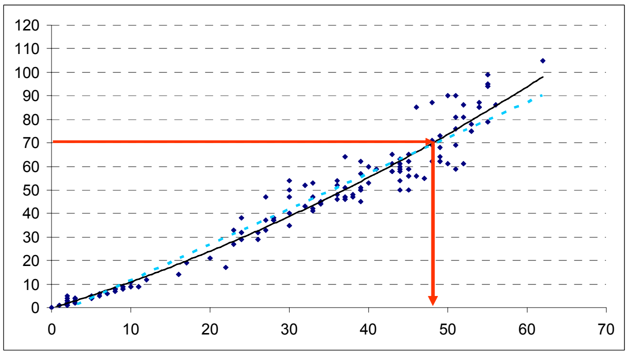

Figure 79: (a) hourly entries and workload; (b) polynomial and linear trends in workload-entry scatter.

Plot workload over entries and find the capacity value where trend line reaches workload of 70 units (Figure 79b). When the simulator is calibrated, the 70 units can be interpreted as 70% workload, which is set as the capacity limit. The capacity is calculated with the binomial trend line. For complexity statements it is the comparison with the linear trend is useful. In this example linear and binomial trends are almost the same, and herewith a linear behaviour of the sector regarding traffic growth can be deducted, which means that there are no specific high complexities appearing with higher loads and the workload per flight remains the same. This is a criterion for the quality of the airspace design.

The capacity figures from the trend line are visualised in the daily traffic to evaluate (Figure 80) whether workload or traffic peaks are too extreme. This may lead to further considerations for capacity management. It is the also possible to relate the workload to its workload categories for a further fine grained analysis.

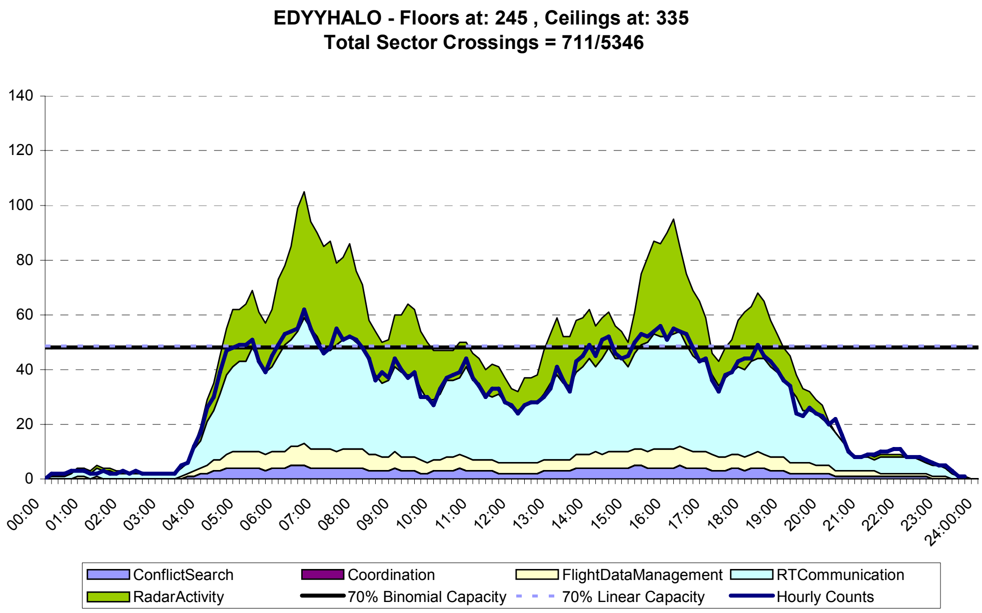

Figure 80: Hourly entries and workload categories with capacity values

The automation model is not measured with the workload model but instead only based on the core activity of air traffic control which is conflict detection and resolution. All procedural tasks that generate work for air traffic controllers and which influence the airspace capacity model as explained above are not considered, under the assumption that they are not key in a highly automated system and can be provided by machines.

The performance of the conflict prediction has been set out of scope for this thesis. However, uncertainties in trajectory prediction are modelled by setting changing values of separation minima. The solver has to find solutions with higher separations to assure that uncertain predictions are outweighed.

The performance of the conflict resolution function is evaluated by the capability of the solver to produce separation. If no solution is achieved it is further investigated what hindered, and is mainly looking to environmental aircraft.

11.3 Simulation Scenarios

Most validation studies in this document are conducted with RAMS 5Plus, which is a very rich fast time simulator. The setup of scenarios for the simulation varied during the studies, with two major setups:

- 5-States scenario from 1997. This scenario has been produced by the 5-States project [75] and is reused here, by focussing on special developments in RAMS and modifications in the setup. The area of this setup extends from London/Paris in the west to Berlin/Prague/Vienna in the east and from Copenhagen/Malmö in the north to Lyon/Milan in the south. More than 140 sectors from 24 ATC Centres were simulated. The measured centres were limited to en-route and to Karlsruhe, Maastricht and Reims, which corresponds to 36 en-route sectors above flight level 245.

  The traffic baseline simulates a traffic sample from 12 Sep. 1997, which corresponds to 100%. This was increased to 150, 200 and 300%, which emulates roughly traffic loads for the year 2005, 2010 and 2025 for optimistic traffic growth predictions.

- FAB[123]-setup from 2007. This scenario has been produced for the FAB study [76] with increased realism for flight trajectories especially concerning the Maastricht area, by including all constraints from Letters of Agreements (LoA).
- MANTAS[124]-setup from 2007 is a merger of the FAB traffic and MANTAS airspace and is used for dynamic airspace studies.

All simulation setups have in common to be the state of the art at their time, and have been extensively validated by the mentioned projects, with the effect that almost all results from the validation studies can be re-validated if necessary.

[123] FAB – Functional Airspace Blocks

[124] MANTAS – MAastricht New Tools And Systems

11.4 Tools

This annex gives a brief overview of the main tools that are used for this thesis. Some of the tools are very rich which makes it impossible to give even an approximate picture of their functions. Therefore the focus is set on specific and innovative functions that have been developed for and by this thesis.

11.4.1 RAMS[125]

RAMS is a tool that was created in the late '90s in the EEC, and which is now further developed by a specialised company called ISA Software. Its main characteristics are the very rich model for en-route and airport air traffic control. All flights are simulated with an aircraft performance model, which was configured with latest BADA[126] data. When flights are simulated through airspace, they generate events. Models of air traffic controllers react on these events and can change navigation of flights. I.e. that RAMS is simulating using active controller agents that act upon the navigation of aircraft and change it; and not only shooting flights through airspace like SAAM (below). The model of the air traffic controller is configurable, like almost everything in RAMS, and can reflect a planner, or radar, or multi sector controller, that can react on currently 158 different events, that can be set in interrelation with a subset of around 30 tasks. An agent of an air traffic controller owns a rule base system which is triggered to evaluate the situations and decide on actions on flights. This rule base is also user programmable. These features make RAMS the tool of choice for some core studies of this thesis.

ISA has been tasked to implement various new functions in support of the thesis, e.g.:

Laterall Offset	This function is extensively described in the study. The model also contains some additional parameters that have not been used in the study, e.g. the complete task load parameters model, and rule base driven manoeuvres of lateral offset type.
Direct-to as conflict resolution manoeuvre for the radar controller	Direct-to as a resolution manoeuvre for the radar controller is described in the related study. Additional features that have not been used are the complete task load model, as well as specific behaviour when military airspace is activated or deactivated.
Direct-to as nominal procedure when aircraft enter airspace	Direct-to as a nominal procedure for planning controllers is described in the related study. The model is complete containing the task load description. Military activation and deactivation influences its behaviour.
New event logging for conflict resolution events	More information is logged when conflict resolutions are executed and task events occur, which allows for better analysis.
Conditional (2D) routes	Conditional routes were supposed to become a full and major part of the thesis. However, the modelling was very cumbersome and even though it was continued over

125 RAMS - Reduced ATC Mathematical Simulator

126 BADA – Aircraft Performance Database

	several years it is not yet at the expected. Nonetheless, the implementation of a full 2-dimensional conditional route concept including task load model was finished.
Air Gates	Air gates are 3 dimensional airspace constructs that help in organising traffic flows with set of rules.
Conflict resolution manoeuvring both aircraft part of the conflict	The conflict resolution model was extended to allow for the manoeuvring of both aircraft involved in a conflict, whereas before only one or the other aircraft could be manoeuvred. The manoeuvres are implemented in the simulation kernel; however, the logic of combinations of manoeuvres is implemented with the configurable rule base system, which allows to very high levels of flexibility. Also double manoeuvres on one aircraft if the conflict have become possible. The task load model is complete.

There is another simulator with similar functions called TAAM[127] that would have had several drawbacks in comparison to RAMS, just to name the price and the impossibility to inject change requests for research. Also the highly configurable setup of RAMS as well as its user defined resolution rule base, and the overall richest workload model, make it the tool of choice not only for research studies.

11.4.2 ATC Playback

ATC Playback [78] is a product from a Belgium company called Luciad B.V. that started to be developed on the Java platform around the year ’98. It is a viewer for simulations results and targets TAAM and RAMS originators of data. The company succeeded to insert its platform into other operational systems in the ATC market.

Luciad has been tasked to implement some new functions in support of the thesis, e.g.:

- Conflict Type Colours
- Conflict Trail
- Conflict Trail Density
- Resolution type Colours
- Resolution Density
- Task Pane
- Trajectory Density Movie
- Enhanced filters and vertical zoom
- Track label information

11.4.3 SimMaker

SimMaker was developed by the author since 2006 on the VBA platforms and .NET framework. Its objective is to automate the workflow for all preparation and analysis steps that are required for sophisticated and realistic fast time simulations. In

127 TAAM - Total Airspace and Airport Modeller

addition it includes many conversions of formats from one simulator to the other e.g. traffic and airspace. It includes a very powerful configurable re-router and constraint-setter function for modifying flight plans. Its analysis part extends to new models for centre capacity evaluations.

11.4.4 SimMaker Configuration Optimisation

SimMaker was extended to allow for sophisticated simulations of optimisations for centre sector configurations. A full environment around the SAAM Configuration Optimiser (section 11.4.6) was customised, which was sometimes inspired by NEVAC [77], but goes beyond some of its capabilities.

Three functions have been implemented:

- Support to setup. One tool to help the user to generate possible configurations out of Elementary Sectors, which was found to be tedious and very error prone when done manually. One tool for checking names between all airspace environment files required for the different steps in preparation of the input files for the optimiser.
- A manual execution of a single optimisation followed by a manual analysis automatically generating one detailed report containing all relevant statistics and graphs.
- A Monte-Carlo simulator for a sensitivity analysis of various parameters for the generation of the input files as well as the parameters of the optimiser itself. It can amongst other produce a sensitivity analysis on capacity settings.

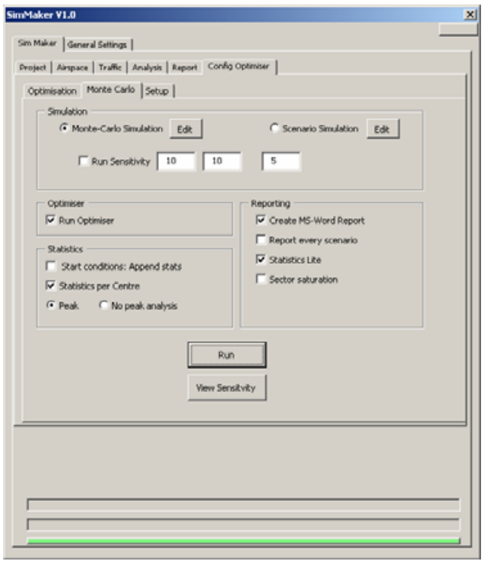

Figure 81: SimMaker Monte Carlo Screens

11.4.5 SAAM

SAAM[128] is a development since the '90s from EUROCONTROL HQ, where it is used for the conception of the future European airspace route networks (ARN). It is renowned for its nice 3d animations of traffic samples in airspace with changing camera views. However, its true value is a rich toolbox for many useful functions e.g. for route and airspace design, shortest path routing under constraints, as well

[128] System for traffic Assignment and Analysis at Macroscopic level

as airspace analysis based on intersection and conflict counts. It also contains some converters to and from other simulators. SAAM cannot be used for conflict resolution models because it does not contain such a model.

There are no specific development in SAAM for this study, but is was used for many analysis tasks; the SAAM airspace format was chosen for the sector optimisation tool (below), and a SAAM Configuration Optimiser (below) was evaluated against the sector optimisation tool in the study (above).

11.4.6 SAAM Configuration Optimiser

The used tool comes from the SAAM tool suite and accesses a mathematical optimisation engine from ILOG company called CPLEX, which is state of the art. Figure 82 depicts its main screens.

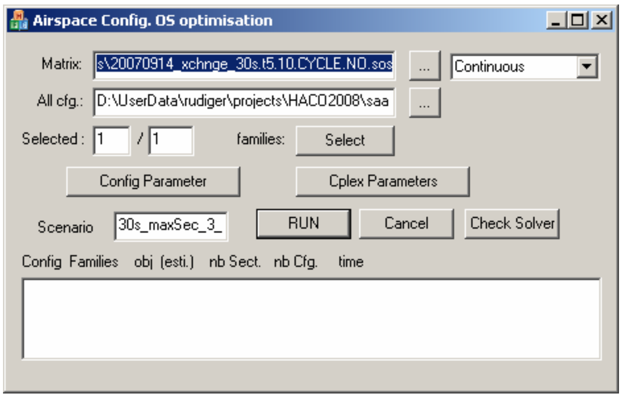

Figure 82: Screenshot 1 for SAAM Configuration Optimiser

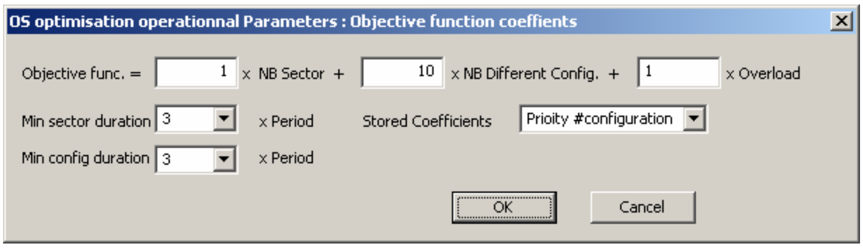

Figure 83: Screenshot 2 for SAAM Configuration Optimiser

Figure 83 shows the constraint and weights page that set the optimisation, with some defaults that can be set for the cost function and the constraints. The cost parameters are the weights for:

- Number of sectors: a high weight will favour the possible maximum number of sectors in a configuration. E.g. if a centre sector configuration has a maximum configuration of n sectors, then a solution containing this configuration will have low cost for high weight and high cost for low weight.
- Number of different configurations: a high weight will favour the use of many different configurations.
- Overload: a high weight will penalise sectors that are overloaded.
- There are a number of presets available for specific objectives of the simulation, which can be e.g. priority to delay (overload minimisation), or priority to configuration stability etc.
- There are two constraints that can be set to reduce the solution space:

- Minimal sector duration expressed in time intervals is the minimal lifetime of a sector.
- Minimal configuration duration expressed in time intervals is the minimal lifetime of a configuration. I.e. that there are settings where the sector lifetime is longer than the configuration lifetime, which means that a sector may not change even if the configuration changes.

All parameters of the SAAM configuration optimiser have been run through several studies; and a sensitivity analysis gave insight into the behaviour of the optimiser.

The input to the optimiser:

- .sos-file. This file contains data for each sector over time intervals. Time intervals are abstract to the optimiser, so that it is not linked to specific semantics like days or minutes etc. Usually the sector data per interval is overload, but can also be other loads like workload. The optimiser will only compute the best cost for whatever data it gets.
- .cfg-files, which list all configurations for all centres.

The SAAM optimiser comes with a minimal environment. This was created in SIMMAKER (section 11.4.3) during this study to automatically generate the input data, execute the optimisations, and do profound statistical and graphical analysis on the output. In addition a Monte-Carlo simulator was developed also in SIMMAKER for sensitivity analysis of various settable input data and optimiser parameters.

11.4.7 Sector Optimiser

The sector optimiser is a development by RWTH Aachen[129] and EUROCONTROL MUAC in 2007 based on the Java platform.

[129] RWTH Aachen – Rheinisch-Westfälisch Technische Hochschule Aachen, Germany

11.5 Library

During the thesis an electronic library was created with an accompanying Excel file for each entry. Each document that was read was commented in about 10 lines. Most of the literature review was undertaken in the first two years of this thesis, but the library continues to grow when new material is found. It contains more than 430 entries from which more than 50% are commented. It contains some scans from otherwise forgotten documents, that sometimes even the authors did not find anymore.

Figure 84 is a homework performance indicator and shows how many titles from which years appear in the library and how many of them have been read and commented during the thesis. Figure 85 shows the categories in which the titles have been catalogued and give an indication of the emphasis of the thesis.

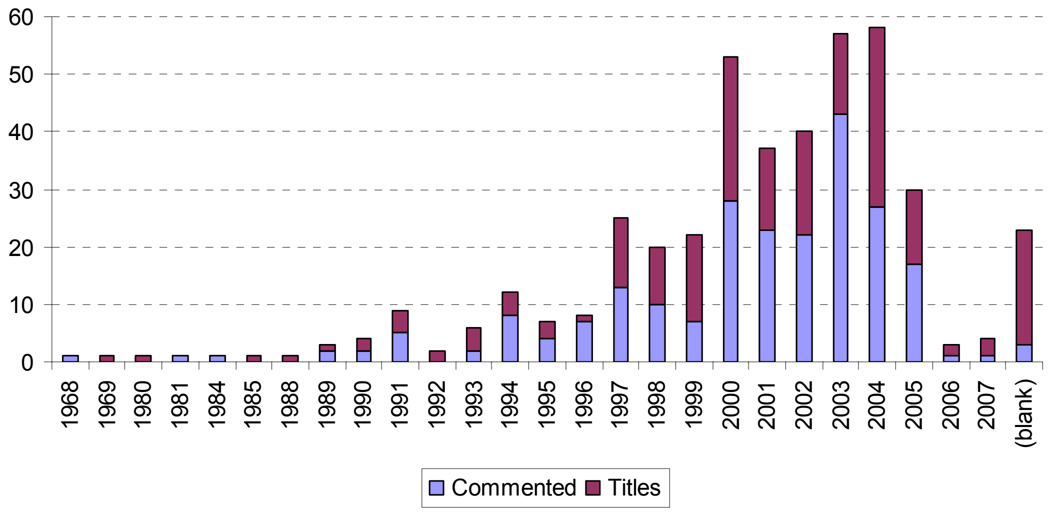

Figure 84: Library titles and year of publication

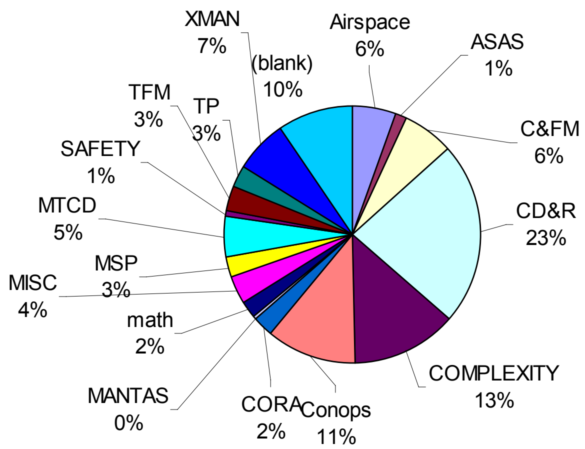

Figure 85: Library categories

12. ACKNOWLEDGMENTS

A long study like this is never done alone and I enjoyed the help and support from many colleges and friends that have accompanied this thesis and without whom it would not have been possible.

My sincere thanks go the management of the EUROCONTROL Experimental Centre and here especially to directors J.-M. Garot and P. Andribet who have permitted this study. Same is true for higher management in EUROCONTROL Maastricht UAC where half of the study was conducted, thanks to P. Naets.

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And last not least I would like to thank my wonderful wife Jacky for her strong support over the years.

13. BIOGRAPHY

Rüdiger Ehrmanntraut is expert in the capacity management team at the Maastricht Upper Area Control centre in the Netherlands and responsible for capacity improvement processes since 2005. He is managing a project for strategic and pre-tact planning processes and tools, and participates to their development. From 1996 to 2005 he has worked at the EUROCONTROL Experimental Centre in ATM research. From 2003 to 2005 he has started this thesis full time. Before, he has been co-ordinator of the TALIS consortium, a European Commission project for very advanced integration of the air and the ground that finished in spring 2004 and was one of the first projects working on system wide information management. From 1999 until 2003 he has been CNS Business Area Manager supervising many projects on air-ground data link related to ADS-B and CPDLC. From 1996 until 1999 he has conducted several projects on air-ground data link and their integration like the lead of the integration team of the PETAL project, and first real time simulations for CPDLC. Before joining EUROCONTROL he worked as a software engineer for an industrial company. He holds a diploma of telecommunications engineer from RWTH Aachen, Germany in 1991.