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SUPEROPT: Problem Definition and Literature Review

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Abstract

This report summarises the output of WP1: Detailed Problem Definition of the SESAR SUPEROPT project. A pair of challenge scenarios is defined and the proposed optimizers described. The set of scenarios are expanded to define the concepts to be studied in future work; these are described in terms of the proposed interactions between the supervisor and the optimisation.

A 3-D performance model is incorporated into a MILP collision avoidance algorithm based on the EUROCONTROL Base of Aircraft Data (BADA). Initial results for constraining the sense of conflict resolution are presented using four separate formulations: one for 2-D and three for 3-D conflict avoidance.

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This deliverable consists of SJU foreground.

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1 Introduction

1.1 Purpose of the document

This report summarises the output of WP1: Detailed Problem Definition of the SESAR SUPEROPT project. The goal of SUPEROPT is to investigate the interaction between an optimization and a human supervisor in performing Air Traffic Management (ATM); several methods were initially proposed. This document presents a more detailed problem definition and proposed solutions.

In summary, the document:

- reviews the current state of the art for route optimization methods;
- develops the two Challenge Scenarios to be addressed in the remainder of the project;
- outlines candidate solutions to the Challenge Scenarios;
- presents the simulation environment to be used throughout the remainder of the project.
- presents a 3-D aircraft performance model for collision avoidance;
- presents results for an initial Challenge Scenario

The remainder of this document is organised as follows: Section 2 introduces the Challenge Scenarios, the parameters that define each scenario, the associated ATM role and the possible interactions; Section 5 presents the simulation environment, performance model and initial results; Section 6 draws conclusions and makes recommendations.

1.2 Inputs from other projects

The Challenge Scenarios are developed around roles developed in the PHARE [12] and ADAHR [2] EUROCONTROL projects.

The Performance Model developed in Section 5.2 uses the BADA [16] database to define the performance of different aircraft.

Where possible the models from the SESAR WP-E ONBOARD project will be used due to the similarities between some of the challenge scenarios and the ONBOARD problem definition.

1.3 Intended readership

- ATM researchers will benefit from the initial results, especially the development of a dynamics model based on BADA for use in an optimizer
- Managers and followers of the SUPEROPT project can use this document to understand the scope of the work foreseen
- The examples of each Challenge Scenario, presented in Sections 3.4 and 4.4, are intended to be shared with experts in control and flow management in order to get feedback on the most useful interaction ideas.

1.4 Acronyms and Terminology

Term	Definition
ADO	Airport Duty Officer
AM	Airspace Manager
AMC	Airspace Management Cell
AOA	Aircraft Operator Agent

Term	Definition
AOC	Airline Operations Centre
AOP	Airspace Operations Plan
APOC	AirPort Operations Centre
ATFM	Air Traffic Flow Management
ATM:	Air Traffic Management
CDM	Collaborative Decision Making
DOC	Direct Operating Cost
EC	Executive Controller
E-ATMS	European Air Traffic Management System
FAB	Functional Airspace Block
GHA	Ground Handling Agent
LTM	Local Traffic Manager
MILP	Mixed Integer Linear Programming
MPC	Model Predictive Control
MSA	Multi-Sector Area
MSC	Multi-Sector Controller
MSP	Multi-Sector Planner
NM	Network Manager
PWA	PieceWise Affine
PC	Planner Controller
RBT	Reference Business Trajectory
ROCD	Rate Of Climb/Descent
SBT	Shared Business Trajectory
SESAR	Single European Sky ATM Research Programme
SJU	SESAR Joint Undertaking (Agency of the European Commission)
SJU Work Programme	The programme which addresses all activities of the SESAR Joint Undertaking Agency.
TMA	Terminal Manoeuvring Area

2 Challenge Scenarios

In order to pose meaningful optimization interactions, a set of challenge scenarios has been created. The scenarios have been chosen such that they are representative of the anticipated airspace structure and provide sufficient richness to investigate a wide range of different optimization interactions.

2.1 Assumptions

The SUPEROPT project was established to investigate technologies for a post SES environment. We have assumed that the time period is in the region of 2035-2050 and that the airspace is managed through free-routing, i.e. not free-flight. Furthermore, it has been assumed that the airspace is composed of Functional Airspace Blocks (FABs) which comprise multiple Airspace Management Cells (AMCs) which in turn can be subdivided into individual sectors as shown in Figure 1. The literature also refers to a Multi-Sector Area (MSA) which is *assumed* to sit between a sector and an AMC.

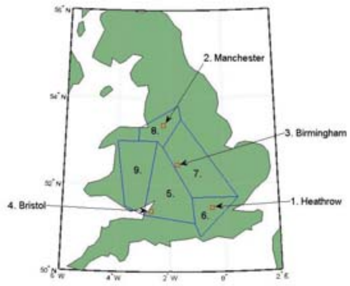
		
a) European FABs [21]	b) UK-Ireland FAB & AMCs [21]	c)Example sectors within an AMC

Figure 1: Assumed airspace structure

The SESAR ATM Target Concept [22] defines 4-D or Business Trajectories evolving over time, specifically the ideas of a Shared Business Trajectory (SBT) and Reference Business Trajectory (RBT) are defined with the SBT being defined several months in advance of a flight and the RBT being finalised shortly before take-off. Furthermore [22] makes provision for modifications to the RBT during flight either through an RBT automatic update should an aircrafts Predicted Trajectory (PT) start to diverge from the agreed RBT; or through an RBT revision due to changed constraints triggered either by ATC or flight crew. For the purpose of SUPEROPT, it is assumed that the ATM environment supports RBTs and the ability to update them during their execution. Aircraft are assumed to have 4-D capability, in that updated 4-D trajectories can be sent to them via datalink and executed by them.

2.2 Overview of Concepts

The different geographic scales covered by FABs, AMCs and sectors suggest possible problems to be considered by SUPEROPT, in order to do this though, the obvious question is: what happens at each level, i.e. what are we seeking to minimise/maximise? One way to answer this question is to consider the actors that are present at each level and look at what their role is. Using the definitions from the ADAHR project the following mappings are *assumed*:

Scale	Actor	Primary function(s)
FAB	Network Manager (NM)	Negotiating agreed RBTs based on SBTs Capacity and sequencing constraints
AMC	Airspace Manager (AM)	Maximise utilisation of available airspace Capacity and sequencing constraints
MSA	Multi-Sector Planner (MSP)	Co-ordination of entry/exit conditions Aircraft separation Sector workload (capacity)
Sector	Planner Controller (PC) Executive Controller (EC)	Co-ordination of entry/exit conditions Aircraft separation

Table 1: Mapping of spatial areas and associated actors

From Table 1, the roles of the future ATM system that have been covered can broadly be classed into:

- low level roles concerned with: aircraft trajectories within one or more sectors; collision avoidance; capacity constraints
- high-level roles: concerned with AMCs and FABs; aircraft flows (sequencing); capacity constraints.

Consequently, we propose to define two challenge scenarios:

- Multi-Sector *Controller*: where the output is defined in terms of 4-D aircraft *trajectories* including collision avoidance and capacity constraints.
- Network Manager: where the output is defined in terms of aircraft flows.

Each scenario has been defined in terms of the proposed: optimizer, scale, planning horizon, timestep, manipulation, and informing capability; these terms are defined in more detail below. Sections **Error! Reference source not found.** to 4 then give details of each scenario with reference to these decisions.

2.2.1 Scenario Fidelity

2.2.1.1 Scale

The scale of each scenario is defined in terms of the number of sectors and the number of aircraft to be considered. Furthermore, the level of detail of the model is addressed at a high level in terms of flow or flight-by-flight modelling.

2.2.1.2 Planning Horizon

The planning horizon is simply the length of the plan produced by the optimization. The start point of the plan also needs to be defined, are we planning for the next 24 hours or tomorrow, i.e. the 24 hours starting at midnight?

2.2.1.3 Timestep

The timestep of the model is intuitive the length of each planning step. Consideration needs to be given to the dynamics of the system under study, for example the timestep for a trajectory planner will need to be shorter than that for a flow model.

2.2.2 Optimizer

SUPEROPT aims to investigate the suitability of a broad range of optimizations for supervisor interaction. In order to ensure as wide a range of technologies as possible is assessed the current literature was reviewed and classified into broad groups as illustrated in Figure 2.

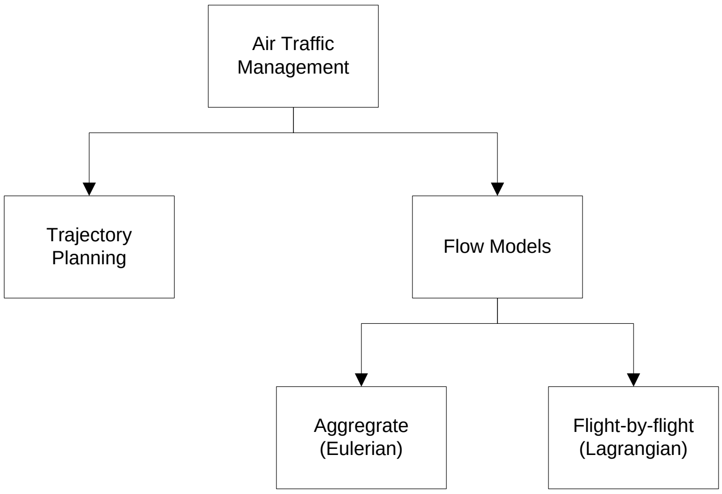


Figure 2: Summary of ATM models

Table 2 shows how these different categories of model are employed by the different roles within the SUPEROPT study and the optimizers that will be employed. This is not in itself intended to be a restrictive specification for the deployment of optimizers and models. Instead, its aim is to verify that SUPEROPT spans the space of optimizers, models and roles.

	Trajectory Planning	*Aggregate Flow*	*Flight-by-Flight Flow*
***M**ulti-**S**ector **C**ontroller*	*Non-linear programming e.g. sequential quadratic*		
***N**etwork **M**anager*			*Stochastic MILP*

Table 2: Summary of optimizers to be applied to different scenarios and classes of ATM model

2.2.3 Supervisor Interactions

The SUPEROPT proposal [1] identified a number of different ideas for routes in and out of the optimizer, grouped into (i) ways for the supervisor to manipulate the optimizer behaviour; and (ii) ways for the supervisor to gain information from, or be informed by, the optimizer. The options to be considered are outlined here, and will be discussed further in the relevant sections on the roles, from **Error! Reference source not found.** onwards.

2.2.3.1 Manipulation

The supervision of the optimizer is broken down into two categories: manipulating and informing. Manipulation is defined as methods by which the supervisor may alter the outcome of the optimization. The approaches to be outlined in [1] were:

- Group Constraint Selection or “Plays”
- Constraint Prioritisation
- Reference Trajectories/Corridors
- Cooperative Optimization

2.2.3.2 Informing

Informing the supervisor describes different forms of post-processing analyses that could provide meaningful justification for the optimization outcome/plan. The approaches to be outlined in [1] were:

- Identifying the Active Constraints
- Sensitivity Analysis
- Ranked Solutions

In addition, the following concepts are also proposed:

- Sector load/time plots (problem specific)
- Trade-space of options (for multi-objective optimisation)

2.2.4 Summary of Concepts

Given the roles to consider, outline concepts for human supervisor interaction with an automated optimization have been created, these are summarised in Table 3 and described in more detail in the remainder of this section with reference to the state of the art literature.

Role	Multi-Sector Controller	Network Manager
Optimizer(s)	Non-linear branch and bound	MILP Stochastic (MOGA?)
Scale	MSA (with scalable number of sectors) Individual Aircraft Trajectories (with multiple, moving obstacle avoidance)	FAB Flight-by-Flight Flow
Planning Horizon	2 hours	1 day
Timestep	30 seconds - 15 minutes (scalable)	15 minutes
Manipulation	Group Constraint Selection Cooperative Optimization Reference trajectories	Group Constraint Selection Constraint Prioritization
Informing	Sector load/time profile (active constraints) Trade-space of solutions(multi-objective)	Ranked Solutions (multi-objective)
Constraints	Collision Avoidance Sector Capacities	Sequencing Sector Capacities

Table 3: Summary of supervised optimization concepts

Each concept is now described in more detail with a brief discussion of the air traffic role associated with each concept. Once the role has been established there are subsections to:

- discuss of how the tool could assist the supervisor
- describe how the supervisor might manipulate the optimization
- describe methods by which the optimization could inform the supervisor.

3 Multi-Sector Controller

For the purpose of SUPEROPT, we define an air-traffic role of Multi-Sector Controller (MSC) based on the common requirements of collision avoidance and capacity constraints but with an undefined or variable problem scale. We are interested in designing a tool to support such a role and we aim to show that a tool/model can be devised with sufficient flexibility to be relevant to multiple problems (on different scales).

The Executive Controller (EC) instructs flight crews by means of vectors (heading, speed or altitude) or a required time over a certain point in order to solve conflicts in an efficient way [2].

Each SC is supported by a Planner Controller (PC); their principal responsibility is to indicate potential future conflicts [2], with a horizon of up to around 10 minutes and coordinate with other sectors. If an aircraft will enter a sector with a different speed or altitude than the standard this should be coordinated between the planner controllers of the different sectors. The planner therefore calls planners in other sectors and receives calls from other sectors.

Air Traffic Flow Management (ATFM) provides a strategic planning service several hours before the aircraft enters the air traffic control sector, compared with the PCs/ECs who are operating only a few minutes ahead of the aircraft conflicts. The role of a Multi-Sector Planner (MSP) is to offer medium-level strategy rather than tactical solutions to overcome traffic complexity. Aircraft trajectories are planned over several sectors [2]. The aim of the MSP is to reduce the workload of sector controllers and provide more optimal trajectories for suitably equipped aircraft (within the scope of SUPEROPT we assume all aircraft have such equipment).

A Multi Sector Planner is responsible for the medium-term planning of the trajectories of the aircraft that enter the region of airspace, called a Multi-Sector Area (MSA), with which they are associated. Currently. As the name suggests, a MSA comprises a number of “traditional” sectors. A different team of controllers is responsible for providing the ATC service in each sector. The purpose of the Multi Sector Planner is to ensure that the controllers of the individual sectors are never subjected to a workload that is so high that safety is jeopardized [12].

3.1 Tool Concept

The MSC is concerned with the detailed trajectories of each aircraft within 4-D, maintaining a safe separation between all aircraft at all times and observing individual sector capacity constraints.

Given that the model must capture the aircraft dynamics, it is likely to be necessary to constrain the planning horizon to a maximum of 2 hours (although it should be noted that this is based on current computing capabilities and that by 2050 this restriction is unlikely to apply). Depending on the criticality of the dynamics to the solution will influence the required timestep, for example: when considering a potential collision it will be necessary to generate a much more detailed trajectory than for a sector occupied by a single aircraft.

To further simplify the problem that must be solved, rather than consider the global optimization of all aircraft, it is proposed to optimize each aircraft trajectory separately (considering other aircraft as moving obstacles). This is likely to produce a non-globally optimal solution but will ensure that all the constraints are met and drastically improve solution times. Once a complete solution has been found the tool should allow interaction with the operator to enable them to tune the solution in accordance with their expert knowledge. As part of the interaction process, further co-operative optimization could be applied to groups of trajectories that interact in order to improve the global solution.

Initial work (Appendix A and Section 5) has focussed on applying MILP optimization to 4-D trajectories across a single sector. However, the additional constraints that are foreseen within the MSC scenario suggest that it will be necessary to move to a different optimization method, since the linearity requirement within MILP may become limiting. The selection of optimizer will be part of the investigation.

3.2 Manipulation

Each aircraft entering the MSA will be initialized with the latest instantiation of its RBT. Subsequently, the supervisor may wish to alter specific trajectories based on their “expert knowledge”, for instance they may know that flight A is a better climber than B so if they collide would rather that A passed over B, or that there is a storm forecast to affect sector X between 15:00 and 16:00.

3.2.1 Constraint Application

Miller et al [9] introduced the idea of a playbook where sets of constraints are grouped together as "plays", i.e. grouped constraint selection. Many existing ATM practices obviously lend themselves to the idea of a play, for example, resolving the sense of a conflict in 2-D using MILP has been study in some preliminary work [4] and this will be generalised to 3-D where the sense of a conflict can be resolved either horizontally or vertically; constraint formulations that are flexible enough to allow the supervisor to manipulate the result to achieve any sense are demonstrated in Section 5. In the context of trajectory optimization, a "play" is related to the application of a particular constraint.

If the constraint were able to generalise to 4-D, i.e. consider time simply as an extra dimension, then this would provide an elegant solution for constraining 4-D trajectories including specifying that aircraft A should reach a point (of conflict) ahead of aircraft B and vice versa.

Focussing primarily on the proposed framework for optimal 4D trajectories, some concepts that will be explored are the ability for the MSC to:

- Restrict the horizontal sense of a conflict resolution, i.e. clockwise or anti-clockwise;
- Restrict the vertical sense of a conflict resolution, i.e. above or below;
- Resolve a conflict in time, i.e. ahead or behind;
- Prioritise or penalise specific sectors, i.e. go-via or avoid sector X;
- Prioritise or penalise specific sectors during a time window, e.g. avoid sector X between 15:00 and 16:00.

3.2.2 Manual Trajectory Manipulation

If the idea of grouped constraint selection did not provide enough flexibility then the supervisor may wish to manually re-route specific aircraft. As each aircraft is optimized individually, making a change to a single aircraft in this fashion raises an interesting question regarding how to ensure that it does not lead to constraint violations. Can the manual intervention be coupled with a rapid re-optimization, or partial re-optimization? If so, which decisions should be frozen and which re-optimized?

3.2.3 Cooperative Optimization

In multi-agent systems, it is known that optimizing for just one agent at a time can lead to greediness and subsequent poor performance. An potentially useful tool for the supervisor would be a cooperative re-optimization, permitting changes to more than one aircraft in order to improve global performance. However, this must be balanced with the greater complexity in a multi-aircraft problem and the challenges of managing the interaction. The supervisor must be able to interpret and evaluate the result, which would be difficult if there were many changes. Therefore, a smart cooperation optimizer that chose only the most important aircraft to re-route could be desirable. Devising the formulation and solver for such a problem is non-trivial and will be part of the research.

3.3 Informing the Supervisor

To facilitate constructive manipulation of the optimizer, it is necessary to provide the supervisor with useful information regarding the reasoning behind the current solution and indeed the affect that any changes may have.

The MSC role requires excellent situational awareness of both the current and future state of the MSA. Whilst it is possible to formulate an optimization to solve the ATM problem subject to capacity constraints, we wish to extract added value from such algorithms such that the supervisor can foresee bottlenecks arising and take appropriate action to resolve them.

If we consider the capacity of each sector as an individual constraint, then identifying the active constraints, or performing a sensitivity analysis, would provide the supervisor with a very clear indication of which sectors were becoming critical. This information could be presented as sector load/time plots for any sectors that are identified as coming within a stated percentage of their stated capacity and would enable the supervisor to react early to the build up of congestion.

The obvious extension to active constraints is a sensitivity analysis to shown how much the solution will be affected by changing each constraint. Global sensitivity [11] provides the bounds on constraint modifications before the constraint becomes active and influences the solution.

Identifying active collision avoidance constraints and presenting them intuitively would alert the supervisor to any potential future conflicts, i.e. where to aircraft will be in close proximity to each other and any deviation from the RBT would require immediate attention.

3.4 Multi-Sector Controller Example

Table 4 presents an example of a sequence of MSC optimizer and supervisor interactions.

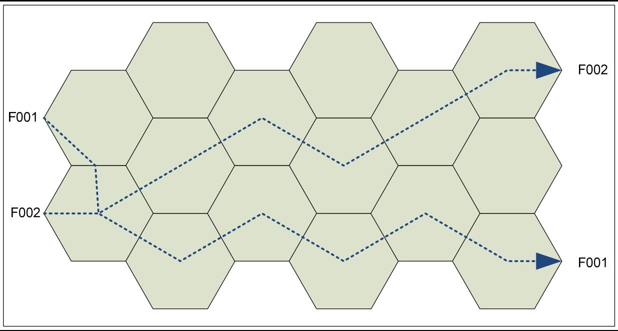
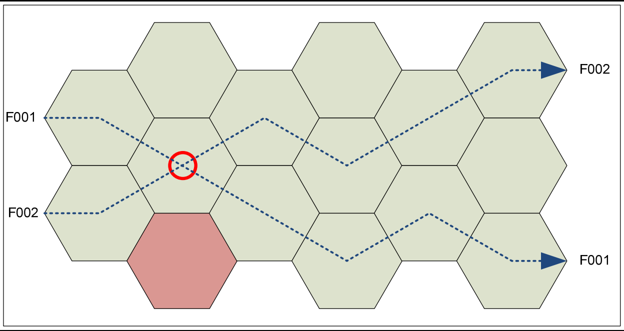
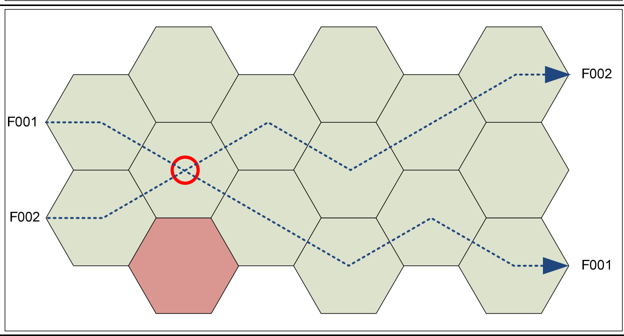
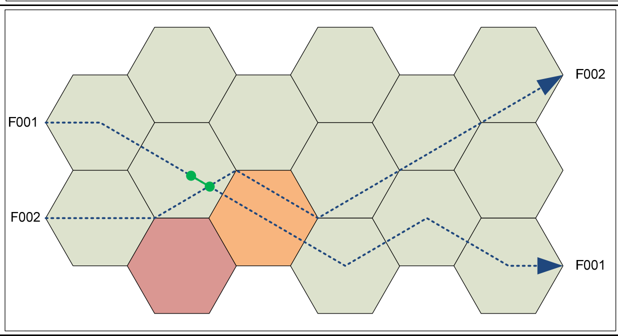
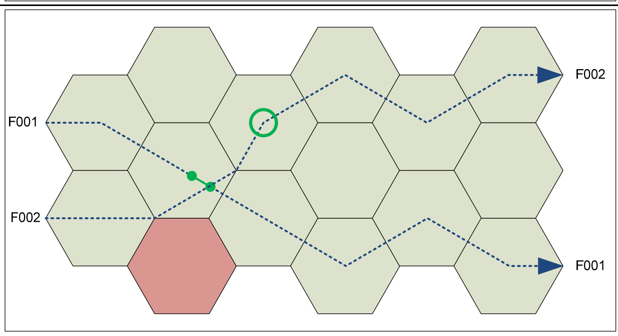
	***Stage 1*** •RBTs are added and optimized to ensure collision avoidance and to satisfy sector capacity constraints. •Avoidance is achieved at the sector level.
	***Stage 2*** •Supervisor indicates that a sector should be avoided. •Trajectories of affected aircraft (identified through active constraints) are recalculated. •Ensuing collision can be resolved in any sense (including time)
	***Stage 3*** •Supervisor indicates a preference for the sense of conflict resolution, e.g. vertically (by altitude)
	***Stage 4*** •Identification of active constraints followed by cooperative replanning leads to the tool suggesting an lower cost route •Horizontal separation achieved •Tool indicates high traffic levels in orange sector possibly augmented with sector load/time plot(s)
	***Stage 5*** •Supervisor chooses to reduce sector loading by manually re-routing F002 to go-via adjacent sector •Trajectory re-optimized taking into account user defined waypoint •Cost history of the changes at each stage presented to supervisor who is satisfied with the latest solution

Table 4: Illustration of possible MSC tool interactions

4 Network Manager

For the purpose of SUPEROPT, the Network Manager (NM) is assumed to be concerned with air traffic flow and capacity management; they will be the highest level decision maker in terms of the network [2]. The primary goal of the NM is to ensure the efficiency of the entire network, obviously this requires monitoring and managing a large amount of information so will benefit from tools with increased autonomy providing that they are able to quickly understand how the solution has been derived and to make any changes that they deem necessary.

For the purpose of SUPEROPT we assume that the NM oversees the process through which Shared Business Trajectories (SBTs) from different Airline Operations Centre (AOCs) are combined to produce the Reference Business Trajectories (RBTs). Furthermore, it is assumed that the NM will be expected to arbitrate the negotiation of deviations from the SBTs. Any deviation from an SBT will be unpopular with the associated airline and should therefore be minimised and will benefit from strong justification.

The role of the NM in this SUPEROPT scenario is based on the role with the same title within the ONBOARD project [17]. This enables us to draw on the models and optimizers that are being developed at Bristol within the ONBOARD project. SUPEROPT's definition of the role is also consistent with the definition of NM according to the ADAHR project. These definitions seem to be more limited than the NM function identified by EUROCONTROL.

4.1 Tool Concept

As the NM operates at a higher level than the MSC it is self-evident that they are concerned with a larger scale problem, in particular, ensuring the flow of aircraft within one or more FABs maximises the use of the airspace while satisfying the sector capacity restrictions.

Where the MSC tool simplified the global problem by solving for each aircraft individually, the NM model will generate a globally optimal solution by solving for all aircraft simultaneously. However, to make the problem tractable it will be simplified by considering only aircraft flow, i.e. the output is in the form of sectors and sector boundary transition times rather than exact spatial coordinates.

There have been several previous formulations that are capable of generating a complete set of RBTs, e.g. [3], which provide a good basis for investigating supervisor interaction. The NM role involves negotiating between multiple airlines who express their desires through the SBTs. The NM must then ensure that final RBTs meet the requirements such as capacity constraints.

In addition to the previous formulations such as [3] it would be interesting to investigate "stochastic optimizers" such as simulated annealing [5], Genetic Algorithms [15] and Rapidly-exploring Random Trees [7]. These techniques all exhibit some degree of randomness in their search of the solution space; whilst any solution generated will meet the requirements (such as capacity constraints) it is not guaranteed to be globally optimal. The principal benefit to such methods is that they potentially offer much faster solution times.

Assuming the NM has "expert knowledge" regarding the airspace, it is reasonable to assume that they would be aware of approaching/developing weather systems as well as have prior warning of events that are likely to produce a lot of unscheduled demand, e.g. major international sports events. Whilst it is difficult to include such knowledge within an optimization, by providing a suitable mechanism for supervisor interaction it is possible to utilise the NMs expert knowledge.

4.2 Manipulation

The amount of detail in a SBT may vary between aircraft, varying from an estimated time of departure and arrival to a complete 4-D trajectory. The project will investigate techniques to ensure that the optimization has sufficient flexibility to accept such a wide range of inputs and investigate the effect on the result/solution time such that recommendations about the most convenient structure for SBTs can be made. The key feature is how to incorporate one trajectory (SBT) in an optimizer to design its successor (RBT), instead of simply replacing it. The concepts of weights for deviations or corridors (in 4-D) are an example of potential formulations that will be investigated.

4.2.1 Constraint Prioritization

Given a solution to the ATM problem, the NM may wish to prioritise some flights or sectors over others, e.g. it may be desirable that flight A is on time rather than flights B *and* C if flight A connects with subsequent flights. Constraint prioritisation has previously been implemented using soft constraints [18] and disjunction constraints [19] as implemented in MILP [20]. New work will introduce the possibility to enforce a prioritized set of constraints with the additional functionality of retaining lower priority constraints in the solution when a higher priority one proves infeasible; this is not possible with previously enforced logical structures. This will apply to both MILP and nonlinear optimizers, although both cases will require some basic research into the right formulation.

4.2.2 Multiple Objectives

An interesting question is: can the NM manipulate the traffic flow such that the flow through individual sectors is simplified? It has been observed that a PCs/ECs workload is dependent not only on the number of aircraft in a sector but also the pattern of the traffic flow through the sector [13], e.g. it is easy to supervise an en-route sector than a Terminal Manoeuvring Area (TMA), so simplifying a sectors flow pattern could effectively increase sector capacity [23]. Metrics on sector flow complexity [23] provide candidate objectives for the NM optimization.

Another consideration is balance of workload across sectors. For example, if an intervention is performed to reduce the workload on a particular sector, can constraints prevent just transferring problems to adjoining sectors? “Chasing” the solution is a common undesirable side-effect of working with optimizers. An interesting possibility to be explored is cooperative optimization [14], in which the optimizer attempts to include the goals of others as well as the immediate activity.

The overall theme in this part of the investigation is the handling and balancing of multiple objectives. Other examples include balancing average performance against worst case performance, or equity across agents. Multiple objectives can always be weighted and summed to form a single cost, but the dependence on these weights is very difficult to predict, leading to challenging interactions. Purpose-design multi-objective optimizers will be considered.

4.3 Informing the Supervisor

As discussed previously, in order to ensure agreement from the airlines, it is important that all interested parties have a clear understanding of how the proposed solution was reached. Whilst trying to justify the solution to an entire ATM problem is likely to be too detailed, it would be interesting to explore the idea of justifying a single trajectory from such a solution, most notably: any deviation from the reference trajectory.

Based on the information output by the optimization and given their knowledge of how the system/airspace is likely to develop w.r.t. weather and unscheduled demand, the MSP may wish to reject the proposed solution. Should such a situation occur then it is obviously necessary for another solution to be derived; rather than re-formulating and re-running the optimization it is possible to extract alternative (sub-optimal) solutions from the existing path through the search space, for example, in the case of a branch-and-bound method such as [10] then these would be the branches with valid solutions but higher costs (additional solutions may be found by completely branching on any previously fathomed solutions); in the case of a stochastic methods different significantly different solutions could be found through clustering algorithms.

Furthermore, there may be additional drivers for the airlines’ preferences about which the NM has no knowledge. In such instances it may be desirable to provide the airlines with a set of alternatives. This raises an interesting question about identifying alternative solutions for a single trajectory without altering other trajectories. The nominal optimizer for this case is MILP, which is normally tuned to generate as few solutions as possible: can it be altered to produce the best *N* without significantly hindering its solution time?

Ranking the alternative solutions (based on the cost function) would enable the supervisor to choose between alternatives based on their expert knowledge of how the system is likely to evolve while maintaining a feasible solution with some concept of optimality. This idea can be extended to the idea of a multi-objective optimisation where several problems are solved in parallel according to different weightings in the cost function, e.g. varying the balance between Direct Operating Costs (DOCs) and time.

4.4 Network Manager Example

Table 5 presents an example of a sequence of NM optimizer and supervisor interactions.

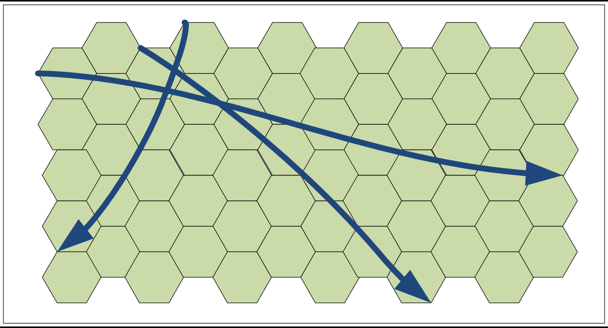
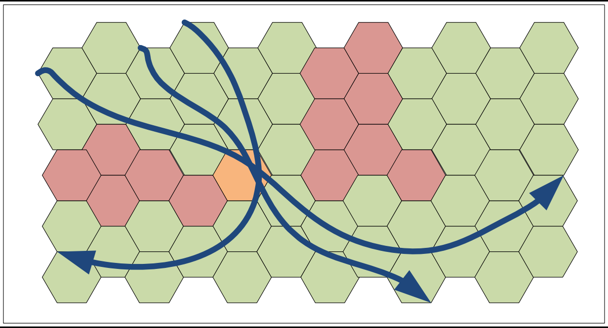
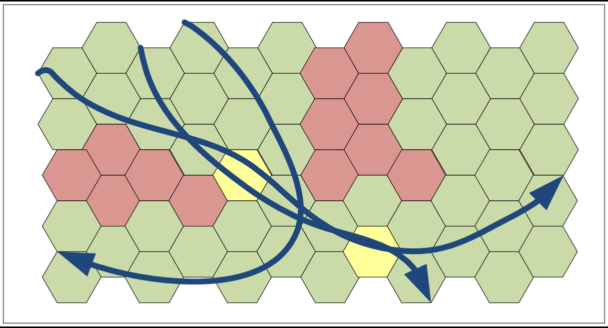
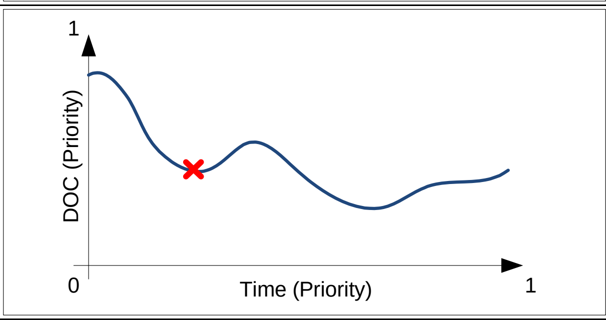
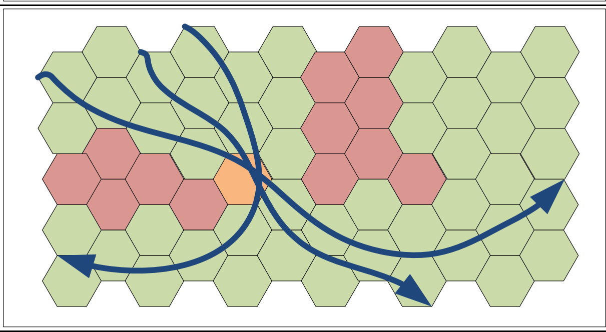
	***Stage 1*** •SBTs are added
	***Stage 2*** •Supervisor adds updated airspace knowledge, e.g. severe weather events •Trajectories of all aircraft optimised for globally optimal solution •Sector capcity limits observed (trajectories not in sufficient detail to consider collision avoidance).
	***Stage 3*** •Supervisor prioritises minimising sector loading over trajectory length. •Trajectories re-optimized to reduce sector loading (both in terms of number of aircraft and traffic complexity)
	***Stage 4*** •Alternative solutions presented to supervisor showing affect on Cost Indices (multi-objective)
	***Stage 5*** •Supervisor reverts to lower cost solution (accepting higher sector loading)

Table 5: Illustration of possible NM tool interactions

5 Initial Sector Controller Results

5.1 Simulation Environment

A flexible development environment has been created using Matlab's GUIDE® tool to investigate the supervision of 4-D trajectory optimizers (Figure 3). Separation of the model from the interface enables rapid prototyping of different algorithms.

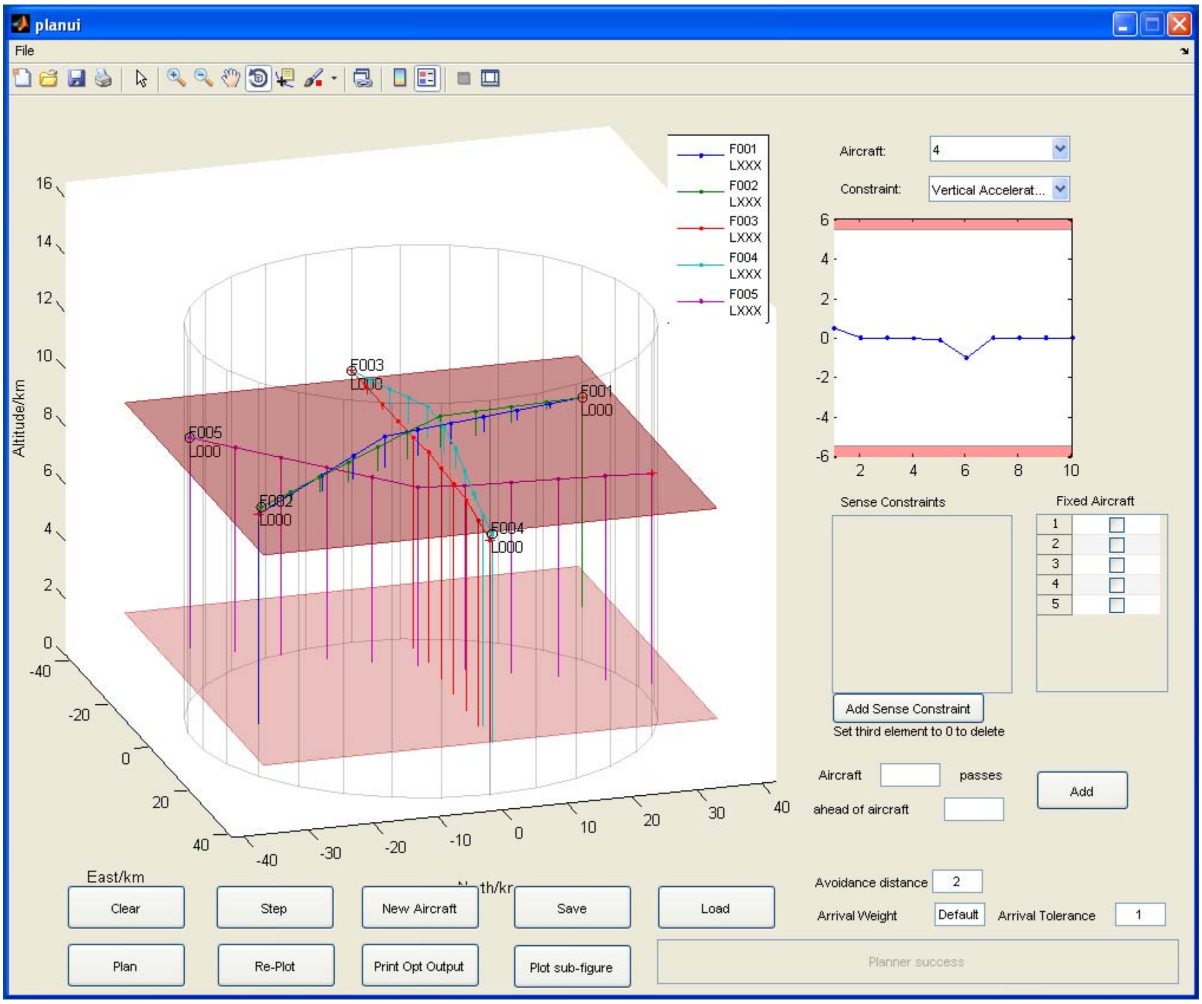


Figure 3: Simulation Interface

5.2 Performance Model

In order to extend the idea of 2-D sense constraints [4] to 3-D while maintaining realistic aircraft dynamics, it is necessary to introduce a performance model to the trajectory generator/optimization.

The EUROCONTROL Base of Aircraft Data (BADA) provides both an analytical model and a database of aircraft performance for typical commercial aircraft. The BADA User Manual [16] states that the longitudinal and normal acceleration for civil airliners is limited to 2 and 5 fps^2 respectively.

To date, the SUPEROPT project has adopted Mixed Integer Linear Programming (MILP) to solve for a globally optimal set of trajectories while enforcing additional logical constraints. Trajectory generation using this method require the use of a global frame of reference. Consequently, the longitudinal and normal accelerations have been approximated as horizontal and vertical respectively:

$\forall\, a \in \{1..N_a\}, k \in \{1..N_t - 1\}, i \in \{1..N_c\}$

$$\dot{v}_x(k,a)\cos\left(i\frac{2\pi}{N_c}\right) + \dot{v}_y(k,a)\sin\left(i\frac{2\pi}{N_c}\right) \leq acc_{horiz}$$ **Equation 1**

$$\dot{v}_z(k,a) \leq acc_{vert}$$ **Equation 2**

Where N_a is the total number of aircraft; N_t is the number of timesteps; N_c is the number of constraints used to approximate the acceleration magnitude; $\dot{v}_w$ is the acceleration in direction w ; acc_{horiz} and acc_{vert} are the horizontal and vertical acceleration limits respectively.

This approximation is reasonable given the relatively small angle of attack and nominal bank angles of civil airliners. The validity of such an assumption could be tested as part of future work using non-linear optimizers.

To model individual aircraft dynamics more precisely, the Rate Of Climb/Descent (ROCD) has been limited according to BADA. Taking the data for a typical aircraft (Airbus A319), operating at its nominal weight, it is clear that the permitted ROCD is dependent on flight regime and level (Figure 3 [BADA]) and that this data can be approximated by suitable Piecewise Affine functions (PWA) for climb and descent.

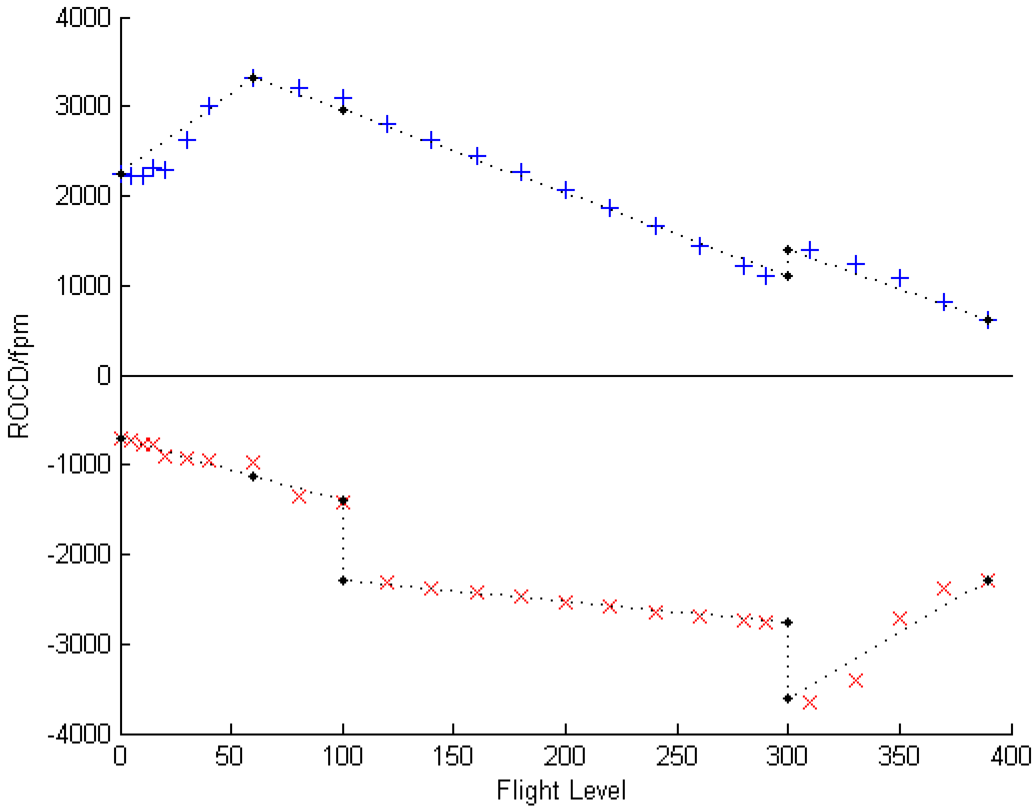


Figure 4: A319 Rate Of Climb/Descent approximated with a piecewise affine function

A PWA can easily be implemented using MILP as follows:

$\forall\, i \in \{1,\dots,N_a\}, k \in \{1,\dots,N_t - 1\}, m \in \{1,\dots,N_{P_{ROCD}}\}$

$$\sum_{m} b_{ROCD}(i,k,m) = 1$$ **Equation 3**

$$\sum_m \lambda_{ROCD}(i,k,m) \geq 0$$ *Equation 4*

$$\sum_m \lambda_{ROCD}(i,k,m) \leq \begin{cases} b_{ROCD}(i,k,m), & for\ m = 1 \\ b_{ROCD}(i,k,m-1) + b_{ROCD}(i,k,m), & for\ m \in [\{2,\dots,N\}]_{P_{ROCD}} \\ b_{ROCD}\left(i,k,N_{P_{ROCD}}(i)-1\right), & for\ m = N_{P_{ROCD}} \end{cases}$$

Equation 5

$$\sum_m \lambda_{ROCD}(i,k,m) B_{ROCD}(i,m) = r_z$$ *Equation 6*

$$v_z(i,k) \leq \sum_m \lambda_{ROCD}(i,k,m) A_{ROC}(i,m)$$ *Equation 7*

$$v_z(i,k) \geq \sum_m \lambda_{ROCD}(i,k,m) A_{ROD}(i,m)$$ *Equation 8*

where $B_{ROCD}(i)$ is a vector of flight levels at which 'the rate of climb or descent function changes' and $A_{ROC}(i,m)$ and $A_{ROD}(i,m)$ are the maximum rate of climb or descents respectively at the altitudes specified in B_{ROCD}.

A final modification to the 2-D formulation [4] was to establish independent horizontal and vertical separation distances; this reflects current ATM practice where typically horizontal separation is 1000ft compared to 5nmi (approximately 30400ft) horizontally. The avoidance constraints are formulated in MILP as follows:

$$\forall i \in \{1,\dots,N_a\}, j \in \{1,\dots,N_a\}, d \in \{1,\dots,2\}, k \in \{2,\dots,N_t\} : \ i > j$$

$$r_d(i,k) \leq r_d(j,k) - D_H + M\left(1 - b_a(i,j,k,d)\right)$$ *Equation 9*

$$r_d(i,k) \geq r_d(j,k) + D_H - M\left(1 - b_a(i,j,k,d + N_d)\right)$$ *Equation 10*

Where $r_d(i,k)$ is the position of aircraft i, at timestep k in direction $d \in \{x,y\}$ which is enumerated over $\{1,\dots,2\}$; D_H is the horizontal avoidance distance (5nmi); M is a large scalar; and $b_a(i,j,k,d)$ is a binary variable used to relax the avoidance constraint in all but one of the directions $+x, +y, +z, -x, -y, -z$. Equation 9 and Equation 10 constrain the distance between i and j to be greater than the horizontal avoidance distance in the positive and negative direction, respectively, for a given dimension d.

In the vertical direction:

$$\forall i \in \{1,\dots,N_a\}, j \in \{1,\dots,N_a\}, k \in \{2,\dots,N_t\} : \ i > j$$

$$r_z(i,k) \leq r_z(j,k) - D_V + M\left(1 - b_a(i,j,k,3)\right)$$ *Equation 11*

$$r_z(i,k) \geq r_z(j,k) + D_V - M\left(1 - b_a(i,j,k,6)\right)$$ *Equation 12*

Where D_V is the vertical avoidance distance (1000ft). Equation 11and Equation 12 constrain the vertical separation in the same manner as Equation 9 and Equation 10 do horizontally.

Finally:

$\forall i \in \{1, \dots, N_a\}, j \in \{1, \dots, N_a\}, k \in \{2, \dots, N_t\} : i > j$

$$\sum_{m=1}^{2 * N_d} b_a(i, j, k, m) = 1 - \sum_{l=1}^{k-1} \sum_{a \in \{i \cup j\}} b_f(a, l)$$

Equation 13

Where $b_f(a, l)$ is the avoidance binary for aircraft a at timestep l. Equation 13 ensures that at least one of the avoidance binaries previously constructed is enforced at each timestep between each pair of aircraft; the sum at the end of the equation is required to ensure that the optimization produces the expected result should an aircraft reach its destination before $k = N_t$.

5.3 Initial 3-D "Plays"

The development environment has been used to investigate possible formulations for different "plays" to resolve the sense of 3-D trajectory conflicts. Three different formulations for the same problem have been proposed; they are outlined here along with some results and are presented in detail in Appendix A. The three formulations proposed are:

1)**Hard Constraints**: considering the binary avoidance variables, it is apparent that if either of the binaries relating to the z-axis are asserted then the separation between the two associated aircraft is being established through the vertical plane (as a minimum). Perhaps the simplest tightening of the formulation of Section 5.2 to enforce this (short of saying that $r_z(k,i) \le r_z(k,j) \forall k \in \{1,\ldots,N_t\}$, i.e. i is below j at all times) would be to require:

$$\sum_{k=1}^{N_t} b_{a_{i,j}}(k, \{z^-, z^+\}) \ge 1 \qquad \text{Equation 14}$$

This forces the separation between two aircraft to be resolved vertically at at least one time step.

If we wish to define the sense of the vertical resolution we can tighten the constraint of Equation 14 further to require, for example, j to pass below i by removing z^+ from the set of dimensions included in the sum.

2)**Permitted Transitions**: generalising the previous work on sense constraints [4] to 3-D is non-trivial due to the number of sense transitions possible in a multi-dimensional space, e.g. $+x$ to any of $+x, +y, +z, \; y, \; z$. Consequently the idea of a rotation matrix R where each row is spatially related to those either side of it, is replaced by a binary transitions matrix T such that $T(p,q)$ defines the connectivity of ``quadrant'' p at time k, and sector q at time $k+1$, where a quadrant is defined as the region of space accessible through the relaxation of a single avoidance binary hence, in 3-D, there are 6 quadrants: $+x, +y, +z, -x, -y, -z$.

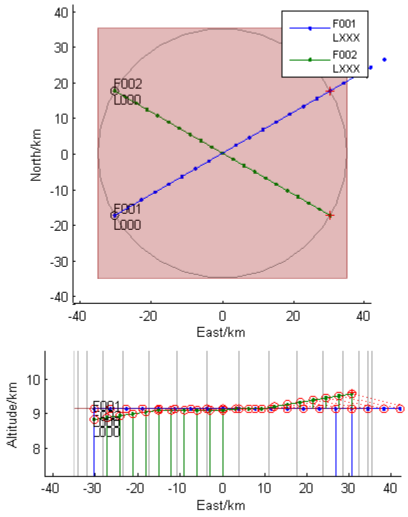
3)**Enforced Proximity**: An alternative approach to constraining the sense with which two aircraft pass each other is to force them to have a particular orientation at one or more timesteps, for example: if there is a conflict between aircrafts i and j, requiring that i is directly below j for at least one timestep then requiring them to be closer than the horizontal separation distance for one step leaves only the z-direction to resolve the conflict at that point, i.e. vertically.

Figure 5 shows the effect of the different methods on a typical scenario on a typical scenario of two aircraft crossing a sector on different vectors but passing through the centre simultaneously.

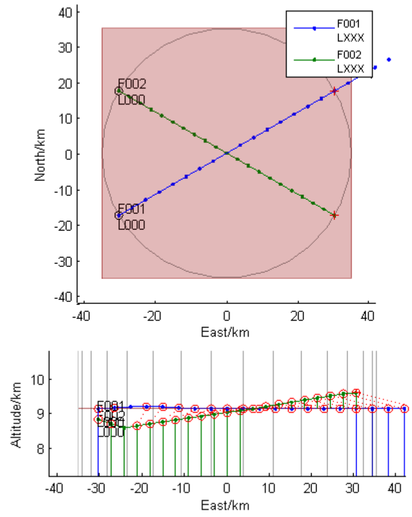
Figure 5a shows that without any additional constraints, the problem is resolved by increasing the velocity of one aircraft relative to the other so that they are separated in time. Introducing the additional hard constraint to enforce vertical separation Figure 5b shows that while the separation between the two aircraft is enforced vertically for at least one timestep (near the beginning of the trajectories) the conflict is still resolved by time, consequently alternative formulations are required.

Figure 5c and Figure 5d show that the permitted transitions and enforced proximity methods are successful in constraining the sense of the conflict resolution between F001 and F002 such that F002 should pass below F001.

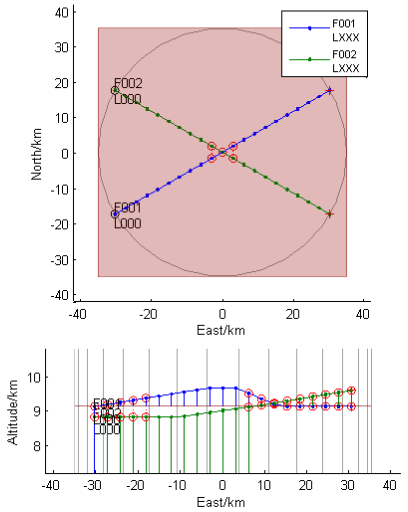
The differences between the permitted transitions and enforced proximity methods are primarily their flexibility and computational complexity which are the subject of current investigations.



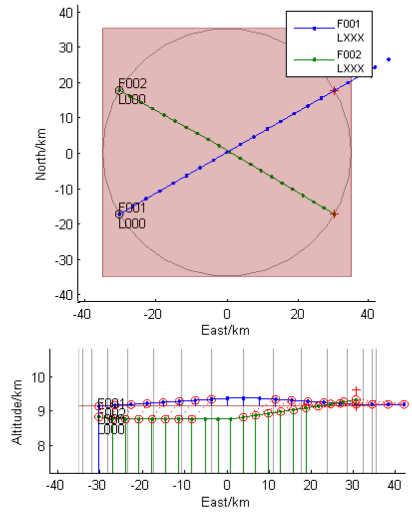
a)Unconstrained conflict resolution.



b)Conflict resolution using ***hard constraints*** requiring F002 to pass below F001.



c)Conflict resolution with no ***permitted transissions*** to $+z$ (of F002 relative to F001)



d)***Enforced proximity*** at one or more timesteps such that F002 is below F001

Figure 5: Effect of "hard constraints" on 3-D conflict

6 Conclusions and Recommendations

A pair of scenarios has been presented with proposed solution methods that cover a broad range of different optimizers and interactions with those optimizers. Particular areas of interest and original research have been identified. These ensure that a representative range of tools and roles will be explored by the SUPEROPT project.

A 3-D performance model for collision avoidance has been introduced and demonstrated. The idea of constraining the sense of collision avoidance has been extended to 3-D and shown to provide useful control over conflict resolution while demonstrating the potential of MILP to simply implement logical constraints on conflict resolution.

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Appendix A- Constraining the Sense of Conflict Resolution: Supervision of Route Optimization

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