

Effects of Vertical Situation Diagram in 4D Trajectory Management Interface

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Effects of Vertical Situation Diagram in 4D Trajectory Management Interface

MASTER OF SCIENCE THESIS

For obtaining the degree of Master of Science in Aerospace Engineering
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E.J.P. Riegman

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DELFT UNIVERSITY OF TECHNOLOGY
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Acronyms

ADS-B	Automatic Dependent Surveillance-Broadcast
ATCo	Air Traffic Controller
ATM	Air Traffic Management
BADA	Base of Aircraft Data
CWA	Cognitive Work Analysis
EID	Ecological Interface Design
FAA	Federal Aviation Administration
FL	Flight Level
IAS	Indicated Airspeed
ISA	International Standard Atmosphere
MTCd	Medium Term Conflict Detection
PVD	Plan-view Display
RBT	Reference Business Trajectory
SA	Situation Awareness
SESAR	Single European Sky ATM Research
STCA	Short Term Conflict Alerts
SWIM	System Wide Information Management
TAS	True Airspeed
TCT	Tactical Controller Tool
TSD	Time Space Diagram
TSR	Travel Space Representation
VSD	Vertical Situation Diagram
WDA	Work Domain Analysis

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Chapter 1

Introduction

Air Traffic Management (ATM) is currently performed with a relatively low level of automation. Air Traffic Controller (ATCo) have access to a top down radar view of the sector and can see the position, speed, orientation and altitude of the aircraft inside the sector. Using this information the air traffic controller has to extrapolate whether or not two or more aircraft will be in conflict in the future and, if so, devise a suitable solution to the conflict (Rantanen & Nunes, 2005).

With the growth of air travel making airspaces busier every year, this method of air traffic control will become harder and harder (STATFOR Team, 2017). Because of this, new methods of keeping flights conflict free are being developed. Many of these methods seek to introduce automation to aid in the air traffic control task, reducing the workload of the air traffic controller (FAA, 2014).

Using Ecological Interface Design (EID), automation can be used to support, rather than replace, human decision making. This rationale has been used to create an air traffic management interface. Using planned 4D trajectories (the 4 dimensions being latitude, longitude, altitude & time) conflicts between aircraft are predicted. Using the arrival time at the airspace border as a fixed constraint, the so-called "solution space" of deviation possibilities is presented to the air traffic controller, within which trajectories can be deformed without delaying the aircraft. This way the controller can use their own preferred method to solve the situation and the automation is there to support the decisions and improve situation awareness.

1-1 Problem Definition

Right now, the existing interface consist of a plan-view display showing a top down Plan-view Display (PVD) of the situation and a Time Space Diagram (TSD), showing the remaining path length over time for an aircraft. In the plan-view display, horizontal deviations can be made to paths; in the TSD, velocity can be adjusted to resolve conflicts. Both displays

show a solution space, mapping all the viable perturbations of the trajectory. This display, therefore, only provides 3D management possibilities (latitude, longitude, time).

What is not included in this interface, however, is a method of observing and controlling the vertical aspect (altitude) of the 4D trajectory. To allow for complete 4D control over the trajectories, this functionality needs to be integrated into the system.

Doing this will add another layer of information which is presented to the user of the interface. The existing Travel Space Representation (TSR) interface already has two viewscreens of some complexity, the addition of altitude will add another, also adding a layer of complexity to the entire interface.

For the interface to work as intended, the users must understand the information they are presented with respect to the reality in the air and they must understand the consequences of their interaction with the system. In short, a certain level of situation awareness is needed. If this awareness is not present, the user will not be able to make the informed decisions needed for robust air traffic control. When the interface becomes more complex, there is a distinct possibility of decreased situation awareness. With these potential issues in mind during the design process, steps can be taken that can minimize their impact (e.g., applying display design principles correctly (Wickens, Gordon, Liu, & Lee, 1998) and aiming to optimize visual momentum (Woods, 1984)).

When changing the interface, it is important to consider how the interface will be used and what the user wants to achieve. The way information is presented to the user can influence the users perception and understanding of the information (Rasmussen, 1983). This can, in turn, influence, the strategy applied by the user. When designing the interface, the possible control strategies need to be identified and what might cause users to gravitate towards certain strategies.

1-2 Research Goal

The goal of this project is to add on to this Travel Space Representation (TSR) interface to make true 4D trajectory management possible. To do this, a third display will be added which presents the altitude of a selected aircraft at any point in the track and presents a solution space to adjust the altitude. EID principles will be applied for this display, like with the existing parts of the interface. This means the addition will be consistent with the rest of the interface in a way that should allow the user to be aware of the system status and the range of solutions available.

Adding another display to an existing interface comes with a set of challenges. What is presented in one interface has to make sense with respect to what can be seen on another. Otherwise it could lead to confusion and decreased situation awareness. Another problem that may occur is that users will too easily disregard parts of the interface, gravitating to the easiest display to understand. This could cause users to apply suboptimal strategies. These problems should become smaller when the disconnect between information presented on different displays becomes smaller. Completely removing this issue is probably only possible with sufficiently trained users.

The research objective is to enable true en-route 4D trajectory management in a strategic manner by adding a Vertical Situation Diagram (VSD) to an existing TSR interface, which already includes a top-down plan-view display and a time-space diagram, thus adding the

fourth dimension of altitude. An experiment will be performed to analyse the level of situation awareness of the users of the interface.

A research question is posed to define the scope of the experiment. Sub-questions have been defined to better define the scope of the project and provide more specific answers. A main research question and sub-questions have been defined as follows:

"What is the effect of adding adding visualization of the altitude and support manipulation of the altitude using Travel Space Representation to an already existing interface, supporting latitude, longitude, and speed manipulation of the trajectory?"

- *"How can current air traffic control strategies be used in the design of a 4D perturbation management interface?"*
- *"What functionality is necessary and expected in a Vertical Situation Diagram and how can these be implemented?"*
- *"What are the expected control strategies that will be applied with a TSR interface with added Vertical Situation Diagram?"*
- *"How does the addition of the VSD affect the performance (e.g. safety, efficiency) and workload when using the interface?"*
- *"How can the negative effects of added complexity by including altitude in the interface be minimized?"*
- *"What control strategies are actually applied with a TSR interface with added Vertical Situation Diagram and how do they compare to the predicted strategies?"*

It is expected that the addition of the VSD will have a significant impact on the control strategies applied by users of the interface. The increased complexity of the interface could cause an increase in workload, however it is expected this is outweighed by the decrease in workload the extra degree of freedom in solving conflicts will provide. Drawing meaningful conclusions on the influence on safety, efficiency and workload will be unlikely as the experiment validating will be small scale, likely not giving enough statistically significant data on these metrics.

Interfaces which allow for real time manipulation of the trajectory have been designed before (e.g., HIPS (Meckiff & Gibbs, 1994)). What the TSR interface with VSD does, however, is visualize a solution space that is complete and intuitive. With the addition of a VSD the interface will allow for the real-time manipulation of all four dimensions of a trajectory.

The largest foreseen difficulty with implementing the VSD will be presenting the information in such a way that it will be coherent with the information seen on the other view-ports. To work best, the parts of the interface have to be seen as one whole, creating a complete picture of the situation. If parts of the interface will be ignored, or it isn't clear how the information from one part connects to another, performance will suffer, making the addition of that part detrimental rather than advantageous.

1-3 Report Structure

The thesis paper is presented in Part I of the report. All the appendices to the paper are presented in Part II. Appendix A contains the literature study, performed to find all relevant information on current ATM practices, future ATM developments, 4D air traffic management, display design principles, and the TSR interface specifically. The Cognitive Work Analysis (CWA) performed to analyze the requirements of a 4D TSR interface is presented in Appendix B and the initial interface concept before development is shown in Appendix C. Appendix D presents the final interface and the rationale behind the design. The validation experiment is detailed in Appendix E and Appendix F contains the briefing that was given to participants. The results are presented in Appendix G. Appendix H contains details of the interface code that was added or altered in the development of the VSD, mostly for reference for further development of the interface. Finally, conclusions are drawn and recommendations for future work are made in Appendix I.

Part I

Master of Science Thesis Paper

Effects of Vertical Situation Diagram in Real-Time 4D Trajectory Management Interface on Control Strategies

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Supervisors: Clark Borst, Marinus M. van Paassen, and Max Mulder

Abstract— With the current and expected growth of air traffic, the need for increased support for air traffic controllers from automation continues to grow. One method of improving air traffic management applies 4D trajectory management to control traffic in real-time. An interface applying this method only allowed for manipulation of trajectory in three dimensions, not supporting altitude. In order for the interface to allow for complete 4D manipulation of the trajectory, the altitude of the aircraft trajectories, as well as the vertical travel space, need to be visualized and manipulation of the altitude needs to be supported. Using the principles of ecological interface design, the existing interface was expanded by adding a Vertical Situation Diagram (VSD). This interface was validated in an experiment where the control strategies were observed as well as metrics on safety, efficiency and user workload. A comparison with an experiment without VSD hints at a decrease in workload for participants while solving conflicts at least as efficiently, if not more efficiently. The VSD is a vital part of the interface, not only for completion's sake but also to achieve improved performance, especially when moving towards more realistic scenarios.

Index Terms—Air Traffic Management, 4D Trajectory Management, Vertical Situation Diagram, Interface Design, Ecological Interface Design, Air Traffic Structure

I. INTRODUCTION

WITH the growth of air travel, making airspaces busier every year, working with existing automation support for air traffic control [1] will become harder and harder [2]. Because of this, new methods of keeping flights conflict free are being developed. Many of these methods seek to introduce automation to aid in the air traffic control task, reducing the workload of the air traffic controller [3], [4]. One of these methods applies 4D trajectory management to the real-time task of an air traffic controller [5] [6] [7]. With 4D trajectory management, the trajectory of a flight is generated beforehand [8]–[11], its four dimensions being position (latitude, longitude, and altitude) and time [12]. This means that at any point in time of the flight, the position will be determined. As such, possible conflicts can be resolved before flights depart [8] and emerging conflicts during a flight can be predicted and visualized. The advantage of this to an air traffic controller is that fewer conflicts will be present in real-time for the same number of flights in a sector and the conflicts that do emerge can be immediately visualized, enabling the controller to handle more traffic and, potentially, lowering workload [13], [14].

When introducing automation, and wanting to keep a human controller actively involved, issues can emerge that impede

performance and human understanding of the system (e.g., ironies of automation, trust in automation) [15] [16]. To minimize these issues, automation needs to be implemented in a way that focuses on the human. Using the principles of Ecological Interface Design (EID), automation can be used to support, rather than replace, human decision making [17] [18]. Doing this can alleviate many of the issues identified with introducing automation in air traffic management [16], [19]–[22]. Besides this, managing 4D trajectories is a complex task when not properly supported. This is because time is used as a dimension, which means that when manipulating one part of the trajectory (e.g., diverting the horizontal trajectory or changing the altitude) the speed needs to be adjusted to adhere to the 4D constraints of the trajectory (e.g., leaving the sector at the right time). The air traffic controller will need to be supported in a way which will make it clear what the effects of their actions are in space and time.

An interface has been designed which applies EID and supports user decision making with real-time 4D trajectory management [7]. Using planned 4D trajectories conflicts between aircraft are predicted. Using the arrival time and location at the airspace border as a fixed constraint, the complete "solution space" of deviation possibilities can be presented to the controller, within which trajectories can be changed without delaying the aircraft [7], [23], [24], [25]. This way the controller can use their own preferred method to solve the situation and automation is there to support the decisions and improve situation awareness [25]. Instead of re-routing an aircraft, a conflict might also be solved by adjusting the speed of an aircraft. This can also be visualized by showing the distance remaining versus time remaining to the sector border [26]. In this visualization, the minimum and maximum speed can be used to generate another travel space which shows the range of solutions when adjusting only velocity.

What is not included in this interface, however, is a method of observing and controlling the vertical aspect (altitude) of the 4D trajectory. To allow for complete 4D control over the trajectories, this functionality needs to be integrated into the system. This paper discusses expanding the existing trajectory management interface by adding altitude visualization of the trajectories and support to manipulate altitude. The effects of this addition on human performance are investigated by analysing the control strategies applied by users of the interface.

Expanding the existing interface is done by applying the

principles of EID and the principles of display design [27] to add altitude visualization of the trajectories and support to manipulate the altitude. A validation experiment is performed to ensure the interface works as intended and to gain some insight into the control strategies applied by users of the interface.

In Section II the theoretical background is expanded upon to justify the inclusion of altitude in an air traffic control interface and detail the difficulties that come with manipulating 4D trajectories. Besides that, the original interface that was expanded is shown. The full interface is shown and detailed in Section III and its design rationale based on the cognitive work analysis and principles of display design are explained. The experiment that was performed is covered in Section IV, results are shown in Section V. Results are discussed in Section VI, where recommendations for further research are made as well. Conclusions are drawn in Section VII.

II. BACKGROUND

A. Current ATC Practices

Air traffic management is currently performed with a relatively low level of automation. Air traffic controllers have access to a top-down radar view of the sector and can see the position, speed, orientation and altitude of the aircraft inside the sector. Using this information, the controller has to extrapolate whether or not two or more aircraft will be in conflict in the future and, if so, devise a suitable solution to the conflict.

To do this, air traffic controllers have developed their own systems and methods to do this efficiently and effectively [1]. Though many different methods exist, and the method employed by the controller often comes down to personal preference, certain standard practices exist and patterns can be identified [28] [29].

Air traffic controllers often analyse their sector in a standard pattern (clockwise, top to bottom), grouping aircraft together based on certain characteristics like a similar altitude or direction of flight [1]. These methods can make it easier to identify potential conflicts and their priorities, even in relatively busy scenarios.

To solve conflicts, certain standard solutions can also be identified [28]. In the simplest form, conflicts are resolved by issuing a change in altitude, speed, direction or a combination of the three to one or more aircraft. For most conflicts and air traffic controllers, issuing a change of altitude is the preferred solution [28]. Compared to other options, an altitude change can be easily analysed for potential conflicts with other flights and can yield results quickly. A velocity change often only works for conflicts that are still a long time away unless the change in velocity is very large. Directional changes can solve conflicts quickly but can become chaotic and cause new conflicts in complex scenarios.

The importance of the ability to observe and manipulate the altitude aspect of a trajectory becomes apparent when looking at current air traffic management strategies. Most commonly, when a conflict is detected, the first solution considered to resolve the conflict is a resolution involving an altitude change

[1] [28] [29]. This does not mean altitude will automatically be as vital in a future 4D ATM system, but it is very unlikely to be of no added value at all and would need to be justified if omitted, especially when one wants to speak of a true 4D trajectory management system.

B. Real-time 4D Trajectory Management Difficulties

When manipulating a 4D trajectory in one sector, it is desirable, or even necessary, to manipulate it in such a way that it does not affect the trajectory in the next. Therefore, the time and location at which an aircraft exits a sector are constraints which limit how a trajectory can be changed. When diverting an aircraft horizontally, the track through the sector becomes longer, therefore the speed needs to be increased as well to adhere to the sector exit time. If the aircraft is diverted too far, the speed would have to be increased further than the speed envelope allows, making the aircraft arrive at the sector exit too late. When adjusting altitude this adds new, somewhat more complex problems that need to be accounted for.

The main velocity metric used by pilot in the aircraft is the indicated airspeed (IAS). This is a useful metric for the pilots because the aircraft will generally respond to control inputs similarly at a given IAS regardless of the altitude or (constant) wind. For navigation, however, true airspeed (TAS) or groundspeed (=TAS when disregarding wind) indicates the progress along the track. The difference between TAS and IAS depends on the pressure and air density outside the aircraft, meaning it depends on the altitude. A certain IAS will result in a higher TAS at a higher altitude than it does on a lower altitude (IAS = TAS at ISA sealevel conditions). [30]

At low altitudes, the IAS is kept at a constant ideal value during a climb or descent. At a certain altitude (around FL 250-300 in most cases), a crossover point is reached where the ideal climbing Mach number is reached at the current IAS [30]. From this point upwards, the Mach number is kept constant instead of the IAS because the maximum Mach number of the aircraft now translates to a lower velocity than the maximum airspeed. For the purpose of this project only constant IAS climbs are considered to keep the initial implementation simple. Crossover altitudes can be introduced when the interface performs correctly.

What this entails for 4D trajectory management is that any alteration of altitude will need to come with an alteration in velocity to ensure that the aircraft will still arrive at its next waypoint at the correct time. This also means that this velocity alteration will need to be taken into account when computing the solution space.

The effect of changing velocity with altitude is illustrated in Figure 1. Two aircraft start at equal altitude of 30000 *ft* and IAS (300 *kts*). One climbs to 40000 *ft* and holds at a steady IAS, the other descends to 20000 *ft*. The climb and climb rate have been chosen as generic but plausible values (as have the descent values). The black lines connect points at the same moment in time between tracks. The sector exit is assumed at 108 *nm* along track from the start (at the last dot of the blue trajectory). As can be seen, though both aircraft have remained at 300 *kts* IAS the aircraft that climbed reaches the

sector exit well before the aircraft that descended. Therefore, in order to adhere to the 4D trajectory constraints at the sector exit, the velocity will have to be adjusted whenever the altitude is adjusted. To minimize the changes for the pilot with this new interface, a new indicated airspeed is given to pilots at the end of the climb or descent.

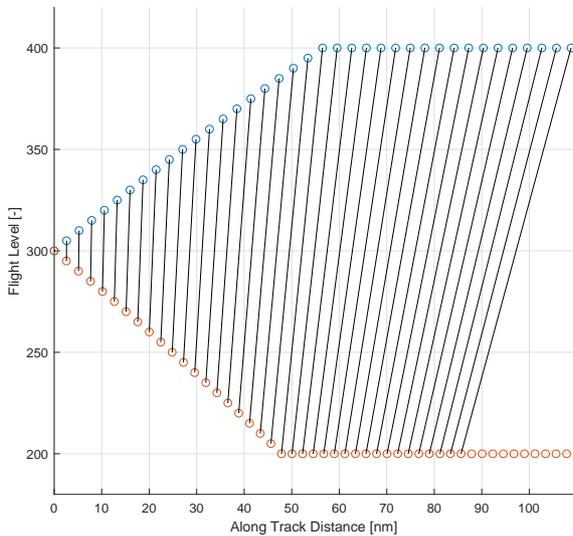


Fig. 1: Two generated aircraft tracks where one climbs and the descends and both remain at constant IAS. The black lines connect positions at the same moment in time.

When generating the solution space in altitude, not only does the possible altitude range of the aircraft need to be considered, but also the velocity range at this altitude. If the required airspeed of the aircraft after a climb is below the stall speed, it is not a possible solution that can adhere to the 4D trajectory. This means it cannot be included in the solution space, even though the altitude as such is reachable. When computing a possible conflict at a different altitude, the change in velocity has to be taken into account as well.

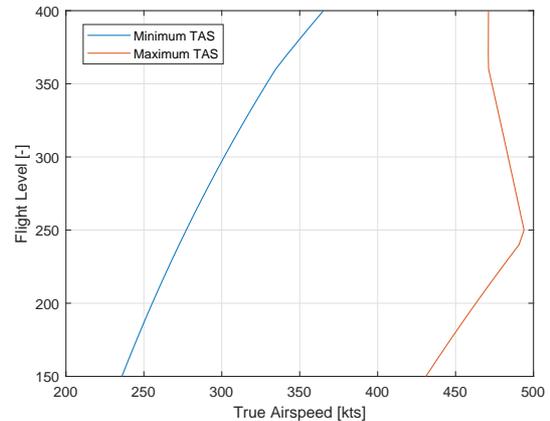
To illustrate the change of the speed envelope, Figure 2 shows the minimum and maximum true (Figure 2a) and indicated (Figure 2b) airspeeds of an Airbus A321 at flight levels ranging from 150 to 400¹.

As can be seen, as the altitude increases, the minimum required TAS to remain above the stall speed increases. As was determined earlier, when an aircraft is ordered to climb it will need to decrease in TAS to reach the sector exit at the correct time. This makes the minimum TAS an important limiting factor when generating a solution space in the vertical plane.

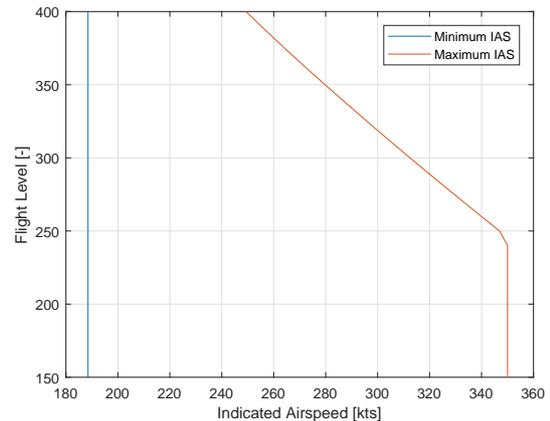
In the same vein, the maximum TAS can become a limiting factor when the aircraft needs to descend. In the figure, three parts of the maximum TAS progression can be observed and two parts in the IAS plot. First, in the lower portion, maximum

¹Service ceiling of the A321 is usually given between 39000-40000 *ft* but, as this example is for illustration purposes only, the round number of FL 400 was used.

IAS is constant, which leads to a rising line in the TAS plot. Here the limiting factor is the absolute maximum IAS of the aircraft in *kts*. Then, around FL 250, the maximum IAS starts decreasing as the altitude increases. Here, the maximum allowable mach number becomes a lower velocity in *kts* than the absolute maximum IAS and must be taken as the limiting factor. Lastly, just above FL 350 and onwards, the maximum TAS remains constant. This is the start of the tropopause where ISA atmospheric conditions remain constant with altitude.



(a) True Airspeed Envelope



(b) Indicated Airspeed Envelope

Fig. 2: Speed envelope of an A321 at varying flight levels showing the minimum and maximum possible TAS and IAS.

The effects of altitude on velocity are minor when only applying altitude changes over a small range of flight levels (e.g., 10-20 FL), but become important when desired altitude changes become larger. When adjusting altitude over a large part of the track, small differences in velocity also become relevant to account for as it would have a larger influence on the sector exit time.

C. Previous Work

The original interface is shown in Figure 3. This interface contains the top-down viewscreen [7] and has a Time Space Diagram (TSD) [26]. On the left side, the top-down plan-view display (PVD) is shown, reminiscent to existing air traffic

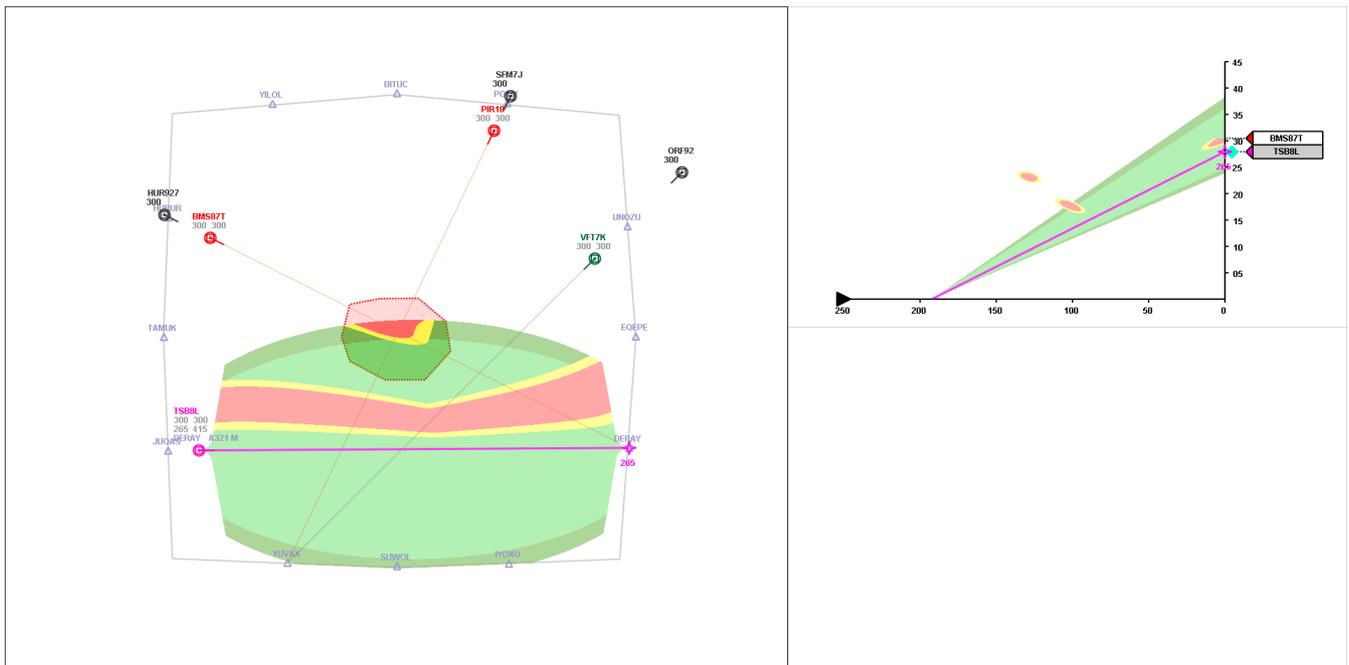


Fig. 3: Current Travel Space Representation Interface

controllers' radar screens. On the top right is the TSD, showing the remaining track length on the horizontal axis and the time in seconds on the vertical axis.

The plan-view display shows a top-down view of the sector. The aircraft are shown on their horizontal position in and around the sector. Each aircraft is labelled with their identification code, the flight level is shown underneath. The red area in the sector is restricted airspace. This could resemble bad weather or airspace which has been closed for any other reason.

When an aircraft is selected, it and its trajectory are highlighted. The available travel space appears, which is the red, yellow, and green area in Figure 3. This area represents all the locations a waypoint could be placed to divert the aircraft with it still being able of reaching the exit waypoint on time. On its current trajectory the aircraft in the figure is not in conflict. Hovering the mouse over the red part of the solution space highlights the aircraft with which it would be in conflict if diverted there. Placing a waypoint in the red area of the travel space changes the trajectory such that a conflict will exist, a waypoint in the green area will resolve the conflict. Diverting the aircraft with a waypoint in the yellow area means that a conflict would be resolved, but the separation between the aircraft would be minimal. This could quickly result in a new conflict if the trajectory (including speed) is not followed exactly by any of the two aircraft.

The time space diagram shows the trajectory of a selected aircraft in time and along track distance. The horizontal axis shows the distance remaining to the sector's edge and the vertical axis shows the time remaining. As with the plan-view display, the detected conflict is shown in red.

Waypoints can be placed in the time space diagram in the same way as in the plan-view display. Instead of altering the

heading, the velocity is altered. To avoid a given conflict, for instance, a waypoint could be placed on the trajectory and dragged down, which means the aircraft would fly at a higher velocity up to that point and then slow down to arrive at the sector's edge at the right time. The aircraft would then pass in front of the aircraft with which it was in conflict.

III. INTERFACE

The interface was expanded on the basis of the findings of a Cognitive Work Analysis (CWA) [31] [32] while attempting to remain consistent with the existing elements of the interface. Important findings from the CWA pertaining to the control strategies and the user competencies are discussed in Subsection III-A. The final layout of the interface is presented in Subsection III-B and the rationale behind the design is detailed in Subsection III-C.

A. Control Strategies & Worker Competencies

To determine the control strategies that can be applied with the interface, the control task is first analysed. A decision ladder for resolving conflicts in an airspace with the interface is shown in Figure 4. Starting at, or near, the bottom left a situation occurs that prompt the user to take action. The user observes whether there is a conflict and identifies the problem. A solution has to be formulated, whether by going all the way up the ladder, formulating a solution using knowledge based behaviour, or using a shortcut, for instance by recognising the situation fits a solution in the strategy the user is applying and using a solution the user has already applied before. Rule-based behaviour can also emerge from experience as users apply the same knowledge-based logic over and over again until it becomes familiar enough.

instead of only when a conflict occurs. The information flow map for this strategy is shown in Figure 7. As can be seen the steps followed are very similar to the first strategy but the travel space and sector perturbations are only considered after applying an altitude change as this is applied regardless of the situation in the sector.

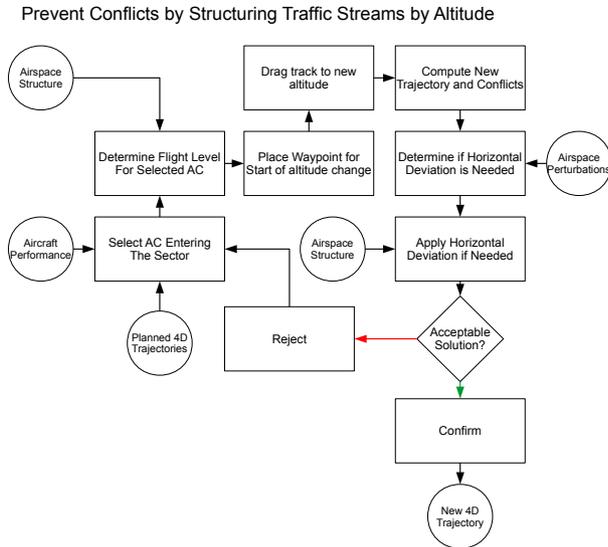


Fig. 7: Information flow map for the TSR interface when preventing conflicts by structuring traffic streams by altitude on sector entry.

The fourth identified strategy applies the first strategy, but considers necessary horizontal changes due to perturbations before applying an altitude resolution. If an horizontal change is needed, the conflict between aircraft is also solved horizontally to make it so only one control action is needed to solve the conflict and avoid the perturbation. The information flow map for this strategy is shown in Figure 8. As can be seen, once the safe travel space has been determined, a check is made whether the trajectory crosses a restricted area. If so, a horizontal solution is applied in the PVD. Otherwise an altitude resolution is applied.

Finally, with the possible strategies identified, it is interesting to look at the expected capabilities of the users of the system. This can help in identifying what kind of behaviour the interface needs to support.

The required worker competencies can be divided into skill (experience, automatic reactions), rule (procedure, if-then), and knowledge (reasoning, problem solving) based categories and allocated to the different tasks that need to be performed [31] [32] [33]. In Figure 9 a worker competencies analysis is shown for the task of conflict resolution with the 4D TSR interface. For each information processing step, the knowledge state needed from the step and the skill, rule, and knowledge based behaviours for achieving that state are detailed.

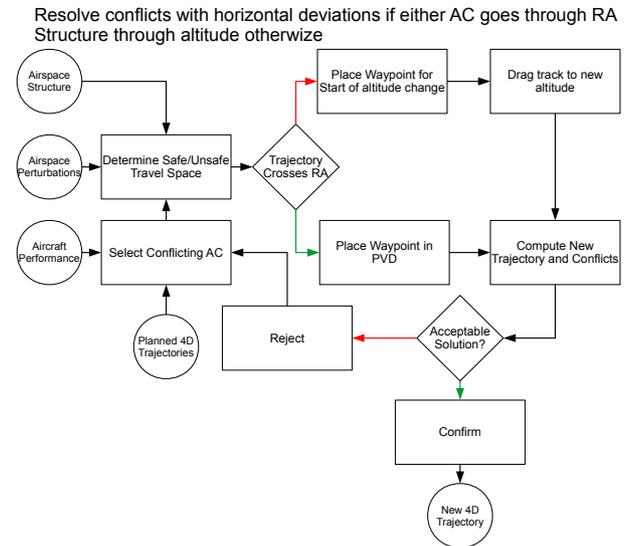


Fig. 8: Information flow map for the TSR interface when solving conflicts by applying horizontal solutions to avoid RAs and structuring by altitude otherwise.

B. Interface Layout & Functionality

The full interface with Vertical Situation Diagram (VSD) is shown in Figures 10 and 11 including the existing viewscreens. The horizontal axis is shown on top of the VSD because it represents the same information as the horizontal axis of the TSD (namely remaining track length) which is above the VSD. The vertical axis is on the right, as this is the common direction of flight when shown in a diagram, and is consistent with the TSD.

When an aircraft is selected on the plan-view display, the aircraft and track are shown in the VSD as in Figure 10. The label with aircraft ID is shown next to the vertical axis. In this example the selected flight is in conflict with a crossing aircraft, as depicted by the red area. A solution space is generated for a climb or descent starting at the aircraft location.

To solve the conflict, a point on the track is selected to start a descent or ascent. This point is marked with a waypoint and a solution space is shown in green. This includes all the achievable altitudes while still being capable of reaching the sector exit in time, at the right altitude, and without exceeding the maximum aircraft or sector altitude or going below the minimum. The slope of the ascending and descending lines are determined by the aircraft's maximum rate of ascent and descent at the given altitudes.

To adjust the altitude the aircraft label can be dragged up or down as depicted in Figure 11. A second waypoint is placed on the top of climb or bottom of descent, a third is placed where the aircraft starts to return to the sector exit altitude and the new track is generated. If the user is satisfied, this new track can be confirmed. The new track is also shown in the plan-view display and the TSD with new solution spaces. As can

Information Processing Step	Resultant Knowledge State	Skill-Based Behaviour	Rule-Based Behaviour	Knowledge-Based Behaviour
Scan for indicated conflicts	Whether one or multiple aircraft are in conflict	Monitoring for signals of conflicts (red ACs)	Identifying conflicts that are present	Reason where conflicts may arise in the future with aircraft not yet in the airspace
Determine conflicts with no-fly zones	Whether one or multiple aircraft will move through a no-fly zone	Monitoring for tracks crossing through red areas	Perceive flights will breach no-fly zones	Reason which source-sink combinations will have paths crossing no-fly zones
Determine most critical conflict	Which conflict has the largest priority in solving	Perceive which ACs in conflict are in close proximity on the TSD	Use heuristics to estimate which ACs will first have LoS or breach no-fly zones	Reason, based on visual data, if conflicts with high priority could emerge
Choose method to solve a conflict	Which approach will be most effective in resolving the conflict	Perceive which methods provide many options based on the solution space	Apply doctrine to determine which methods will be tried first	Reason which method is least likely to cause more conflicts in the future while having minimal impact on the trajectory
Determine conflict resolution	The conflict resolution to be executed	Perceive the areas in the solution space that provide conflict resolutions	Apply doctrine/common sense rules to determine a suitable waypoint location in the solution space	Reason whether a waypoint location can cause conflicts in the future and whether it is in line with previous conflict resolutions

Fig. 9: Worker competencies analysis for the resolution of conflicts with the novel air traffic control system.

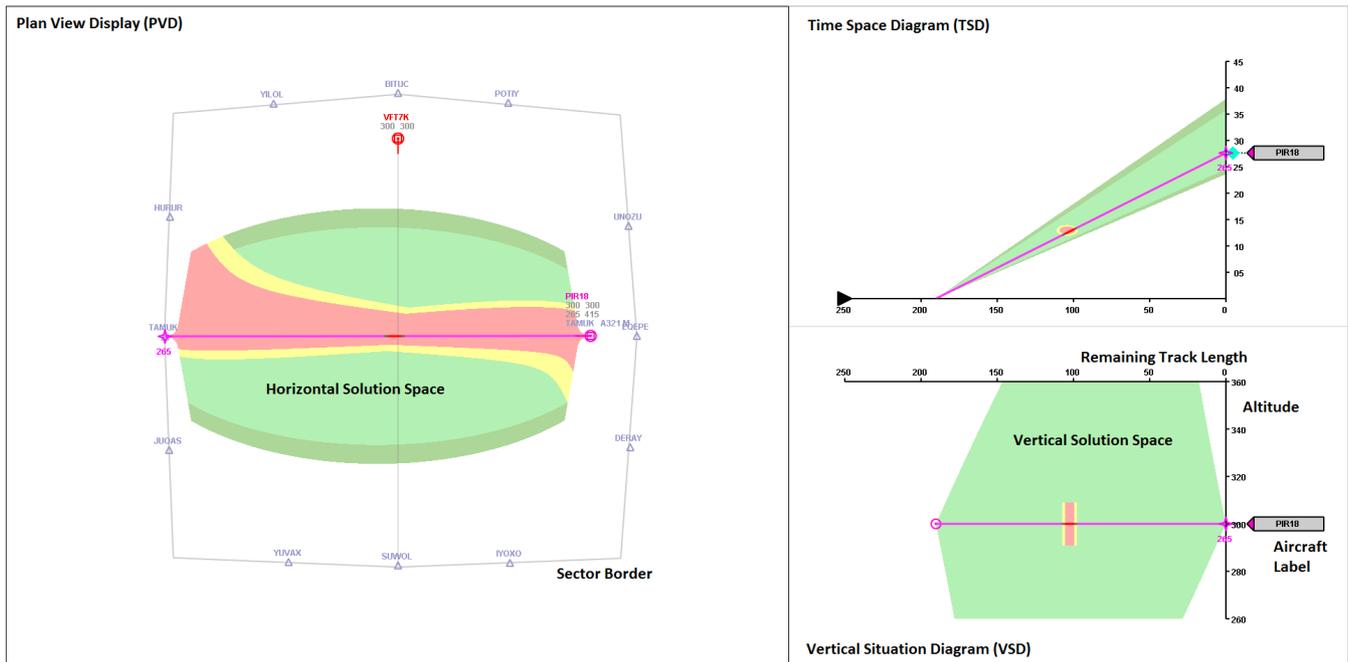


Fig. 10: Display concept with a selected aircraft in conflict with a crossing flight.

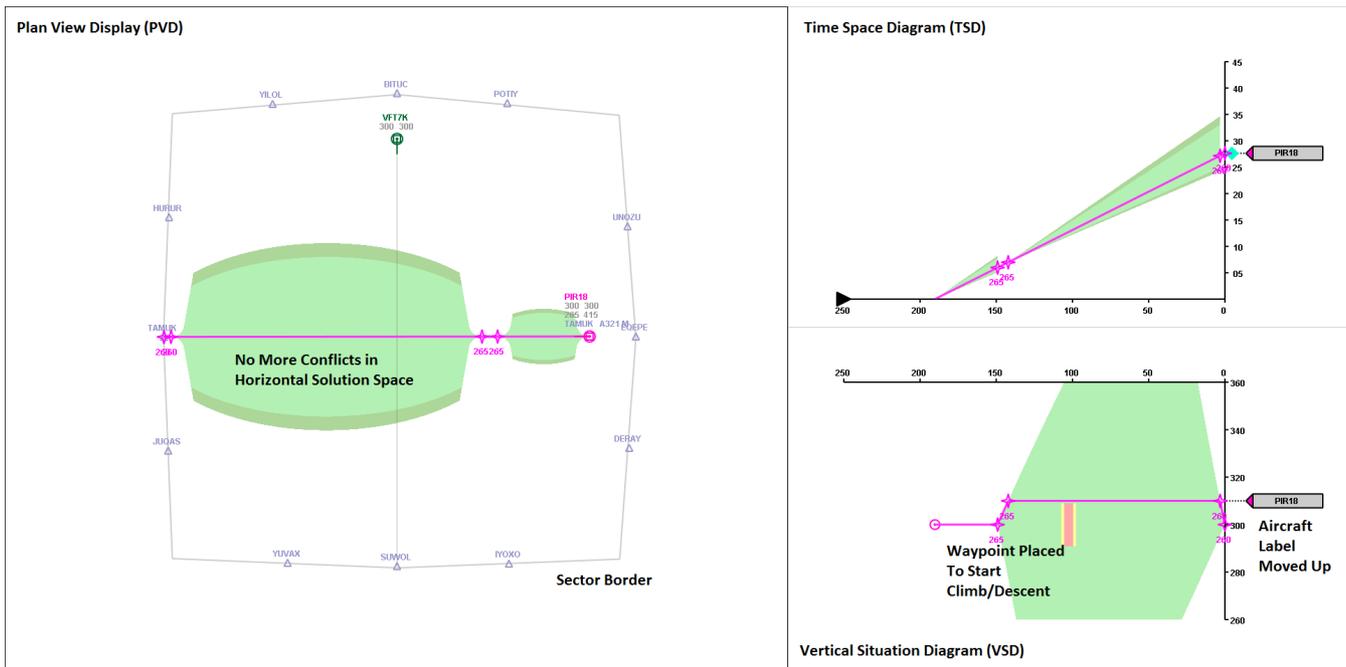


Fig. 11: Display concept with a selected aircraft in conflict with a crossing flight. A waypoint has been placed in the VSD on the track. The label has been moved down to avoid the conflict. A new track is generated and shown in all view screens.

be seen in the TSD the velocity of the aircraft is affected by the altitude change.

What different situations look like in the VSD is sketched in Figures 12, 13, and 14. Figure 12 displays a situation where an aircraft crosses the trajectory of the observed aircraft at the same altitude, creating a conflict.

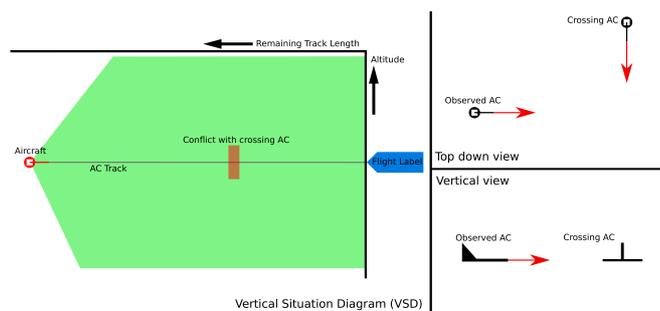


Fig. 12: Visualization of the VSD showing a conflict with a crossing aircraft at the same altitude with a top down and vertical view.

Figure 13 shows a situation where an aircraft is travelling in the opposite direction of the observed aircraft at a lower altitude. If the altitude of the observed aircraft were lowered to the red area, a head on conflict would be created. Note how the red area is wider for the crossing aircraft than for an aircraft coming head-on. This is because the loss of separation would be shorter with both aircraft travelling in opposite directions.

Figure 14 displays a situation where an aircraft is travelling along the same horizontal trajectory as the observed aircraft but at a higher altitude and a higher TAS; the aircraft is overtaking the observed aircraft. If the altitude of the observed

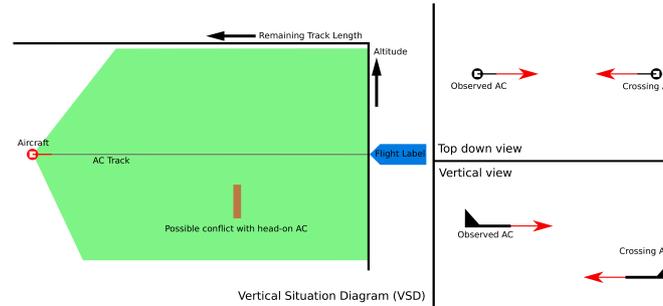


Fig. 13: Visualization of the VSD showing a potential conflict with an aircraft coming head on at a lower altitude with a top down and vertical view.

aircraft were increased to the red area, a conflict would be created with the overtaking aircraft. Note how the red area is very wide in this case. This is because the aircraft travelling in the same direction would be in close proximity for a long time.

C. Design Rationale

In the figures shown in the previous subsection, the previously existing parts of the interface — these being the PVD and TSD — are depicted alongside the concept of the new VSD. As much as possible, an attempt was made for the VSD to be observed and used in a similar fashion to the rest of the interface. Due to the nature of ascents and descents, however, the approach differs somewhat. If, like with the other displays, one waypoint could simply be placed anywhere in the altitude solution space, the aircraft could be ascending or descending

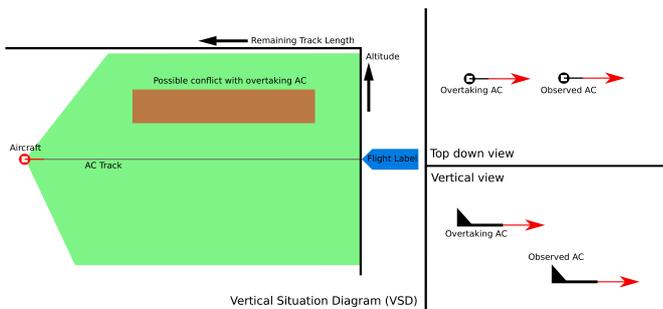


Fig. 14: Visualization of the VSD showing a potential conflict with an overtaking aircraft at a higher altitude with a top down and vertical view.

slightly for very long periods of time which is undesirable for the pilot even when ignoring the fact that the pilot would need to adjust the velocity throughout this climb or descent to remain on schedule. Instead, two waypoints are used marking the start and end of the climb or descent. The pilot can execute the climb or descent at constant indicated airspeed (IAS), as they are used to, and, at the end of the climb/descent, a new target IAS is given in order to arrive at the sector exit at the right time. How altitude changes affect velocity was explained in Subsection II-B.

To minimize the changes for the pilot with this new interface, a new indicated airspeed is given to pilots at the end of the climb or descent. This means that, for instance, in a descent, the TAS decreases until the end of the descent where the aircraft changes speed to arrive at the planned time at the sector exit. The altitude at the end of the sector is also constrained so, in a descent, there will be a climb back to the required altitude at the end of the sector. The effect of this climb is also taken into account in the TAS change.

When generating the solution space in altitude, not only does the possible altitude range of the aircraft need to be considered, but also the velocity range at this altitude. If the needed airspeed of the aircraft after a climb is below the stall speed, it is not a possible solution that can adhere to the 4D trajectory. This means it cannot be included in the solution space even though the altitude is reachable. When computing a possible conflict at a different altitude, the change in velocity has to be taken into account as well.

Because of the way altitude changes work with this interface, it cannot be assumed the altitude will be the first conflict resolution option considered, like it is with current day air traffic management. Whereas giving an altitude change currently is the easiest and fastest way of resolving conflicts, with this TSR interface, speed and heading changes are just as straightforward. With a short-term conflict, altitude change will still be fastest solution, but, compared to current ATM, conflict resolutions will mostly be done with more time left before the closest point of approach. Therefore, heading and velocity changes could prove more viable as conflict resolution methods compared to current ATM. Because of this the VSD has been given no particular prominence over the PVD or the TSD.

To better show the connection between TSD and VSD, the shared dimension of the horizontal axis (remaining track length) is shown in close proximity. The physical proximity of this should increase visual momentum [34] when adjusting attention between these displays.

With these three displays the PVD, showing the physical shape of the sector and all the aircraft in it, is bound to be seen as the main display, taking up most of the attention. This is expected and, in itself, is not immediately a problem as it is the most useful display for gathering information on the overall situation and the conflicts that need to be solved. It is also the only display which shows all the aircraft in and around the sector. This makes it a natural starting point when scanning the situation. The remaining displays only show information on a selected aircraft and the conflicts it has. What is important is that these displays do not go ignored completely as they will be vital in reaching the optimal conflict resolutions.

Using the shared dimension of remaining track length, it is easier for the user to shift their attention to the TSD and VSD and away from the PVD in one go. The altitude is shown on a vertical axis to be immediately understood as it is congruous with the mental picture of altitude. All the conflicts are shown in red and the solution space in green, obviously in line with the other displays. Superfluous information needs to be omitted as much as possible from the TSD and VSD especially as to not discourage the user to shift their attention away from the PVD due to a perceived complexity of the other displays.

In the work domain analysis of the CWA, the Abstraction-Decomposition Space has identified the elements that need to be identifiable in the interface. Most of these elements have already been integrated in the existing two displays, what remains are the vertical elements. These are integrated in a manner consistent with how the horizontal elements are visible in the PVD. The vertical flight profile is visualized by the cyan trajectory line, rates of climb and descent are visible in the solution space shape with the altitude limits (due to sector limits or time constraints) making up the rest of the solution space limits. Vertical conflicts and waypoints are shown analogous as in the PVD as well.

The control strategies identified in the CWA are also supported in the interface design. Conflicts are easily identified and more information on the conflicting flights can be found by selecting aircraft in conflict. The safe travel space is clearly visualized and the user can use their own judgement when formulating a solution to a conflict. The implications of the chosen solution on the trajectory are shown in all displays before the user confirms it.

IV. EXPERIMENT

To validate the interface, explore the influence of the addition of the VSD, and analyse the way it is used, an experiment was performed. Data on safety, efficiency, workload, and user activity were collected.

A. Previous Experiment

An experiment was performed with the interface before the VSD was added [35]. This experiment was repeated for

the interface with VSD as a validation of the interface. This allows for a basic comparison between results of the both experiments. This comparison can give some insight into the influence of the added VSD. The interface without VSD only allows for 3D control (latitude, longitude, time) of the trajectory and supports decision making in those dimensions; the VSD adds both control and decision making support for the vertical dimension to the interface. Because of this, a direct quantitative comparison between performance and efficiency results cannot be done. However, because the experiment is mostly about validation of the interface and an analysis of user interaction with the interface, it is still useful to make a qualitative comparison between those results and the workload data.

The experiment conditions of this earlier experiment are detailed later in the section as they were the same for both experiments. Different was that 12 participants performed the experiment without VSD, including domain experts and novices with ATC (in equal proportions).

Within the relevant metrics analysed there was no significant difference in the results between converging and diverging traffic. Only the presence or absence of a restricted area resulted in significant differences between results. Relevant visualizations of data can be found in Section V where results of the experiment with the complete interface are also presented.

As can be expected, the added track miles were significantly higher when a restricted airspace was present. The user activity in the PVD (both total clicks and trajectory edits) was also significantly higher in these scenarios, as was the total number of trajectory edit executions. For the TSD there was no significant difference between scenarios, both in introduced delay and user activity. The number of conflicts and total conflict duration was also not significantly different between scenarios. Experienced workload was found to be significantly higher for scenarios with restricted airspace.

B. Experiment Goal

The goal of the current experiment is to validate the functionality of the interface, and to analyse how the interface is being used. The interactions of the participants with the interface were observed to determine if the control strategies defined in the CWA can actually be observed with the completed interface. This experiment was performed under the same conditions as an experiment performed with the interface before the VSD was added. This allows for a basic comparison of the results and to analyse the influence the addition of the VSD has on controller performance and behaviour.

The same scenarios as the experiment without VSD were used. This means it is possible to resolve all scenarios without VSD and all aircraft start at the same altitude. This makes it possible to observe how the methods of solutions change with the availability of the VSD. With all the aircraft starting at the same altitude, creating any kind of traffic structure in altitude was completely up to the user.

C. Conditions

1) *Independent Variables:* Two different traffic structures were analysed. All scenarios have two traffic streams: north-south and east-west. The independent variables determine whether these traffic streams are convergent or divergent and whether there is a restricted area in the middle of the sector. Thus, the following 4 scenarios exist:

- Converging, no restricted airspace (C_n)
- Converging, with restricted airspace (C_r)
- Diverging, no restricted airspace (D_n)
- Diverging, with restricted airspace (D_r)

2) *Dependent Measures:* To determine which strategies are applied, observations were made about the participant's actions during the experiment. These observations were then discussed with the participants after the experiment to confirm the observed strategies. To provide insight into user activity the mouse position was tracked as well. This can provide insight in where the attention of the participant was focussed.

To get a measure of performance, losses of separation, restricted area intrusions and intrusion times were tracked as a measure of safety. Efficiency was measured by looking at the impact on the trajectory of user actions. Small actions mean the aircraft does not have to divert much from its original trajectory and is therefore more efficient. Total added track miles, the total introduced delay and the average and maximum altitude changes were tracked as a measure of efficiency. Whether a certain altitude change is more efficient than a certain horizontal track change was not considered in this experiment.

During the simulation, prompts were given the user to provide a workload rating on a 0-100 scale. The number of actions in each viewscreen was tracked as well. Besides this notes were made on any unexpected behaviour during the experiment which might have influenced the workload.

3) *Control Variables:* The control variables are the test parameters which will be kept consistent throughout every scenario. This will ensure variance in the data will be independent of these parameters. The following have been defined as control variables:

- Sector parameters (size, shape, etc.)
- Traffic density (1 aircraft enters the sector every 90 seconds)
- Aircraft type (A321)
- Scenario duration (1 hour in scenario time)
- Availability of the interface
- Experiment environment

4) *Participants:* A 4x4 experiment matrix is shown in Table I. The scenario order is different for every participant to prevent any remaining learning effects after the training, emerging from a certain scenario order, from being reflected in the results. The scenarios are also rotated differently for each participant to ensure the traffic streams can come from different sides for each scenario. With four scenarios, at least 4 participants are needed.

The four experiment participants all have some experience with the basics of air traffic management but are not experts. In addition all had interacted with the interface without VSD before. The control task asked of the participants was to control the sector as safely and efficiently as possible.

TABLE I: Latin square experiment matrix for validation experiment. Rotation is clockwise, trial 3 and trial 4 were also flipped vertically (north-south)

	Trial 1	Trial 2	Trial 3	Trial 4
Participant 1	$C_r 0^\circ$	$D_n 180^\circ$	$C_n 90^\circ$	$D_r 270^\circ$
Participant 2	$D_n 180^\circ$	$C_n 0^\circ$	$D_r 270^\circ$	$C_r 90^\circ$
Participant 3	$C_n 0^\circ$	$D_r 180^\circ$	$C_r 90^\circ$	$D_n 270^\circ$
Participant 4	$D_r 180^\circ$	$C_r 0^\circ$	$D_n 270^\circ$	$C_n 90^\circ$

D. Scenarios

As stated when defining the independent variables, 4 scenarios were tested. All aircraft were of the same type and entered and exited the airspace at FL300. It was up to the participant whether or not to introduce any sort of structure in the vertical space. Each scenario is 1 hour long, run at four times the speed (making each scenario take 15 minutes in real time). Every 90 seconds, in scenario time, an aircraft enters the sector, flying either north-south or east-west (north-south or south-north is determined by the rotation of the sector, also for the east-west stream). Figures 15 and 16 show two of the scenarios used during the experiment, the first having converging traffic and a restricted zone present and the second having diverging traffic and no restricted zone.

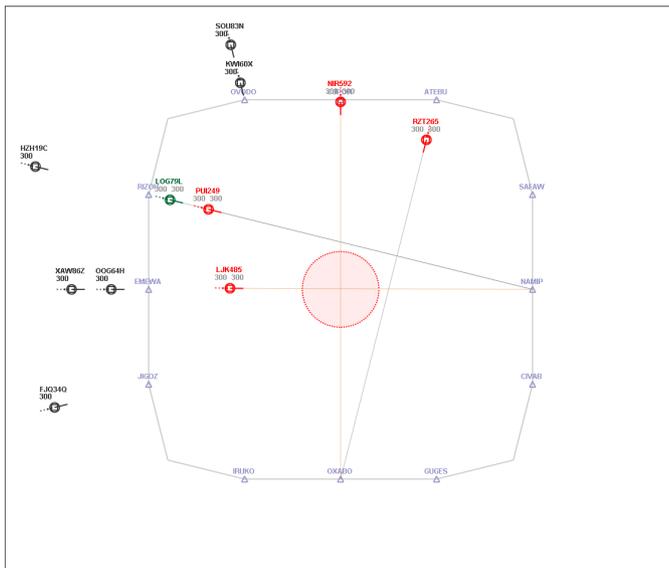


Fig. 15: Plan view display of the interface with the converging traffic scenario with restricted zone present.

E. Procedure

Before the experiment, participants were provided with a training script which guided them step by step through simple scenarios to familiarize them with the interface and its different viewscreens. After that, six training scenarios of increasing difficulty were run where the final scenarios were comparable in difficulty to those of the actual experiment.

Once the participants completed these training scenarios successfully and were comfortable with the interface, the

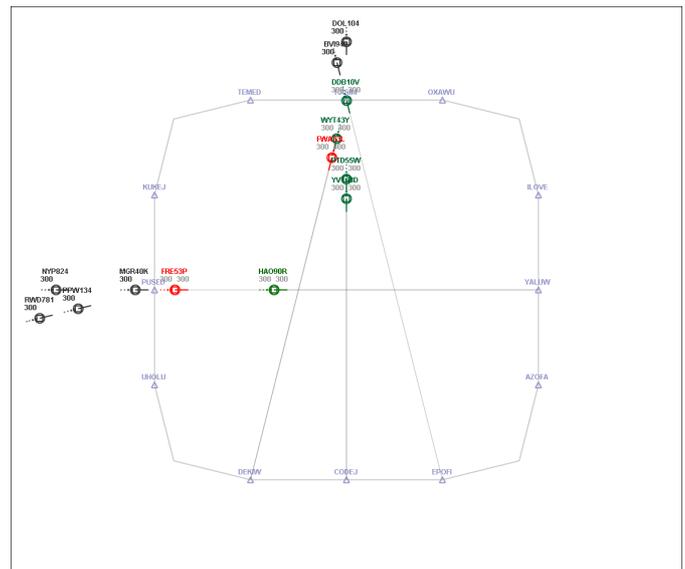


Fig. 16: Plan view display of the interface with the diverging traffic scenario without restricted zone present.

experiment began. The four scenarios of 15 minutes each were run with a few minutes of rest in between should the participant desire this. During the experiment, notes were made to try and define the participant's strategy in each scenario and whether or not they adhered to these strategies. At the end of the experiment, the participants were asked about their experience and what strategies they had in mind themselves.

F. Hypotheses

Based on the goal of the experiment and the data that would be collected, the following hypotheses were made about the possible results:

- I The applied strategies will not differ noticeably between converging and diverging traffic scenarios
- II The applied strategies will focus more on the VSD in scenarios without restricted areas and more on horizontal actions in scenarios with restricted areas
- III Like with the experiment without VSD, the safety metrics will provide insufficient data to make any significant statement on safety
- IV The experiment with VSD will result in more efficient solutions, especially in the scenarios with restricted area
- V Workload is expected to be similar for both experiments in the scenarios with restricted area but is expected to be lower for scenarios without restricted areas

It is not hard to imagine the extra degree of freedom of the altitude could make the scenarios significantly easier. It was hypothesized the scenarios without restricted area could be so easy as to become almost trivial if the participant decided to structure traffic in altitude. This would, of course, also greatly reduce the workload. It was expected that participants would mostly structure traffic based on altitude in the scenarios without restricted area.

In the scenarios with restricted area, horizontal trajectory manipulations are always needed. It was hypothesized this would shift focus away from the VSD and TSD to the PVD. Workloads in these scenarios were expected to be comparable to those of the scenarios with restricted area in the experiment without VSD.

V. RESULTS

Because there was no significant difference between converging and diverging traffic in any of the results of the previous experiment and the experiment with the full interface, and the control strategies observed during that experiment were identical between converging and diverging traffic, the results have been combined in this section to focus on results between the other independent variable: whether or not there is a restricted zone. This will make the results more clear without obscuring relevant data.

A. Control Strategies

During the experiment with VSD, observations were made to try and identify the strategy applied by the participant during each scenario. After the experiment some questions were asked to check whether these observations also matched what the participants thought they were doing. Though the strategy differed per participant, interesting consistencies can be identified.

In the scenarios without restricted area, the main strategy applied by all participants was to resolve most conflicts using altitude. Almost all participants applied consistent solutions to keep traffic separated. For example, when a conflict occurred the aircraft in the north-south traffic stream would be moved up 1000 ft . A strategy like this ensured the diverted traffic was always diverted the same way making it easy to track what was going on. One participant took this idea a step further by deciding to immediately structure traffic on entry into the sector, whether or not it was in conflict. With only two traffic streams, this ensured traffic was never in conflict, though it potentially led to higher control activity and less efficiency than necessary.

To illustrate the resulting traffic structures, the horizontal trajectories have been plotted inside the sector for each experiment. Figure 17 shows the horizontal traffic structure of the converging scenario without RA for different participants. As can be seen, for the participants with VSD, not much has changed as the participants solved most of the conflicts vertically. The same can be observed for every scenario without RA for every participant. Comparing this to a participant in the experiment without VSD, it looks far less structured, conflicts were mostly solved without trying to introduce a new structure. Similar observations can be made for most participants of the experiment without VSD. Participants with fewer deviations in the PVD had largely introduced delays.

In the scenarios with restricted area, solution strategies were generally applied less consistently. Because horizontal actions were required to keep flights from entering the restricted area, most participants chose to apply only horizontal solutions to conflicts unless they had no other options. Exceptions occurred

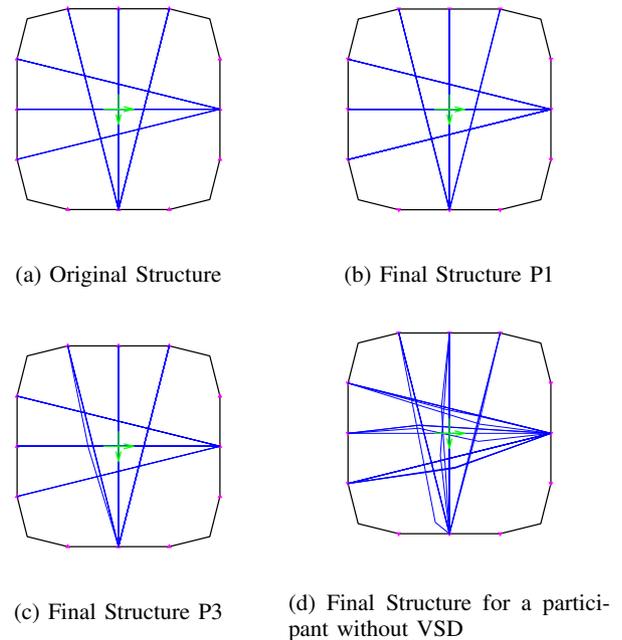


Fig. 17: Horizontal traffic structure in the Converging scenario without RA. The Green arrows indicate the direction of traffic streams

when conflicts between two aircraft appeared which would not fly through the restricted area. In this case a similar strategy was applied to the scenarios without restricted area. In these scenarios the strategy of vertically separating aircraft on entry seemed to be especially useful, as the horizontal deviation to avoid the restricted area could now be applied consistently without needing to worry about conflicts between crossing traffic streams, keeping the workload low and the traffic structured.

Figure 18 shows the horizontal traffic structure of the diverging scenario with RA for different participants. As can be seen, there is now a clear difference between the structure for P1, separating the traffic by altitude on entry, and P2. Though it is still reasonably structured, traffic had to be diverted in a larger variety of ways, also having to pass on both sides of the RA. Similar observations can be made for the other participants not separating traffic on entry. Comparing this to a participant in the experiment without VSD, the resulting structure again looks far less structured. Similar observations can be made for most participants of the experiment without VSD.

During the experiment with VSD, the mouse position on the interface was also tracked. These positions can be processed into heatmaps to visualize user activity and which part of the interface are given attention. These heatmaps provide interesting insight into the parts of the interface which are given more or less attention and can support the observations of applied strategies.

In Figure 19 the heatmap is shown of one participant for a scenario without restricted area and converging traffic,

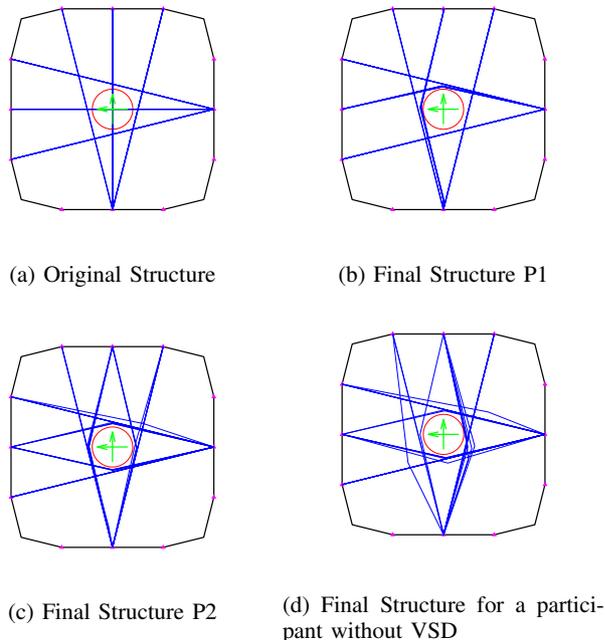


Fig. 18: Horizontal traffic structure in the Diverging scenario with RA. The Green arrows indicate the direction of traffic streams

Figure 20 shows the heatmap of another participant doing the same scenario. The black lines in the heatmap indicate the different areas in the viewscreen. The vertical part on the left is where the workload rating scale appears, the square to the right of that is the PVD, to the right of that are the TSD on top and the VSD below it. The horizontal part on top is where the controls of the simulation are.

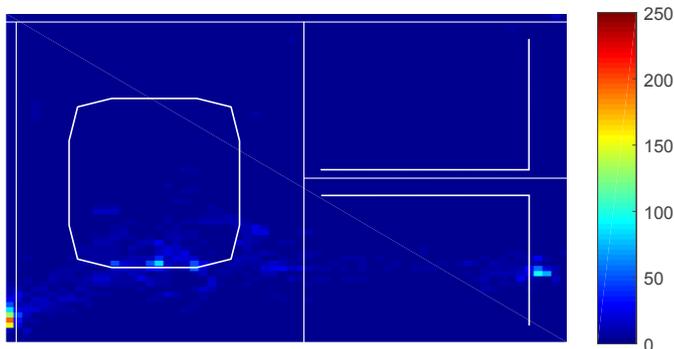


Fig. 19: Heatmap of mouse activity on the interface of P1 in the Converging scenario without RA

As can be seen, the activity in both heatmaps differs visibly. The first heatmap the strategy of separating the aircraft vertically upon entry was applied and in the second a strategy of separating vertically when a conflict occurs was applied where sometimes conflicts were solved horizontally if only a small deviation was needed. Interestingly, some activity can be seen in the TSD here although no track edits were made in the TSD (see Subsection V-D), meaning it did see some

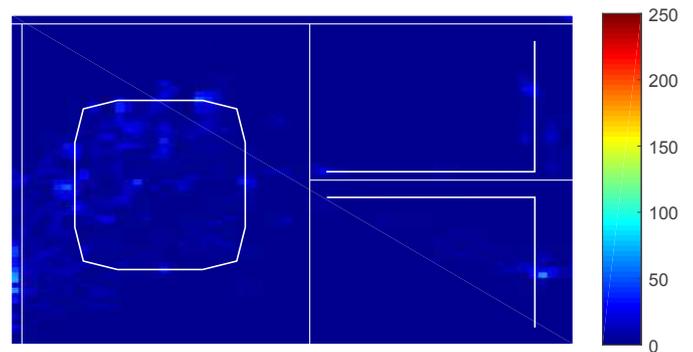


Fig. 20: Heatmap of mouse activity on the interface of P3 in the Converging scenario without RA. Note the scenario is rotated wrt the same scenario for P1 (See Table I)

consideration as opposed to the first heatmap where the TSD was untouched.

In Figure 21 the heatmap is shown of one participant for a scenario with restricted area and diverging traffic, Figure 22 shows the heatmap of another participant doing the same scenario. The first heatmap again shows the strategy of first separating the traffic vertically on entry into the sector.

As can be seen, most of the activity for the second heatmap is on the PVD where the VSD is used more sparingly. Activity in the first heatmap is much more concentrated as similar solutions are applied consistently. There is also more activity on the VSD as all the aircraft from one traffic stream are given a new altitude.

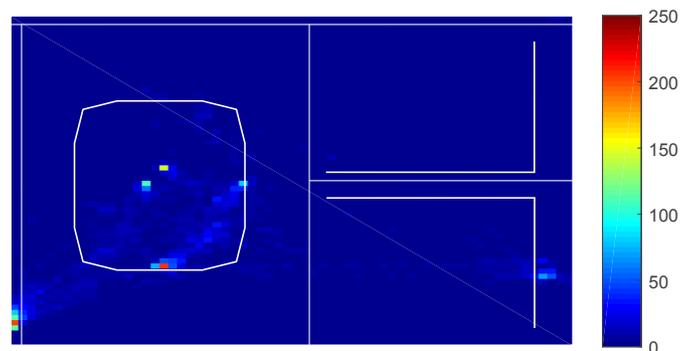


Fig. 21: Heatmap of mouse activity on the interface of P1 in the Diverging scenario with RA

B. Safety

To measure safety, the number and duration of losses of separation between aircraft was tracked as well as the number and duration of the restricted area incursions. Neither the experiment without VSD nor the experiment with VSD had any restricted zone incursions.

With the experiment without VSD there were a small number of losses of separation, in both the scenarios with and without restricted area. In the experiment with VSD there were no losses of separation.

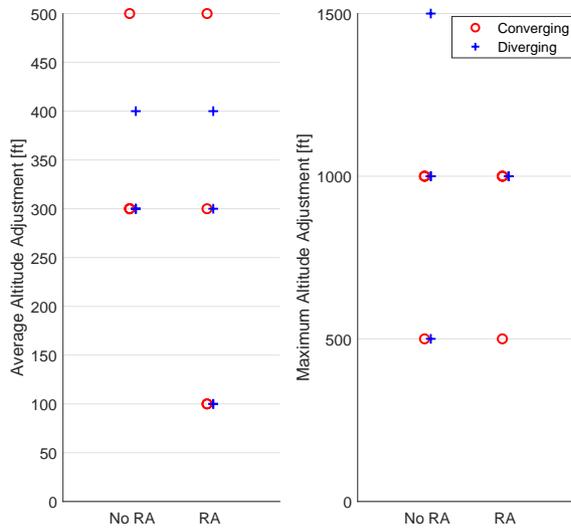


Fig. 25: Results of average (left) and maximum (right) altitude changes in *ft* for the experiment with VSD

at least 1000*ft* apart, meaning an average altitude adjustment between the aircraft of 500*ft*. As can be seen, more altitude adjustments were applied to resolve conflicts in the scenarios without restricted area.

The maximum altitude change shows the largest altitude deviation applied in a scenario. As can be seen, most maximum changes are 1000*ft*, the change required to resolve a conflict vertically by deviating only one of the aircraft. There were also a few cases where cooperative solutions were applied by deviating both conflicting aircraft by 500*ft* up and down. The plots also show there were no scenarios where a participant applied no trajectory adjustments in altitude.

D. Workload

To measure workload, participants were prompted on screen for a workload rating every 2 minutes in the scenario on a 0-100 scale and their activity in the different viewscreens was tracked.

In Figure 26 the workload ratings are shown for both experiments and the normalized Z-scores are shown as well. The crosses indicate the individual values and the bars indicate the mean of each set.

As the way one participant scores workload on a 0-100 scale can differ strongly from another participant, using the raw data as a method of comparison is inadvisable, especially looking at data of different experiments with different participants. Visually, the data seem to suggest the workload is noticeably lower in the experiment with VSD for both scenario types, but other data would be needed to confirm this.

Using the z-scores of the workload, the workload between scenario types can be compared. For both experiments, the difference between scenario types was found to be statistically significant. Looking at the z-scores, the difference in workload between scenarios with and without restricted area is larger

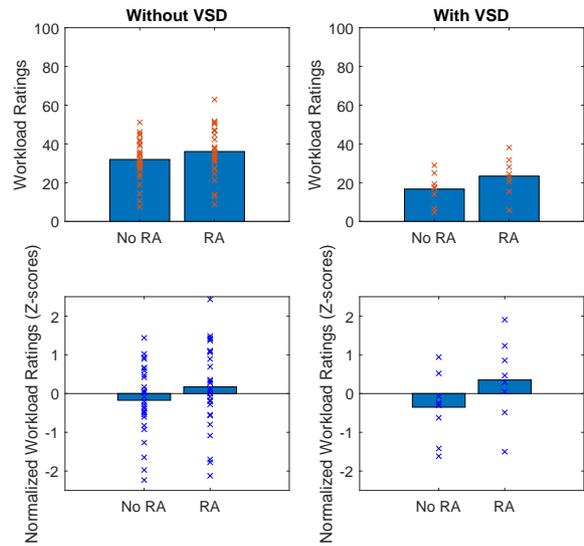


Fig. 26: Workload ratings and Z-scores of both experiments. The crosses indicate the individual values and the bars indicate the mean of each set.

with the experiment with VSD. This could be in line with the hypothesis that the scenarios without restricted area become trivially easy with the interface with VSD.

Besides workload ratings, the user actions were tracked to gain insight in the workload. The number of trajectory edits made in each viewscreen was tracked (including edits that were not executed) and the total number of executed trajectory changes. Figure 27 shows the trajectory edit actions and executions for the experiment without VSD and the trajectory edit actions and executions for the experiment with VSD.

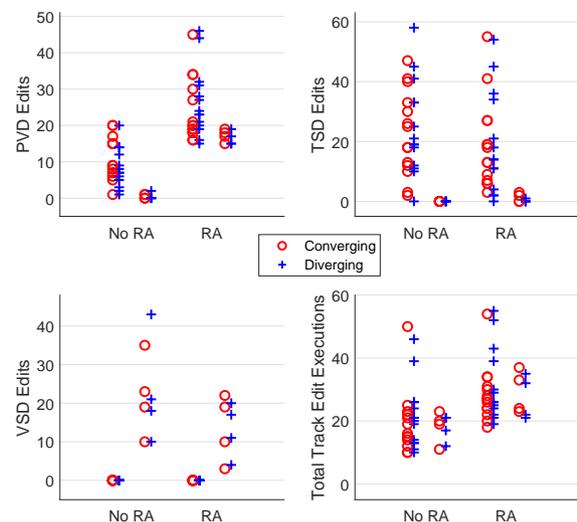


Fig. 27: Results of trajectory edit actions per viewscreen and total executed trajectory changes for the experiment without (left) and with (right) VSD

As can be seen the total number of executed trajectory changes is comparable for both experiments, though the experiment with VSD is slightly lower overall. The experiment with VSD does clearly have fewer edit actions in the viewscreens (which includes actions which were not executed). Of course, the experiment without VSD has no actions performed in the VSD. Especially in the PVD when there was no restricted area there were very few edit actions and the TSD went almost unused throughout the experiment.

VI. DISCUSSION & RECOMMENDATIONS

The experiment performed was small scale and mostly about validating the functionality of the interface. However, some interesting qualitative observations can be made in comparison to the experiment performed without VSD. Besides this the interface itself and its functionality will be discussed.

A. Discussion of Results

The data gathered were from a small subject group and, as expected, little statistically relevant results were found. However, some useful observations can be made as well as a qualitative comparison of results between experiments with and without VSD. What is of most interest is which strategies were applied by participants. In terms of control strategies, similarities in strategy can be identified between participants. A comparison with the experiment without VSD cannot be easily made as control strategies were not directly observed, nor was the mouse tracked during that experiment. As predicted in hypothesis I, there was no observable difference in strategy between diverging and converging scenarios, nor did participants not they approached them differently.

In the scenarios without restricted area, all participants chose to resolve conflicts mainly with altitude changes. Some participants chose to resolve conflicts which only required a small horizontal change in the PVD. A notable strategy was separating the traffic streams in altitude on entry into the sector. This ensured that no conflicts arose in the sector and resulted in a very low workload for the user. As can be seen in the heatmap of Figure 19 activity was relatively low and concentrated compared to the activity of a participant solving conflicts as they arose (Figure 20). The disadvantage is that this ended up being slightly less efficient than resolving conflicts in altitude as they arose because half of all aircraft, whether they would be in conflict or not, were given a new flight level.

As noted earlier, in the scenarios with restricted area many strategies shifted to be focused more on solutions in the PVD. Even when conflicts arose with aircraft not going through the restricted area, some participants chose to try and resolve these in the PVD instead of applying vertical separation in the VSD. The strategy of applying vertical separation on sector entry appeared especially useful here. Not only did the separation allow the user to always divert traffic around the restricted area with minimal horizontal manipulation, but the difficulty of applying both a horizontal and vertical change in trajectory was averted as a vertical change was always the first step in the strategy. Besides this, the strategy was now more

efficient as the horizontal changes were almost minimal which could not be achieved without traffic separated by altitude. These observations with and without restricted area support hypothesis II.

A last important observation from the experiment is that the TSD went almost completely untouched. Most participants tried a solution in the TSD at one point or another but only a few small conflicts were solved with it and most did not return to it. One participant noted how large the needed velocity changes were to resolve conflicts and decided other methods were more efficient. Another participant resolved a conflict by decreasing the speed of one aircraft, only to end up in a new conflict when a new aircraft entered behind it, travelling faster. Yet another participant noted how all aircraft always exit the sector at a set time with no conflicts and decided that messing with the speed could therefore create issues where there were none.

The issues brought up somewhat reflect reasoning that causes speed resolutions to be the least applied in current air traffic management, namely needing large velocity changes well ahead of the conflict to have a significant effect and causing the timing of aircraft to be influenced. Though it saw little use, this might not necessarily be an issue with the TSD. It is possible that with larger sectors, where smaller velocity changes can have larger effects, the TSD will be used more often.

Though safety is arguably the most important metric to account for when developing a new air traffic management interface, both experiments resulted in little relevant information about safety, as was predicted with hypothesis III. By only tracking the occasions where things actually go wrong (losses of separation and restricted area incursions), this would have to happen regularly to result in relevant data. When no losses of separation or restricted area incursions happen at all, or only in a very small percentage of cases, one can't compare the safety of one situation to another.

One way of resolving this is making scenarios so dense such that it would be nearly impossible to solve all conflicts all the time. This, however, would result in very unrealistic scenarios that would bear little relevance when looking at real-life scenarios. Alternatively the metric of safety has to be determined another way, such as determining the robustness or flexibility of solutions applied by participants. This would provide insight in safety even when every aircraft remains safe. This was already done to some degree in the original experiment but was outside of the scope of the validation experiment.

The most important observation in terms of efficiency is that, with the experiment with VSD, no delay was introduced in any scenario. Even though the participants had the same access to and instruction about the TSD in both experiments, delays were introduced when there was no possibility of altering altitude. With 4D trajectory management, it is important the flights exit the sector on the right time so conflicts are not created in other sectors due to flights entering too soon or too late. This could cause a lot of unnecessary work for air traffic controllers in the next sector. When the interface causes users to regularly change the moment of sector exit, this should be

resolved before the interface can be a useful 4D trajectory management tool.

With the ability to manipulate altitude, the total added track miles flown was noticeably lower throughout scenarios. Whether adding a certain number of track miles is more efficient than climbing or descending a certain number of feet is more efficient was not considered for this experiment. With a very rough estimate using data from the Base of Aircraft Data (BADA) and its performance model [36], a $1000ft$ climb is about as efficient as adding $1.8nm$ horizontally in terms of fuel consumption. This suggests the solutions applied were slightly less efficient to comparable in the experiment with the VSD available, disregarding the introduced delays in the experiment without VSD. With hypothesis IV, it was expected the efficiency would be increased with VSD. The results do not confirm this for all metrics, but the fact that there was no delay with VSD certainly hints at improvement.

The workload ratings and user activity data suggest workload during the experiment without VSD was lower, especially in the scenarios without restricted area. Besides the lower workload ratings, which are not conclusive by themselves, participants tried fewer solutions before arriving at one they found acceptable, as evidenced by the lower ratio of trajectory edits to actual executions of trajectory changes. This was helped by the fact that, especially in the scenarios without restricted area, the thought-out strategies of the participants could be carried out very consistently, allowing them to resolve conflicts with only a single edit.

Another thing to note about the workload ratings is the increased difference in workload between scenarios with and without restricted area. In the scenarios with restricted area, participants were less inclined to separate traffic in altitude due to the need to deviate traffic horizontally already. Besides the unwillingness to perform both a horizontal and vertical trajectory manipulation, observations during the experiment also suggest that some participants were having trouble combining the two actions the right way. Because of the way the VSD works, combining an altitude change with a horizontal change, the altitude has to be changed first before the horizontal trajectory is changed. On several occasions, participants did this incorrectly. If the way of altering altitude in the VSD were more flexible, this may have been easier for participants and made it more likely they would implement this solution, creating more separation between traffic streams. This could reduce workload in scenarios with restricted areas. The observations do not confirm hypothesis V, as that would require a clear, direct comparison between the experiments. However, the low workload in the scenarios without restricted area and the larger difference with the scenarios with restricted area do confirm the expectation that the largest effect on workload would be in the scenarios without restricted area.

B. Discussion of Experiment

Due to the small scale of the experiment, significant results on the metrics collected can't be found. Though the individual strategies applied can be identified and analysed, no conclusions can be drawn which are and aren't common

strategies. As can be noted in the strategy observations, even when a similar strategy was applied by participants, different individual approaches were used by each participant. On the one hand this is a good sign as the interface should be designed to allow each user to apply their own preferred methods of controlling traffic. On the other hand, with only four participants, no conclusions can be drawn as to whether these observed strategies would be common or rare.

To this end it is recommended a full scale experiment is performed similar to the small scale experiment performed in this project. This way patterns between control strategies can be identified and the most common solution methods can be found. Additionally, significant results can be obtained on safety, efficiency and workload data. As stated before, more appropriate metrics on safety should be chosen. Additionally, to properly judge the efficiency of different solutions, it must be properly determined how efficient different solution types compared to each other (e.g., how efficient is a horizontal trajectory change compared to an altitude change or a velocity change). This way, a judgement can be made on the desirability of different strategies being applied because, for instance, certain strategies might be especially inefficient. If this is identified, changes to the interface might be introduced to discourage certain types of strategies and encourage others.

C. Discussion of Interface

During the experiment the interface held up, performing without serious unexpected behaviour. Aside from some non-critical issues which did not impede functionality the interface performed as required. As the main goal of the experiment was validating the interface, this is the most important takeaway from the experiment. Besides this, observations were made that can help improve the interface in future iterations.

As noted before, the method of changing altitude caused some issues when combining it with a horizontal trajectory change. This negatively impacted workload and performance. By changing the way altitude is altered in the VSD and making this more flexible to work with other parts of the interface, this can be alleviated.

A method that could work and be intuitive is to allow the changing of altitude by dragging the line section of the trajectory up or down instead of dragging the label. This will remove the limitation of only being able to edit the last segment of the trajectory. Besides this, the ability to drag a waypoint up or down, and thereby editing the altitude of the segments before and after the waypoints, can eliminate the need to perform a vertical and horizontal change in a certain order. When starting to grab a waypoint, the two solution spaces on both sides of the waypoint will need to be replaced by one, spanning both segments in order for the user to properly see what they are doing. This functionality could also be applied to the PVD as, currently, dragging a waypoint there does not show the user the right information and was therefore disabled for the experiment.

Another observation noted earlier was the fact that the TSD was used very little. Though it cannot be stated that the TSD in its current form is flawed, this is something that needs to

be investigated in the future. Different scenarios might see the TSD used more or less and perhaps it could be argued that low usage of the TSD is actually the desired outcome.

During the experiment, it was not always immediately clear to the participants which direction one would have to drag the label or a waypoint in the TSD to slow down or speed up the aircraft. This may have been caused by the fact that dragging something up to slow down and down to speed up is somewhat counter-intuitive. This could possibly be resolved by flipping the positions of the VSD and TSD. This way, the vertical axis of the TSD can be logically flipped, making dragging something up mean speeding it up and vice versa. This could help in the natural understanding of the interface. Having the VSD on top would only require the horizontal axis to be at the bottom rather than the top of the display, this would change nothing about the way the display is interpreted.

When further developing the interface, some basic improvements to the VSD could improve the performance and flexibility of implementation greatly. As already mentioned earlier of the interface, enabling the trajectory to be manipulated in the VSD by dragging the trajectory segments up or down can reduce the complexity for the users and increase performance. In a similar vein, and also mentioned earlier, dragging waypoints and properly visualizing the effects of this action in every viewscreen can improve user experience.

Right now the VSD can only implement a standard climb or descent which is the achievable rate for the altitude. Introducing different kinds of climbs and descents for users to implement in the trajectory would likely needlessly add complexity without really improving the interface. However, allowing the interface to work with different sector entry and exit altitudes and also introducing intermediate waypoints from which climbs or descents are set to start or end will be necessary when looking at realistic scenarios the interface will need to be able to handle.

When considering realistic scenarios, other important things to consider are the effects of wind and the average pilot's ability to adhere to the trajectories. Currently, the interface assumes there is no wind and the aircraft always follow the trajectory perfectly, meaning it is entirely deterministic. Wind and uncertainty are important factors to deal with properly when wanting to implement this interface in the real world. Besides this, a good way to test the interface would be to see how a more realistic scenario is handled. An existing sector could be implemented in the interface with traffic as it is encountered in the real world (translated to 4D trajectories).

VII. CONCLUSIONS

The goal of this project was to extend an existing trajectory management interface to include the visualization of altitude and decision making support to manipulate the trajectory in altitude. This was done by adding a Vertical Situation Diagram to the interface. This would make the interface fully 4D, visualizing all the dimensions of the trajectories and enabling manipulation in all four dimensions. Besides this the interface was validated with a small experiment, the results of which were compared to the results of an experiment without VSD

to attempt to say something meaningful about the addition of the VSD.

Using the principles of ecological interface design and the principles of display design, the VSD was designed and implemented into the interface. Special care was taken to ensure that the information presented was consistent and presented in a similar manner as in the existing parts of the interface to optimize visual momentum. The resulting interface allowed for and supported full 4D trajectory manipulation with a limited increase in complexity.

The interface performed as intended during the experiment. Participants applied recognisable strategies to control the scenarios and the VSD was used as intended, though more flexibility in manipulating the trajectories in the VSD could have been beneficial. A comparison with an experiment without VSD hints at a decrease in workload for participants while solving conflicts at least as efficiently, if not more efficiently. No meaningful observations could be made comparing performance in terms of safety, as no significant safety data was found.

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Part II

Thesis Book of Appendices

Appendix A

Literature Survey¹

This chapter presents the review of literature done before the design project. This review helps frame the project and its relevance in the field of air traffic management, looking at the trend of research in the field, projects with similarities to this design project, and research which helps inform the project.

Section A-1 takes a look at the current state of air traffic management and the research being done in the field. A closer look is taken at 4D air traffic management in Section A-2. Section A-4 details the travel space representation (TSR) interface which will be expanded upon in this project.

A-1 Current State of Air Traffic Management

Before going ahead and designing something new, it is important to understand what the field of air traffic management looks like today. In Subsection A-1-1 the current strategies of air traffic controllers are detailed, which will help determine what could be important for them in a new management method or interface. Subsection A-1-2 tries to paint a picture of where air traffic management is going in the future. Subsection A-1-3 analyses the problem of the acceptance of automation in the air traffic management field.

A-1-1 Air Traffic Management Strategies

Air traffic management is currently performed with a relatively low level of automation. Air traffic controllers have access to a top down radar view of the sector and know the position, speed, orientation and altitude of the aircraft inside the sector. An example of a current interface used by air traffic controllers is shown in Figure A-1. Using this information the air

¹*The content in this chapter has been graded as part of the preliminary thesis report under AE4020.*

traffic controller has to extrapolate whether or not two or more aircraft will be in conflict in the future and, if so, devise a suitable solution to the conflict.

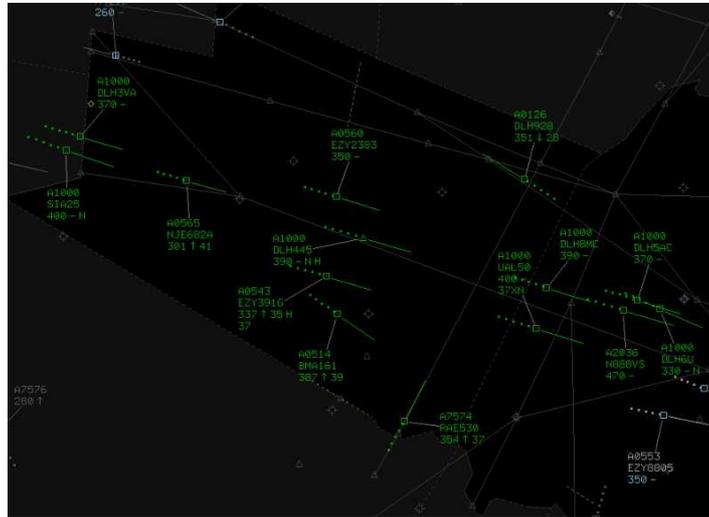


Figure A-1: Part of the Upper Area Control sector of Maastricht radar screen (Eurocontrol, 2012)

To do this, air traffic controller have developed their own systems and methods to do this efficiently and effectively (Rantanen & Nunes, 2005). Though many different methods exists, and the method employed by the air traffic manager often comes down to personal preference, certain standard practices exist and patterns can be identified (Fothergill & Neal, 2013) (D'Arcy & Rocco, 2001).

Air traffic controller often analyse their sector in a standard pattern (clockwise, top to bottom), grouping aircraft together based on certain characteristics like a similar altitude or direction of flight (Rantanen & Nunes, 2005). These kinds methods can make it easier to identify potential conflicts and their priorities, even in relatively busy scenarios.

To solve conflicts, certain standard solutions can also be identified (Fothergill & Neal, 2013). In the simplest form, conflicts are resolved by issuing a change in altitude, speed, direction or a combination of the three to one or more aircraft. For most conflicts and air traffic controllers, issuing a change of altitude is the preferred solution (Fothergill & Neal, 2013). Compared to other options, an altitude change can be easily analysed for potential conflicts with other flights and can yield results quickly. A velocity change often only works for conflicts that are still a long time away unless the change in velocity is very large. Directional changes can solve conflicts quickly but can become chaotic and cause new conflicts in complex scenarios. With the current system of air traffic management, some basic automation is being applied. Short Term Conflict Alerts (STCA) can predict trajectories up to 2 minutes ahead and give an alert if any conflict is found (Eurocontrol, 2009). This is used as a safety net function. Other forms of automation which have not been implemented but have had trials include Medium Term Conflict Detection (MTCD) (Eurocontrol, 2018), which could look ahead up to 20 minutes and only used flight plan data and controller input, and the Tactical Controller Tool (TCT) (Leone, 2009), which looked ahead from 5-8 up to 20 minutes, using surveillance data and provided conflict resolutions.

With the increase in air traffic movements over the years (STATFOR Team, 2017), the density of the average airspace will increase more and more. This provides problems for the current state of air traffic management because every aircraft added to a sector increases the complexity exponentially (because every aircraft in the sector could be in conflict with any of the other aircraft). This could quickly cause the workload for air traffic managers to become too high to handle and new methods will need to be implemented to prevent this.

A-1-2 Envisioned Future of Air Traffic Management

There are two major initiatives trying to modernize air traffic management are NextGen by the Federal Aviation Administration (FAA) in the United States of America (FAA, 2014) and Single European Sky ATM Research (SESAR) (SESAR JU, 2015), funded by the European Union, Eurocontrol and the industry. Both initiatives run a wide range of research projects involving the future of air traffic management with the most important aims among both being to increase airspace capacity, safety, efficiency, and reduce environmental impact.

Whether it is researching the possibility of free flight (Duong & Zeghal, 1997) (Paielli & Erzberger, 1997), drastically increasing sector size (or doing away with them altogether) (Korn et al., 2009) (Birkmeier, Korn, & Kügler, 2010), generating optimal conflict resolutions (Erzberger, 2005), or increasing cooperation between the flight deck and the air traffic controller (Korn & Kuenz, 2006), the role automation needs to play to achieve the goals will need to greatly increase. With a larger role for automation, the air traffic controller's role will have to change as well (Prevot, Homola, Martin, Mercer, & Cabrall, 2012).

With the introduction of new systems as Automatic Dependent Surveillance-Broadcast (ADS-B) and System Wide Information Management (SWIM), which are already being implemented in some form (FAA, 2014), more information will be available to air traffic controllers and pilots on the flight deck. Because of this, different data can be used to detect and resolve conflicts. For instance, instead of extrapolating a conflict from a heading, velocity, and altitude, intent information or complete trajectory information can be used to determine conflicts and show them to the air traffic controller and/or the pilot.

Going a step further, detected conflicts could also be solved by an algorithm. Knowing the intended trajectory of every aircraft in the sector, a number of conflict resolutions could be generated and scored on their robustness, using the best solution to resolve the conflict. Moreover, because these trajectories can be known before flight will even take off, this kind of conflict resolution could even be performed well ahead of the flight.

Of course, this amount of automation causes its own kind of issues (Hilburn, Parasuraman, Jha, & McGarry, 2006). When problems occur, air traffic controller might not have the oversight to spot them or the skill to resolve them. To leave humans out of the loop in such a safety-critical process as air traffic management would require the automation to work all but perfectly in every situation.

A-1-3 Automation Acceptance in Air Traffic Management

When implementing automation in any system it is important to understand how humans would interact with and respond to this. Simply replacing parts of the human task can often lead to undesirable effects, especially if this is done in an opaque manner (Hilburn et al., 2006). This can lead to reduced understanding of the system by the user and reduced

trust. If the automation takes over too much of the user's tasks, this can lead to vigilance problems and skill degradation, which would make the user unable to deal with problems the automation cannot handle (Metzger & Parasuraman, 2001).

Because of these issues, it is important to understand how automation affects the user and what makes air traffic controllers accept automation.

A large factor in automation acceptance is one that seems rather obvious: reliability. It is clear that if the automation does not perform to a certain standard, its acceptance will be very low. Research has also shown, however, that introducing imperfect automation could cause conflicts to be missed that would have been caught without any automation (Metzger & Parasuraman, 2005) (Rovira & Parasuraman, 2010).

What this implies is that it is important for the operator to remain actively involved in the system and the decision making. This will allow them to retain situation awareness and catch potential automation malfunctions early. What this also does is leave the operator in control of their own decision making with the automation supporting the ability to make effective and fast decisions instead of making them for the operator (Metzger & Parasuraman, 2001). Setting up automation to support air traffic controllers' decision making can also make it easier for the controllers to adapt to the automated system. This way, the controllers can largely apply their own control strategies, using the automation system as validation for their own decisions and a way to more quickly gain insight in the situation (Merritt & Ilgen, 2008).

A-1-4 Future Air Traffic Structures

When choosing traffic structures with which to test a future air traffic management interface, it is best to use realistic potential air traffic structures. To this end, the research of the METROPOLIS project will be used as a guideline for plausible future air traffic structures (Sunil et al., 2015). This project investigates the airspace under extremely high density conditions with a focus on urban areas, but the proposed structures can be applied as plausible solutions under less extreme circumstances, as the relation between traffic structure and capacity in general is also analysed.

Four airspace structures are defined with increasingly strict structuring (Sunil, Ellerbroek, et al., 2016). These structures are presented in Figure A-2.

With full mix, the airspace is completely unstructured. There are no restrictions on how a trajectory can be planned, meaning trajectories will mostly be planned to optimize fuel consumption and trip time.

The layered concept is reminiscent of air traffic control practices in place today (hemispheric rule (International Civil Aviation Organization, 2005)), but applied to a finer degree. The airspace is vertically segmented in layers. Each layer only allows travel across a certain range of headings (e.g. 0° - 45°). This separates crossing aircraft by altitude but limits the vertical freedom of a trajectory.

The zones concept is similar to the layers but, instead of constraining the altitude, the horizontal positions are constrained. Aircraft follow pre defined horizontal airways, which increases path length from the ideal trajectory, but are free to choose their ideal altitude.

With tubes, the airspace is maximally structured. Trajectories have to run between nodes

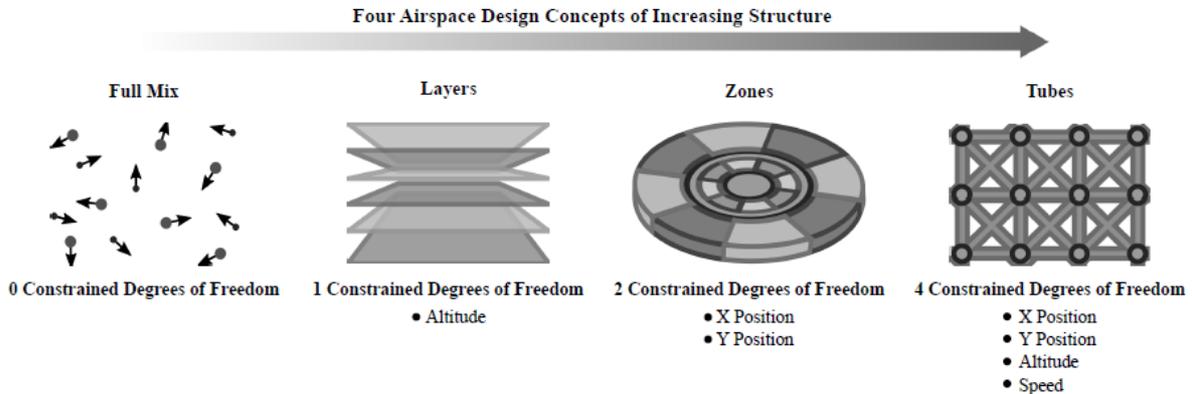


Figure A-2: Proposed air traffic structures analysed by the METROPOLIS project (Sunil, Ellerbroek, et al., 2016)

in the tubes and are not only position, but also time constrained. This is done to ensure separation between the nodes. Though this concept bears similarities with 4D trajectory management, the tubes are not the same. They represent a framework through which a 4D trajectory must be drawn. As such, it limits the options of a planned 4D trajectory. Simulations have shown the zones and tubes concepts to perform poorly in comparison to the others (Sunil et al., 2015) (Sunil, Ellerbroek, et al., 2016) (Sunil, Hoekstra, et al., 2016). This was to such a degree that it will be excluded when testing the interface.

A-2 4D Air Traffic Management

This section details the concept of 4D air traffic management which is at the core of the interface, as 4D air traffic management capabilities are necessary to enable trajectory based operations. The concept of 4D air traffic management is explained in Subsection A-2-1. Subsection A-2-2 provides a glimpse into the many applications of 4D air traffic management and the research being done in the field.

A-2-1 4D Air Traffic Management Meaning

The idea behind 4D air traffic management is managing the full four dimensional trajectory of an aircraft during its flight. The four dimensions in question are position (latitude, longitude, altitude) and time (SESAR Joint Undertaking, 2010). This means that at any point in flight the position of the aircraft will be known in advance, and any conflict with another aircraft will be known.

To apply this, 4D trajectories need to be created for flights in advance. These are referred to as Reference Business Trajectories (RBTs) (Eurocontrol, 2014). These can be analysed and de-conflicted before the flight takes off and used en-route to predict any emerging conflicts or needed re-routing due to, for instance, bad weather.

The potential advantages of 4D trajectory management are many (Eurocontrol, 2014) (Enea & Porretta, 2012). Using time as a dimension in the creation of the trajectory, delays become

more predictable. Most potential conflicts are resolved before the flight, resulting in fewer en-route trajectory changes. This would likely result in lower fuel consumption and fewer delays. The improved predictability and decreased amount of en-route conflicts would also improve the ability of air traffic managers to handle larger amounts of traffic.

Implementing 4D trajectory management would require the introduction of new technology. Systems like ADS-B, SWIM, and a digital uplink between controller and flight deck are required to be able to give controllers access to 4D trajectories, to track pilot's adherence to their trajectories and allow controllers to send trajectory updates (Eurocontrol, 2014) (Enea & Porretta, 2012).

The benefits of 4D trajectory management also depend on its level of implementation (Eurocontrol, 2014). If the system is only applied in certain sectors or only a certain fraction of aircraft are able to use it, many of the advantages become minor or disappear completely. Conflicts between flights with a full 4D trajectory and a flight without would still have to be resolved, delays and disturbances in sectors not using 4D trajectory management would be unpredictable and carry over to the rest of the flight route.

A-2-2 Applications of 4D Trajectory Management

4D Air traffic management can be applied in a variety of ways. The majority of the applications of 4D trajectory management are strategic, as the idea is mostly to plan ahead rather than to react to emerging conflicts. In Figure A-3 all the phases through which 4D Trajectory Management can be applied are shown. The interface which is the primary focus of this project is more tactical in nature, the only phase in which it is used is the execution phase. This interface will be discussed in Section A-4.

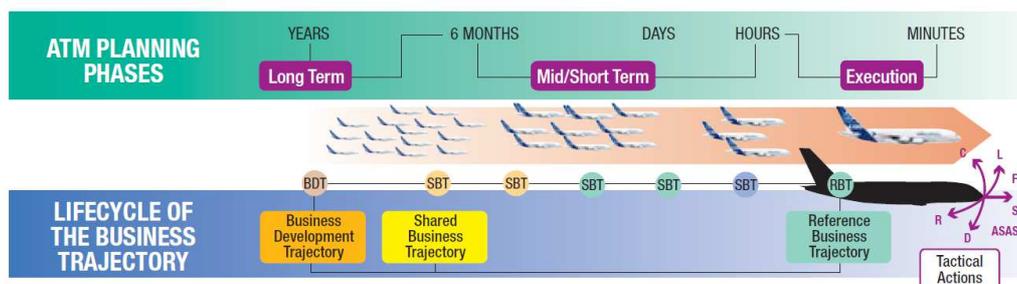


Figure A-3: Desired future planning phases and accompanying business trajectories (SESAR Consortium, 2007)

One application is the de-conflicting of trajectories in advance of the flight. (Tang, Zhang, Chen, Li, & Han, 2016) Here, arrival and departure time adjustments are used to generate trajectories which are conflict free with minimal sensitivity to possible perturbations. Tested in simulations it has shown the ability to de-conflict flights, though it is limited by only being able to make temporal changes.

The automatic generation of 4D trajectories has also been a subject of research (Ramasamy, Sabatini, Gardi, & Liu, 2013) (Gardi, Sabatini, Kistan, Lim, & Ramasamy, 2015) (Gardi, Sabatini, Ramasamy, & Ridder, 2013). The trajectory generation system receives desired flight paths from multiple flights and negotiates an optimized trajectory for all these, solving

possible conflicts. This could provide solutions without conflicts, but would leave human operators out of the loop. An operator would likely not be able to see why certain decisions have been made, reducing their situation awareness and capability of responding to system errors.

As part of Eurocontrol's the PHARE project (SESAR's predecessor) (Van Gool & Schröter, 1999), 4D trajectory management was investigated as well. To this end the HIPS (Highly Interactive Problem Solver) was designed (Meckiff & Gibbs, 1994). This interface allowed an air traffic controller to manipulate trajectories and visualised "no-go" areas where the flight would be in a conflict. However, the way these no-go areas changed when changing the trajectories was very unpredictable to the controller, making conflict resolution more like trial and error than making informed decisions.

It is also possible to bring 4D trajectory management to the flight deck (Marwijk, Borst, Mulder, Mulder, & Paassen, 2011). This would allow pilots to manipulate their own trajectories in order to, for instance, navigate around weather cells. With further development this could have the potential of moving most, if not all, en-route air traffic control tasks to the flight deck.

One application is applying 4D air traffic management in a 3D representation of the sector (Amaldi et al., 2005). A concept for this is shown in Figure A-4. Instead of multiple 2D views, this tries to show a world where the controller can move around in. Trajectories, flights, waypoints, etc are all visible in 3D space. Whether this method has any actual added value remains to be seen as any experiments have not progressed beyond proof of concept and demonstration experiments.

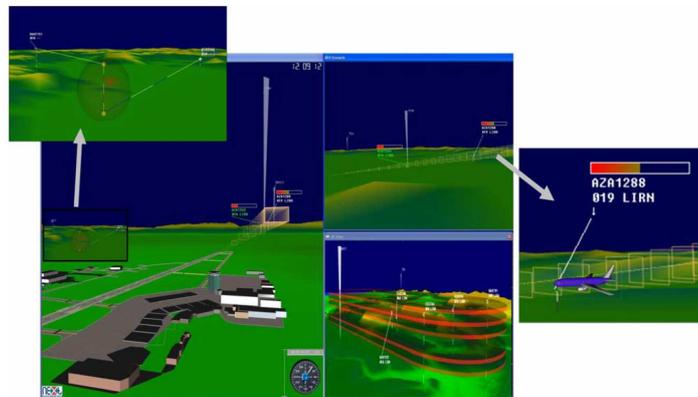


Figure A-4: Concept of the 3D representation of a 4D air traffic management system (Amaldi et al., 2005)

A-3 Display Design Principles

When designing an interface it is important to be able to reason why certain elements should look the way they do. There may not be a rulebook that can be followed step by step that leads to the exact interface that is needed, but there are certain principles and logic that can help rationalize decisions.

To explore the ecology and the needed functionality of the interface and the capabilities of

the user of the interface, a cognitive work analysis (CWA) can be performed. This can be used when trying to apply principles of ecological interface design (EID). What a CWA is, how its components work, and how it is implemented for the interface is shown in detail in Appendix B, what EID entails is explained in Subsection A-4-3.

In Subsections A-3-1 and A-3-2, principles of display design are discussed. These principles were applied where possible when designing the interface, more detail on this can be found in Appendix D. Subsection A-3-3, the concept of situation awareness and how it could be measured is discussed.

A-3-1 13 Principles of Display Design

A very important, and occasionally overlooked, factor when designing an interface is the humans who will use it. It is their strengths and weaknesses that will determine what elements of the interface will be useful and how. Principles that help determine this are commonly referred to as the 13 principles of display design (Wickens et al., 1998). These principles can be grouped in four categories: perceptual, attention based, mental model, and memory.

Perceptual principles range from the essential principle that the display be legible to avoiding absolute judgement limits and presenting important information in multiple forms to introduce redundancy. Put very simply, it must be hard to misinterpret a signal to mean another and it must be as clear as possible what a certain signal means.

Attention based principles concern the grouping of signals. Presenting similar information grouped orderly can reduce the effort it takes for the user to move between these sources of information. Grouping similar information visually can also make it easier to spot values that are out of the ordinary.

Mental model principles are about presenting the information in a way with the perception of the real situation in the user's head. A simple example is showing the altitude of an airplane on a vertical scale (like on the primary flight display) instead of on a circular display (like the analogue altimeters).

The principles of memory concern the balance of information that is shown on the display and what needs to be remembered. Also aiding the user in predicting the future state of the display and applying consistency between displays can improve the interface.

A-3-2 Visual Momentum

Besides the 13 principles of display design another concept can be used which applies to designing an interface with multiple displays. This is the concept of visual momentum (Woods, 1984). The principle of visual momentum concerns the ability of the human to gain and use relevant information from multiple displays.

Visual momentum is a measure to tell how easy it is for a user to refocus their attention from one display to another and integrate information to create a bigger picture. Influencing factors are how much attention a display grabs, how hard it is to extract the relevant information from a display, how consistent displays are with information presented (also seen in the 13 principles of display design), and how hard it is to integrate the information

presented in one display into the information gained from the display(s) viewed previously. Low visual momentum can cause the perceived workload of the user to increase because of the harder mental task of switching between displays. It can also cause the user to focus their attention on one, or a subset, of the displays, completely ignoring some parts. When this happens the parts that are ignored could be too complex or too different from the rest of the interface to be of any use. This could cause the user to miss vital data because it was presented in too obtuse a manner.

A-3-3 Situation Awareness

Situation Awareness (SA) is a measure of understanding the user has with respect to the system they are controlling. It includes being able to perceive the elements of a system, understanding what they mean and being able to think ahead and understand the consequences of changing certain elements. The framework of SA, as defined by Endsley (Endsley, 1995b) (Endsley, 1995a), defines three levels of SA. Perception, being able to perceive the elements, attributes and state of the system. Comprehension, understanding the implications of and relations between the elements defined in the first level. Projection, being able to predict future states and consequences of actions taken in the system.

Being able to measure the level of SA of a user of a system can provide very useful insights. It can help determine whether a user is taking an action because they understand what they are doing or because that option was coloured green, which means it was good (without understanding why this option was green).

Actually measuring SA, however, does come with some issues (Endsley, 1995a) (Durso & Gronlund, 1999). As SA is a measure of the user's understanding of the system, getting an objective measurement of this is problematic. To get a measure of SA, two important systems have been developed.

A self report system has been developed by Taylor, the Situation Awareness Rating Technique (SART) (Durso & Gronlund, 1999) (Taylor, 1990). This is able to provide some measure of SA but is subjective and, besides the common problems of subjective measures, there can be a difference between subjective and actual SA which could also indicate problems with the system (Durso & Gronlund, 1999).

A more objective measure is the Situation Awareness Global Assessment Technique (SAGAT) (Endsley, 1988) (Endsley, Selcon, Hardiman, & Croft, 1998). With SAGAT the simulation is frozen periodically to present the subject with a number of questions relevant to the simulation, the answers of which provide an indication of the subjects level of SA. These questions need to be specific to the system that is being simulated and in-depth enough to cover all levels of SA. Though SAGAT is objective, it does require freezing the simulation, which may be intrusive, and may depend heavily on the subject's memory (Sarter & Woods, 1991), though the significance of these disadvantages may be minor (Endsley, 1995a).

A-4 Travel Space Representation

The travel space representation interface is the interface which will be expanded upon in this research project. Subsection A-4-1 details the idea behind the travel space representation

interface and relevant previous research. The specific interface which will be expanded upon is shown in Subsection A-4-2. The ecological rationale behind the interface is expanded upon in Subsection A-4-3.

A-4-1 Travel Space Representation Definition

The travel space representation interface has been designed to use pre-planned RBTs which have, theoretically, been de-conflicted beforehand (Klomp et al., 2012) (Paassen et al., 2013). Because of en-route perturbations in the trajectory of emergent environmental factors such as weather, real-time re-routing is necessary to resolve emerging conflicts and evade bad weather.

The time and horizontal location where an aircraft leaves the sector need to be a hard constraint in order to prevent re-routing to cause perturbations in the trajectory to carry over to the next sector. With this in mind, a solution space can be generated on the horizontal plain based on the aircraft's performance characteristics. Any place in this solution space can be reached by the aircraft while still being able to reach the sector exit location at the right time. Possible conflicts within this travel space can be visualized to show a safe field of travel. (Paassen et al., 2013) (Klomp et al., 2012) (Klomp, Borst, Paassen, & Mulder, 2016) Instead of re-routing an aircraft, a conflict might also be solved by adjusting the speed of an aircraft (Klomp et al., 2012). This can also be visualized by showing the distance remaining versus time remaining to the sector border. In this visualization, the minimum and maximum speed can be used to generate another travel space which shows the range of solutions when adjusting only velocity.

Experiments performed with the existing interface have yielded promising results. Though points of improvements remained, users seemed to be able to solve conflicts effectively with a sufficient degree of situation awareness. Expert air traffic controllers were able to make more effective use of the interface's capabilities than novice users, taking a more active approach and providing more robust solutions (Klomp et al., 2016).

The visualization of the travel space and how it is utilized in the interface is clarified in Subsection A-4-2 and the rationale behind the TSR is clarified in Subsection A-4-3.

A-4-2 Interface Layout

The interface is shown in Figure A-5. On the left side, the top down plan-view display (PVD) is shown, reminiscent to existing air traffic controllers' radar screens. On the top right is the time space diagram (TSD), showing the remaining track length on the x-axis and the time in seconds in the y-axis. The bar on top shows whether the simulation is running, the time passed in the simulation and contains buttons to control the simulation speed.

The plan-view display shows a top view of the sector. The aircraft are shown on their horizontal position in and around the sector. Each aircraft is labelled with their identification code, the flight level and sector exit waypoint are shown underneath. Beneath that is the aircraft type. The red area in the sector is restricted airspace. This could resemble weather

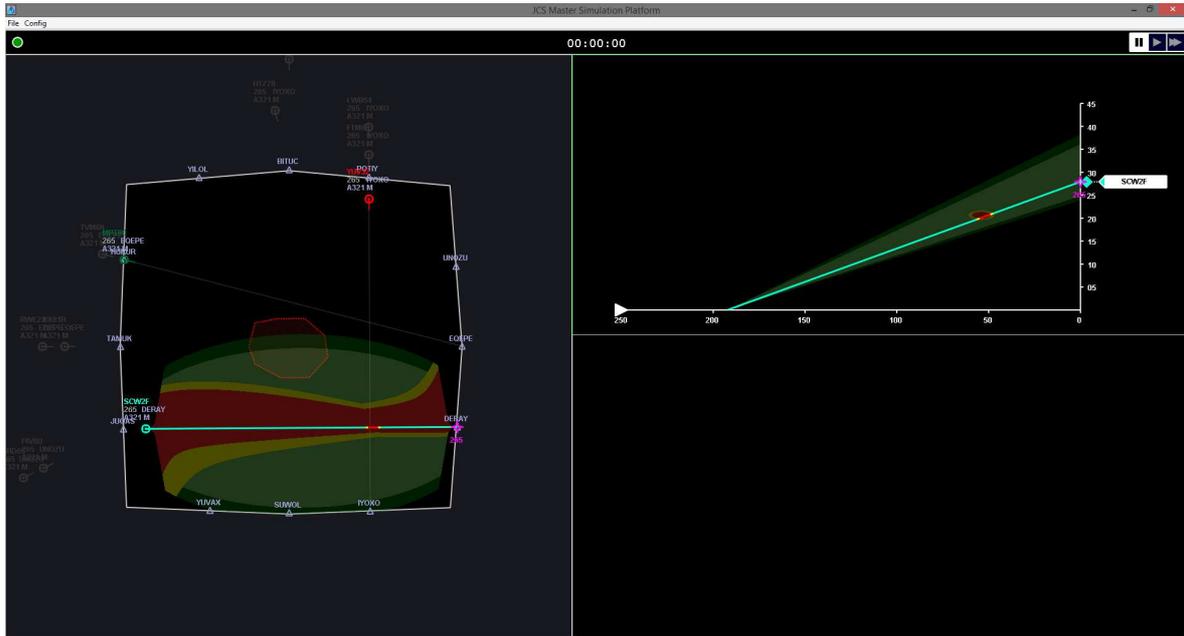


Figure A-5: Current Travel Space Representation Interface

or airspace which has been closed for any other reason.

When an aircraft is selected, it and its trajectory are highlighted. The available travel space also appears, which is the red, yellow, and green area in Figure A-5. This area represents all the locations a waypoint could be placed to divert the aircraft with it still being able of reaching the exit waypoint on time. On its current trajectory the aircraft in the figure is in conflict, as is evident from the red part of the trajectory. Hovering the mouse over this part highlights the aircraft with which it is in conflict (in this case YUV32). Placing a waypoint in the red area of the travel space changes the trajectory such that the conflict is not resolved, a waypoint in the green area will resolve the conflict. Diverting the aircraft with a waypoint in the yellow area means the conflict would be resolved, but the separation between the aircraft would be minimal. This could quickly result in a new conflict if the trajectory (including speed) is not followed exactly by any of the two aircraft.

The time space diagram shows the trajectory of a selected aircraft in time and along track distance. The x-axis shows the distance remaining to the sector's edge and the y-axis shows the time remaining. As with the plan-view display, the detected conflict is shown in red.

Waypoints can be placed in the time space diagram the same way as in the plan-view display. Instead of altering the heading, the velocity is altered. To avoid the given conflict, for instance, a waypoint could be placed beneath the red area, which means the aircraft would fly at a higher velocity up to that point and then slow down to arrive at the sector's edge at the right time. The aircraft would then pass in front of the aircraft with which it was in conflict.

A-4-3 Ecological Rationale

The travel space representation interface has been designed with the principles of ecological interface design in mind (Paassen et al., 2013). The idea behind this is to make sure the interface's user, though supported by automation, remains aware of the work environment and the meaning of the actions they are performing (Vicente & Rasmussen, 1992) (Flach, Tanabe, Monta, Vicente, & Rasmussen, 1998). By visualising a constrained solution space, the user's decision own making is supported instead of supplanted.

The goal is to support the user with automation while trying to avoid common pitfalls of introducing more automation. These are commonly referred to as the "ironies of automation" (Bainbridge, 1983). In short, automating basic controller tasks leaves the human operator in a supervisory role making lapses in concentration and over-reliance on the automation likely, causing skill degradation for the operator's basic skills, lowering their situation awareness due to not being actively involved, causing high workload peaks in situations the automations can't handle (which were already the most difficult situations for the operator to begin with), and increasing system complexity which could potentially obscure problems with the system. With EID it is the goal to alleviate these issues by connecting the user with the automation in a way that keeps them involved and aware of the work environment without making the task harder (Vicente & Rasmussen, 1992). Possible actions are presented by showing the constraints of the solutions. When using the interface, the user has to solve every conflict actively. Doing this increases the likelihood the user is constantly aware of the situation in the sector. When unanticipated events occur, they can intervene and will know what they are doing. Skill degradation and vigilance problems don't occur because the operator is actively making decisions.

The TSR interface also presents the entire range of solutions to the user instead of presenting one or a set of "ideal" solution(s). This allows operators to apply their own logic and preferred methods to the problem, using the automation to validate their own solution. This could be especially helpful with existing air traffic controllers transitioning to a new kind of interface.

When expanding the interface it is important to follow similar logic and understand why the current parts function as they do. This way a new view-port can be complementary to the existing ones rather than disrupting.

Appendix B

Cognitive Work Analysis

To inform the design decisions made to reach a valuable interface, a cognitive work analysis will be performed. By doing this, the required functions and environment of the interface, and the interaction between the interface and the user are analysed. This will help in deciding what is important to include in the interface and how information should be presented to the user. (Bisantz & Burns, 2008) (Lintern, 2009)

The CWA commonly consists of five parts, ranging from analysing the system environment to the capabilities of the user. The steps are detailed in Sections B-1-B-5, initial analysis of the TSR interface to be designed is shown to help sketch the steps.

B-1 Work domain analysis

With a Work Domain Analysis (WDA) the ecology, or environment, of the system is analysed. Starting with identifying the most basic purpose of the system, more specific functions can be identified. Relationships between functions and purposes can be identified. This analysis is only focussed on the work domain and is independent of possible users or interfaces. The WDA will help create a structured view of the work domain which will help in designing the elements which will make up the interface to fit the ecology.

To visualise a work domain analysis an Abstraction Hierarchy can be constructed. On the top level the basic purposes of the system are identified. The functions needed to achieve these goals are shown in the level underneath. Going down through the levels, each level becomes less abstract and more concrete until the lowest level shows the physical form of the work domain.

The items in each level show the purpose of the items in the level below it and are the means with which the items in the level above it can be achieved. These relationships create a connection between the purpose of the system to the physical characteristics of the work domain.

Expanding the abstraction hierarchy, the elements of the work domain can also be decomposed from the whole to the part. This combination of abstract to physical and whole to

part is called an Abstraction-Decomposition Space. An Abstraction-Decomposition Space for the current work domain is shown in Figure B-1. From top to bottom this is still an abstraction hierarchy, but the work domain is now also broken down into its parts going from left to right.

This work domain analysis shows the elements that would need to be present in a future 4D perturbation management ATC system. Besides the vertical elements, they can all be found in the existing interface. What needs to be included, therefore, are the elements that allow for observation and manipulation of the altitude components of the trajectories.

	Future Air Traffic Control System	Airspace	Sector	Aircraft
Functional Purpose	<div style="display: flex; flex-wrap: wrap; gap: 5px;"> <div style="border: 1px solid black; padding: 2px;">Productivity</div> <div style="border: 1px solid black; padding: 2px;">Safety</div> <div style="border: 1px solid black; padding: 2px;">Efficiency</div> </div>			
Abstract Function	<div style="display: flex; flex-wrap: wrap; gap: 5px;"> <div style="border: 1px solid black; padding: 2px;">Locomotion</div> <div style="border: 1px solid black; padding: 2px;">Separation</div> <div style="border: 1px solid black; padding: 2px;">Economy</div> </div>	<div style="border: 1px solid black; padding: 2px; text-align: center;">Horizontal & Vertical Locomotion</div> <div style="display: flex; justify-content: space-around; margin-top: 5px;"> <div style="border: 1px solid black; padding: 2px;">Network Constraints</div> <div style="border: 1px solid black; padding: 2px;">Airway Flows</div> </div>		
Generalized Function		<div style="border: 1px solid black; padding: 2px; text-align: center;">Horizontal & Vertical Constraints</div> <div style="display: flex; justify-content: space-around; margin-top: 5px;"> <div style="border: 1px solid black; padding: 2px;">Perturbations</div> <div style="border: 1px solid black; padding: 2px;">4D Trajectories</div> </div>	<div style="display: flex; flex-wrap: wrap; gap: 5px;"> <div style="border: 1px solid black; padding: 2px;">Sources & Sinks</div> <div style="border: 1px solid black; padding: 2px;">Obstacles</div> <div style="border: 1px solid black; padding: 2px;">Borders</div> </div>	<div style="display: flex; flex-wrap: wrap; gap: 5px;"> <div style="border: 1px solid black; padding: 2px;">Horizontal Flight Performance</div> <div style="border: 1px solid black; padding: 2px;">Vertical Flight Performance</div> <div style="border: 1px solid black; padding: 2px;">Horizontal Flight Profile</div> <div style="border: 1px solid black; padding: 2px;">Vertical Flight Profile</div> </div>
Physical Function			<div style="border: 1px solid black; padding: 2px; text-align: center;">Weather & Other No Fly Zones</div> <div style="display: flex; justify-content: space-around; margin-top: 5px;"> <div style="border: 1px solid black; padding: 2px;">Source & Sink Waypoints</div> <div style="border: 1px solid black; padding: 2px;">Traffic</div> </div> <div style="border: 1px solid black; padding: 2px; text-align: center; margin-top: 5px;">Horizontal & Vertical Sector Limits</div>	<div style="display: flex; flex-wrap: wrap; gap: 5px;"> <div style="border: 1px solid black; padding: 2px;">Waypoints</div> <div style="border: 1px solid black; padding: 2px;">Speed Envelope</div> <div style="border: 1px solid black; padding: 2px;">Turn Performance</div> <div style="border: 1px solid black; padding: 2px;">Acceleration Performance</div> <div style="border: 1px solid black; padding: 2px; text-align: center;">Climb & Descent Performance</div> </div>
Physical Form			<div style="border: 1px solid black; padding: 2px; text-align: center;">Weather & Other Location & Size</div> <div style="display: flex; justify-content: space-around; margin-top: 5px;"> <div style="border: 1px solid black; padding: 2px;">Source & Sink Waypoint Locations</div> <div style="border: 1px solid black; padding: 2px;">Traffic Trajectories</div> </div> <div style="border: 1px solid black; padding: 2px; text-align: center; margin-top: 5px;">Horizontal & Vertical Sector Geometry</div>	<div style="display: flex; flex-wrap: wrap; gap: 5px;"> <div style="border: 1px solid black; padding: 2px;">Min & Max Speeds</div> <div style="border: 1px solid black; padding: 2px;">Waypoint Locations & RTAs</div> <div style="border: 1px solid black; padding: 2px;">(Max) Turn Rate</div> <div style="border: 1px solid black; padding: 2px;">Max Acceleration & Deceleration</div> <div style="border: 1px solid black; padding: 2px;">Rates of Climb</div> <div style="border: 1px solid black; padding: 2px;">Rates of Descent</div> </div>

Figure B-1: Abstraction-Decomposition Space for a future 4D perturbation management air traffic control system. (Means-ends links omitted for clarity)

B-2 Control Task Analysis

The work domain analysis has provided some information on the environment of the system. The control task analysis focusses on the goals a user will want to achieve with the system and how certain tasks could be approached. This can help determine the information a user needs to use the system properly and how a user might be more effective.

The control task performed with the system can be mapped onto a decision ladder which

visualized the decision process. The decision ladder showing the task of solving a conflict with the TSR interface is shown in Figure B-2.

Starting at, or near, the bottom left a situation occurs that prompts the user to take action. The user observes there is a situation that requires action and identifies the problem. A solution has to be formulated, whether by going all the way up the ladder, formulating a solution using knowledge based behaviour, or using a shortcut, for instance by recognising the situation and using a solution the user has already applied many times before. A situation could also be observed for which a standard procedure exists, which would utilise rule based behaviour. This had been omitted from the ladder as no standard procedures have been formalised for the TSR interface, but rule-based behaviour could also emerge from experience as users apply the same knowledge-based logic over and over again until it becomes familiar enough. Either way a task needs to be performed and a procedure is formulated and executed. Activation can occur when a conflict between aircraft is detected and the involved aircraft turn red. A user can also observe an aircraft that may require deviation for a different reason (e.g. a possible incursion in restricted airspace), in which case the decision process starts at the observe stage. If it should occur that the possible conflict is so close immediate action is needed, the user will not consider more details on the conflict or find the most ideal solution but take immediate action, taking the bottom shortcut in the figure.

Otherwise, the user can observe the current situation and identify the conflict, which other aircraft or restricted zones are involved and how far the problem is. If the identified situation is familiar, the user may already know a suitable action to resolve the situation and take the middle shortcut in the figure. With the system state identified, the user can apply knowledge based behaviour to formulate a desired solution, this is depicted in the top loop of the figure. If a user applies similar logic many times over, they may develop rule based behaviour and use the top shortcut in the figure.

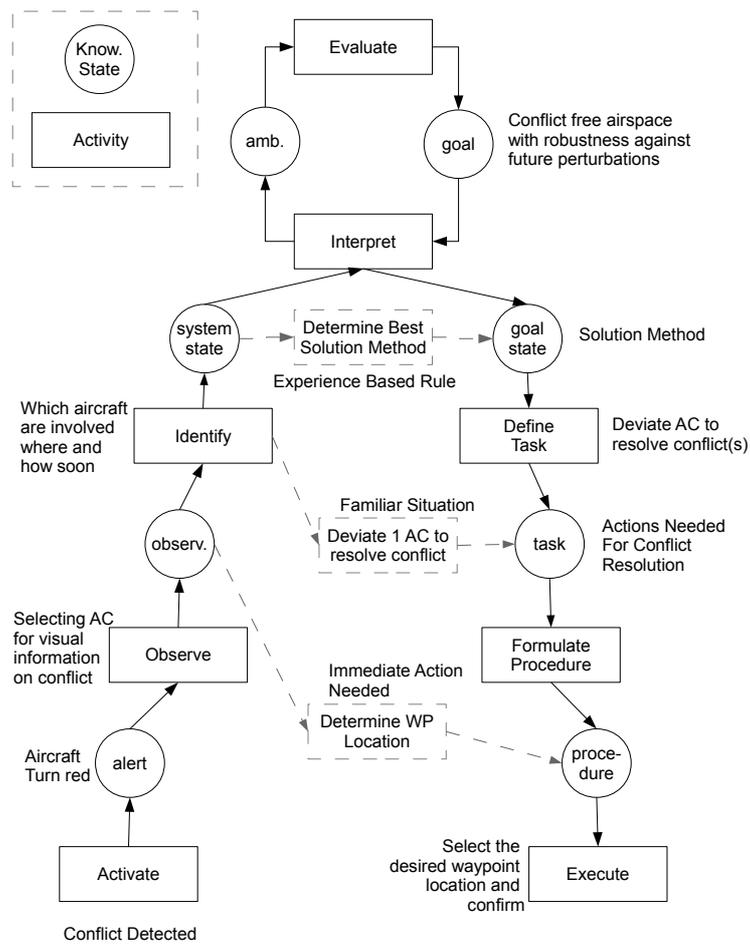


Figure B-2: Decision ladder for the TSR interface.

B-3 Strategies Analysis

A strategies analysis is performed to find out how a certain control task can be achieved. This can be visualized with an information flow map of a specific control task. The flow map shows the steps followed through a certain task in rectangles. It does not show the actors that are performing the task but the method that is used. The information used at the steps is shown in circles. Four main strategies have been identified that might be used to resolve conflicts in an airspace with the interface.

The first identified strategy is identified as resolving conflicts by structuring traffic by altitude, meaning that when a conflict is detected it is resolved by altering the altitude of one or both (cooperative solution) aircraft dependent of the traffic stream (e.g. aircraft from a north-south stream are consistently sent up 1000ft if in conflict with aircraft from a east-west stream). The information flow map for this strategy is shown in Figure B-3. When a conflict is detected, the aircraft is selected and the travel space is analysed. An altitude change is implement congruent with the way the user has chosen to implement the strategy. After this a horizontal change might be necessary dependent on the perturbations in the sector. If the user is satisfied with the solution, it is confirmed.

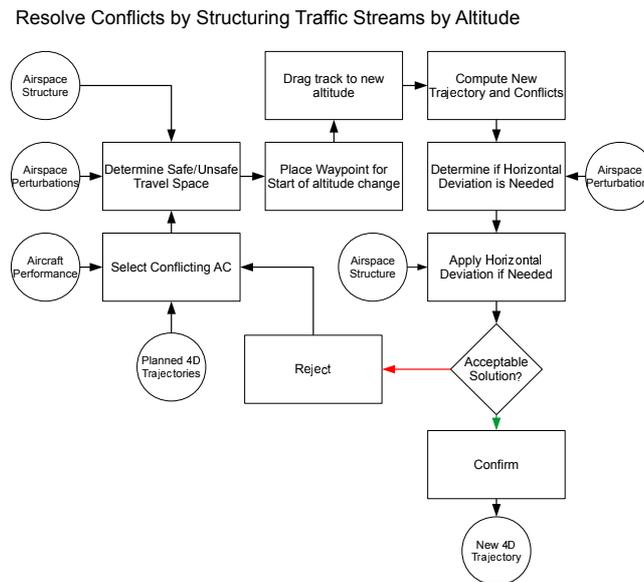


Figure B-3: Information flow map for the TSR interface when solving a conflict by changing altitude.

The second identified strategy is that the implemented VSD goes completely ignored and the sector is controlled only with horizontal and velocity resolutions. This is also how conflicts would have been resolved before the VSD was implemented. The information flow map for this strategy is shown in Figure B-4. When a conflict is detected, the aircraft is selected and the travel space is analysed. The user chooses whether to apply a solution in the PVD or TSD and applies the desired solution. If the user is satisfied with the solution, it is confirmed.

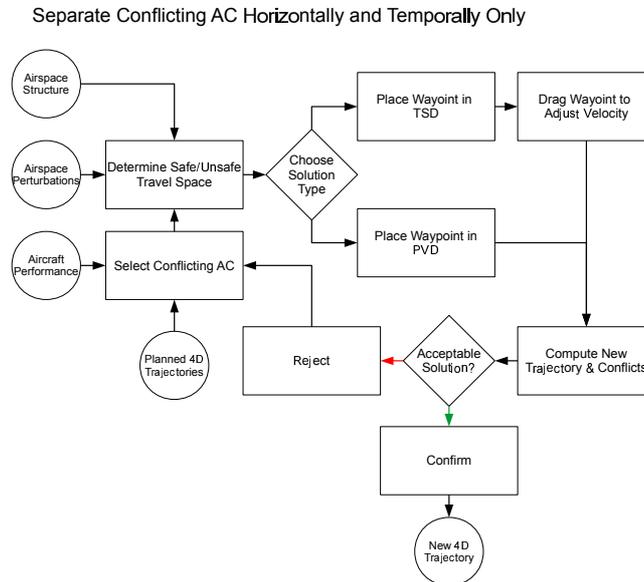


Figure B-4: Information flow map for the TSR interface when solving a conflict by changing altitude.

The third strategy involves preventing conflicts whether than resolving them. Similar to the first strategy, aircraft are separated by altitude, but now aircraft are separated on sector entry instead of only when a conflict occurs. The information flow map for this strategy is shown in Figure B-5. As can be seen the steps followed are very similar to the first strategy but the travel space and sector perturbations are only considered after applying an altitude change as this is applied regardless of the situation in the sector.

The fourth identified strategy applies the first strategy, but considers necessary horizontal changes due to perturbations before applying an altitude resolution. If an horizontal change is needed, the conflict between aircraft is also solved horizontally to make it so only one control action is needed to solve the conflict and avoid the perturbation. The information flow map for this strategy is shown in Figure B-6. As can be seen, once the safe travel space has been determined, a check is made whether the trajectory crosses a restricted area. If so, a horizontal solution is applied in the PVD. Otherwise an altitude resolution is applied.

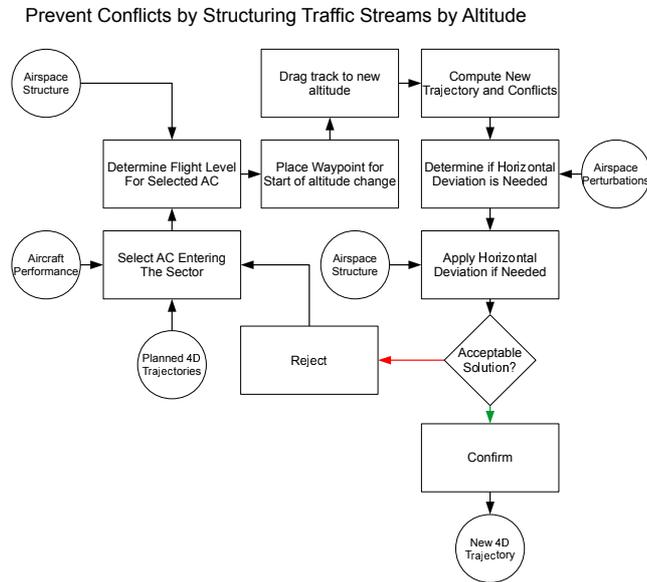


Figure B-5: Information flow map for the TSR interface when solving a conflict by changing altitude.

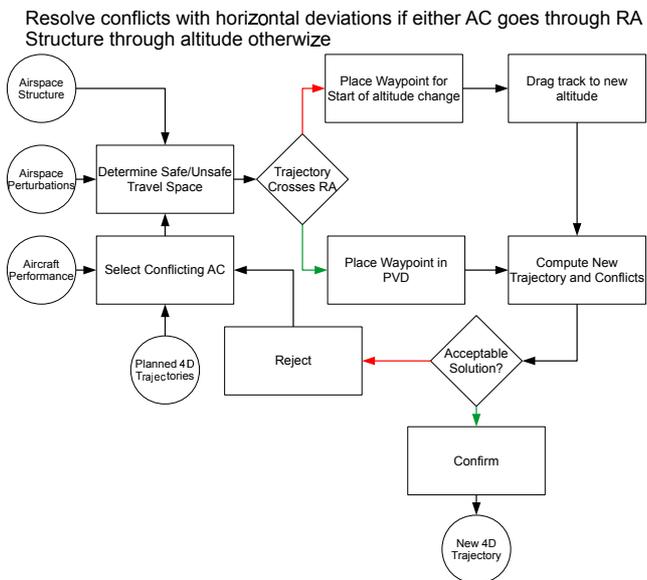


Figure B-6: Information flow map for the TSR interface when solving a conflict by changing altitude.

B-4 Social Organization

In a strategy analysis it is determined how a task can be executed. The next step is determining the actors that perform the steps painted out in the strategy analysis. Figures B-7, B-8, B-9, and B-10 show the social organization for the information flow maps shown earlier. The social organization shows which tasks are handled by the automation or the user and which tasks are shared. As shown, the decisions are taken by the user where main task of the computer is showing coherent information and computing the consequences of the user's actions.

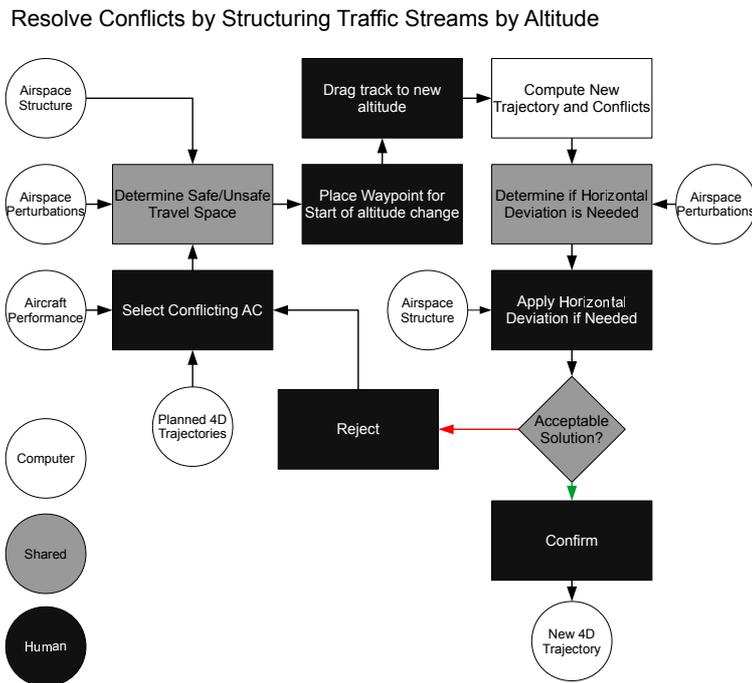


Figure B-7: Social organization for the information flow map.

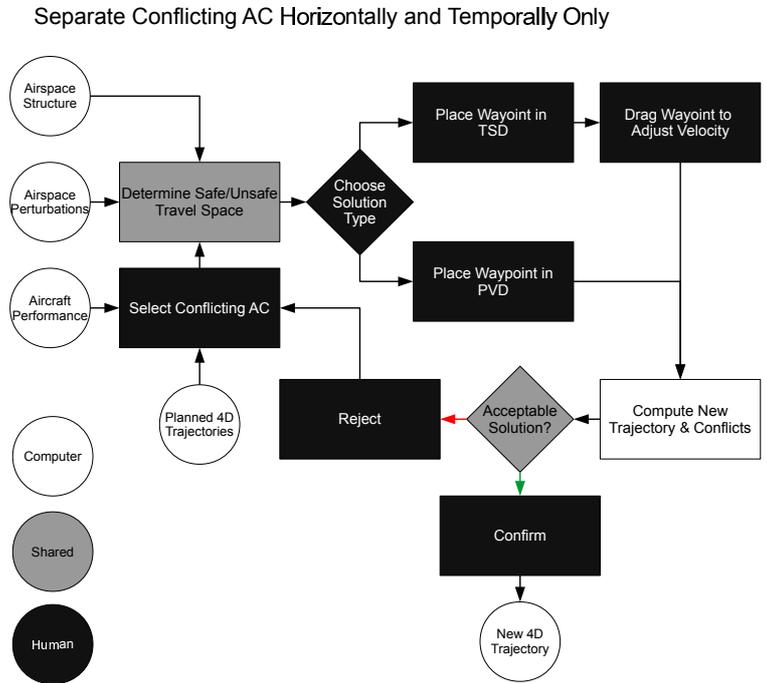


Figure B-8: Social organization for the information flow map.

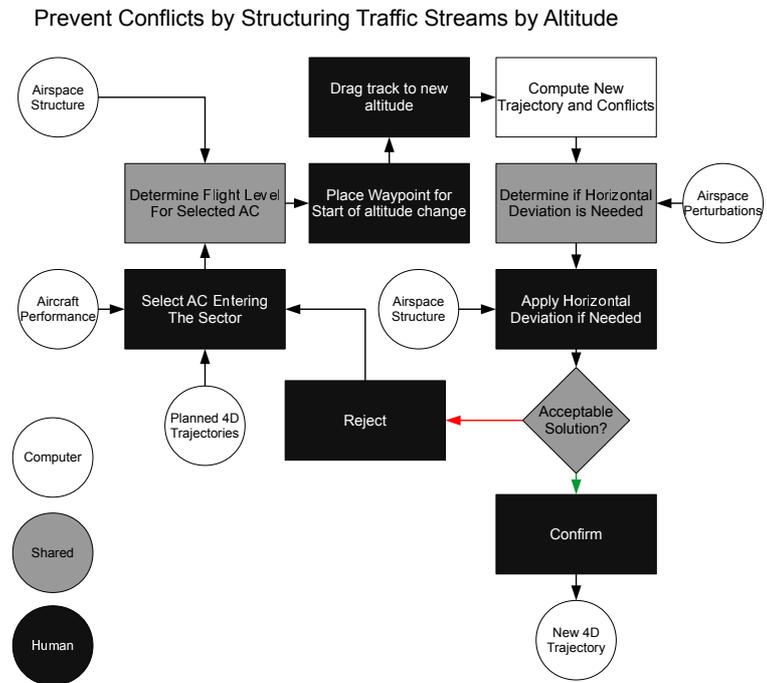


Figure B-9: Social organization for the information flow map.

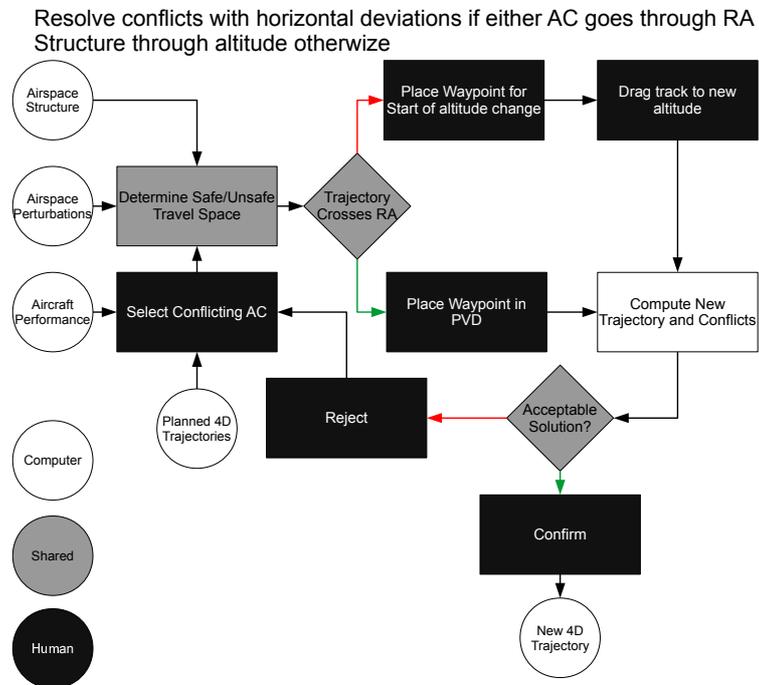


Figure B-10: Social organization for the information flow map.

B-5 Worker Competencies Analysis

A worker competencies analysis looks at the capabilities of the user. It is important to know the strength and weaknesses of the user to use the system to effectively complement the strengths and compensate for the weaknesses. By identifying the behaviour needed from the user, the interface can be designed to support this.

The required worker competencies can be divided into rule (procedure, if-then), skill (experience, automatic reactions) and knowledge (reasoning, problem solving) based categories and allocated to the different tasks that need to be performed. In Figure B-11 a worker competencies analysis is shown for the task of conflict resolution with the 4D TSR interface. For each information processing step, the knowledge state needed from the step and the skill, rule, and knowledge based behaviours for achieving that state are detailed.

Information Processing Step	Resultant Knowledge State	Skill-Based Behaviour	Rule-Based Behaviour	Knowledge-Based Behaviour
Scan for indicated conflicts	Whether one or multiple aircraft are in conflict	Monitoring for signals of conflicts (red ACs)	Identifying conflicts that are present	Reason where conflicts may arise in the future with aircraft not yet in the airspace
Determine conflicts with no-fly zones	Whether one or multiple aircraft will move through a no-fly zone	Monitoring for tracks crossing through red areas	Perceive flights will breach no-fly zones	Reason which source-sink combinations will have paths crossing no-fly zones
Determine most critical conflict	Which conflict has the largest priority in solving	Perceive which ACs in conflict are in close proximity on the TSD	Use heuristics to estimate which ACs will first have LoS or breach no-fly zones	Reason, based on visual data, if conflicts with high priority could emerge
Choose method to solve a conflict	Which approach will be most effective in resolving the conflict	Perceive which methods provide many options based on the solution space	Apply doctrine to determine which methods will be tried first	Reason which method is least likely to cause more conflicts in the future while having minimal impact on the trajectory
Determine conflict resolution	The conflict resolution to be executed	Perceive the areas in the solution space that provide conflict resolutions	Apply doctrine/common sense rules to determine a suitable waypoint location in the solution space	Reason whether a waypoint location can cause conflicts in the future and whether it is in line with previous conflict resolutions

Figure B-11: Worker competencies analysis for the resolution of conflicts with the novel air traffic control system.

B-6 Conclusions

Most importantly, from the WDA, the missing elements in the interface to create a full 4D perturbation management ATC system are the vertical elements. One needs to gain insight into the vertical trajectory manipulation possibilities and possible conflicts of the aircraft in the sector and be able to execute trajectory manipulations.

The user needs to be able to easily see where problems occur and which elements of the environment are involved with these problems. When analysing the situation the safe fields of travel need to be clearly distinguishable from the unsafe. The user must have the ability to manipulate trajectories in a consistent and preferably intuitive and simple manner. The implications of the trajectory manipulation need to be clear to the user before deciding to execute the change.

Appendix C

Interface Concept

The initial concept for the VSD is shown in Figures D-1, D-2, and D-3 including the existing view screens. The x-axis is shown on top of the diagram because it represents the same information as the x-axis of the TSD (namely remaining track length) which will be above the VSD. The y-axis is on the right as this is the logical direction of flight and consistent with the TSD.

When an aircraft is selected on the plan-view display, the aircraft and track are shown in the VSD as in Figure D-1. The label with aircraft ID is shown next to the y-axis. In this example the selected flight is in conflict with a crossing aircraft, as depicted by the red area. A solution space is generated for a climb or descent starting at the aircraft location.

To solve the conflict, a point on the track is selected to start a descent or ascent. This situation is depicted in Figure D-2. This point is marked with a waypoint and a solution space is shown in green. This includes all the achievable altitudes while still being capable of reaching the sector exit in time and without exceeding the maximum aircraft or sector altitude or going below the minimum. The slope of the ascending and descending lines are determined by the aircraft's maximum rate of ascent and descent at the given altitudes.

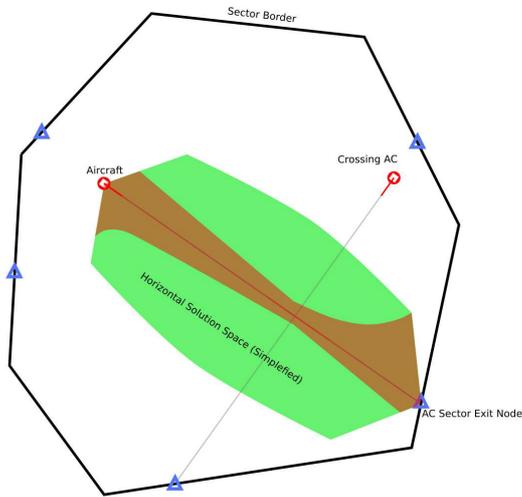
To adjust the altitude the aircraft label can be dragged up or down as depicted in Figure D-3. A second waypoint is placed on the top of climb or bottom of descent and the new track is generated. If the user is satisfied, this new track can be confirmed.

The new track is also shown in the plan-view display and the TSD with new solution spaces. As can be seen in the TSD the velocity of the aircraft is affected by the altitude change, this is discussed in more detail in Section C-1.

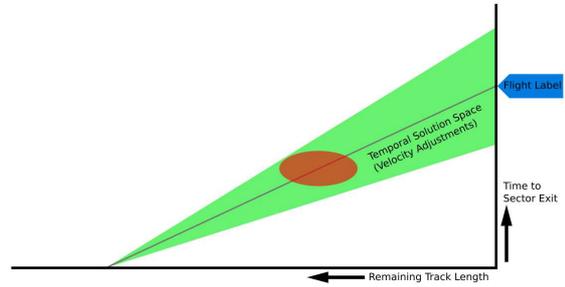
C-1 Altitude Influence on Velocity

The main velocity metric used by pilot in the aircraft is the Indicated Airspeed (IAS). This is a useful metric for the pilots because the aircraft will generally respond to control inputs

Plan View Display



Time Space Diagram



Vertical Situation Diagram

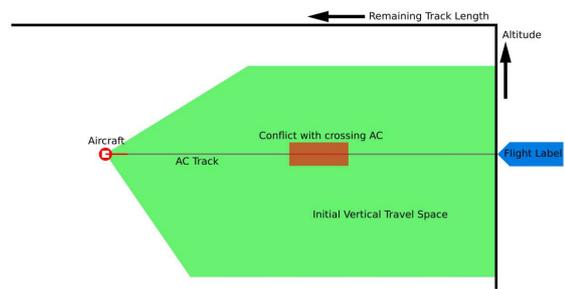
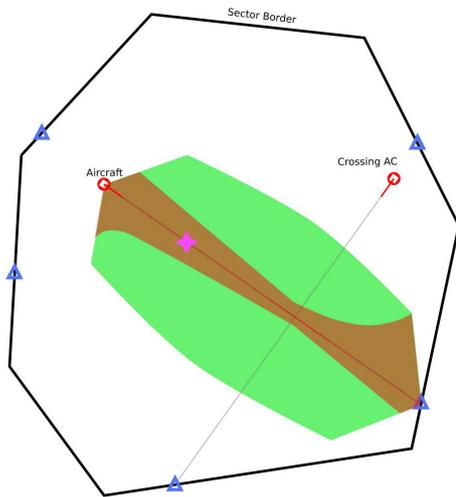
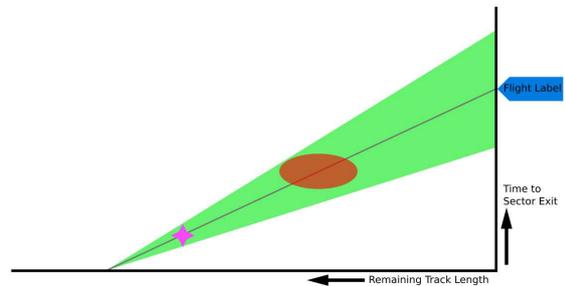


Figure C-1: Display concept with a selected aircraft in conflict with a crossing flight.

Plan View Display



Time Space Diagram



Vertical Situation Diagram



Figure C-2: Display concept with a selected aircraft in conflict with a crossing flight. A waypoint has been placed in the VSD on the track.

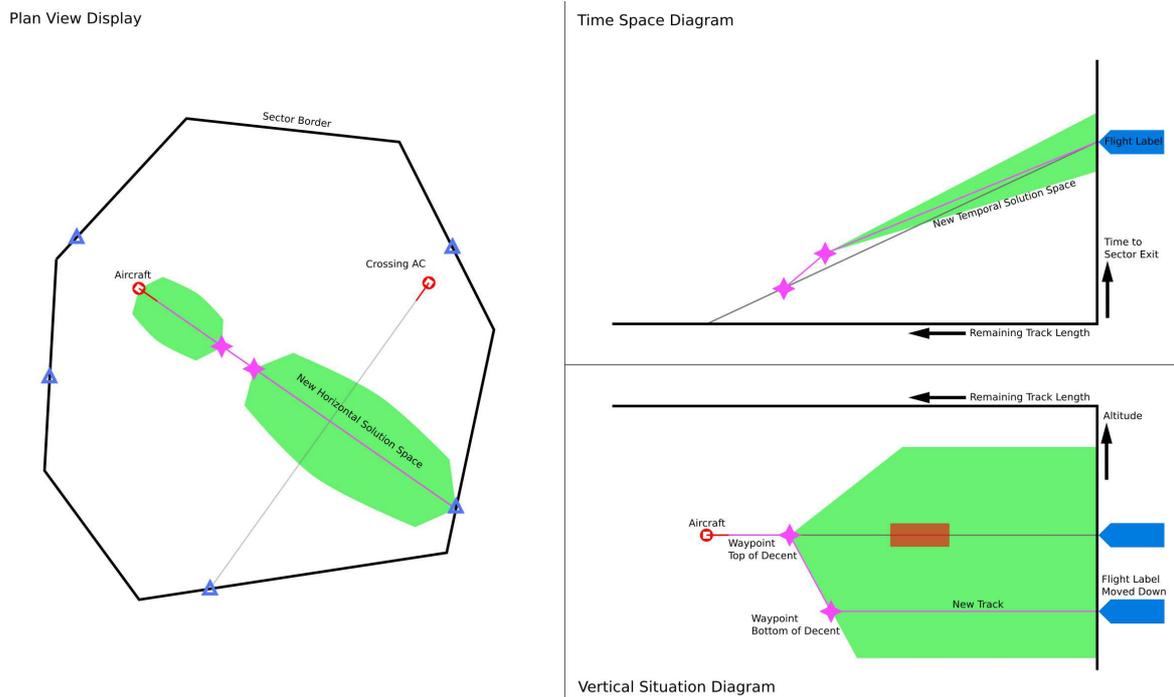


Figure C-3: Display concept with a selected aircraft in conflict with a crossing flight. A waypoint has been placed in the VSD on the track. The label has been moved down to avoid the conflict. A new track is generated and shown in all view screens.

similarly at a given IAS regardless of the altitude or (constant) wind. For navigation, however, True Airspeed (TAS) or groundspeed (=TAS when disregarding wind) indicates the progress along the track. The difference between TAS and IAS is dependent on the pressure and air density outside the aircraft, meaning it depends on the altitude. A certain IAS will result in a higher TAS at a higher altitude than it does on a lower altitude (IAS = TAS at International Standard Atmosphere (ISA) sealevel conditions). (Ruijgrok, 2009)

At low altitudes, the IAS is kept at a constant ideal value during a climb or descent. At a certain altitude (around Flight Level (FL) 250-300 in most cases), a crossover point is reached where the ideal climbing Mach number is reached at the current IAS. From this point upwards, the Mach number is kept constant instead of the IAS because the maximum Mach number of the aircraft now translates to a lower velocity than the maximum airspeed. (Ruijgrok, 2009) What this entails for 4D trajectory management is that any alteration of altitude will need to come with an alteration in velocity to ensure the aircraft will still arrive at its next waypoint at the correct time. This also means this velocity alteration will need to be taken into account when computing the solution space.

This effect is illustrated in Figure C-4. Note only IAS was used in this example and no crossover to Mach to keep the illustration simple. Two aircraft start at equal altitude of 30000 *ft* and IAS (300 *kts*). One climbs to 40000 *ft* and holds at a steady IAS, the other remains at the 30000 *ft*. The climb and climb rate have been chosen as generic but plausible values. The black lines connect points at the same moment in time between tracks. The sector exit is assumed at 108 *nm* along track from the start. As can be seen, though both aircraft have remained at 300 *kts* IAS the aircraft that climbed reaches the sector exit well

before the aircraft that did not.

Figure C-5 shows the same two tracks, but now the climbing aircraft has been given a new IAS at the top of climb. This new IAS has been calculated by determining the TAS needed to reach the sector exit at the time prescribed by the 4D trajectory at this new altitude. This TAS is then converted to IAS and given to the pilot. As can be seen, both flights reach the sector exit at roughly the same time.

The difference becomes even more pronounced when one aircraft climbs and the other descends and do not change IAS, as shown in Figure C-6. While the climbing aircraft experiences increasing TAS, the descending aircraft experiences decreasing TAS.

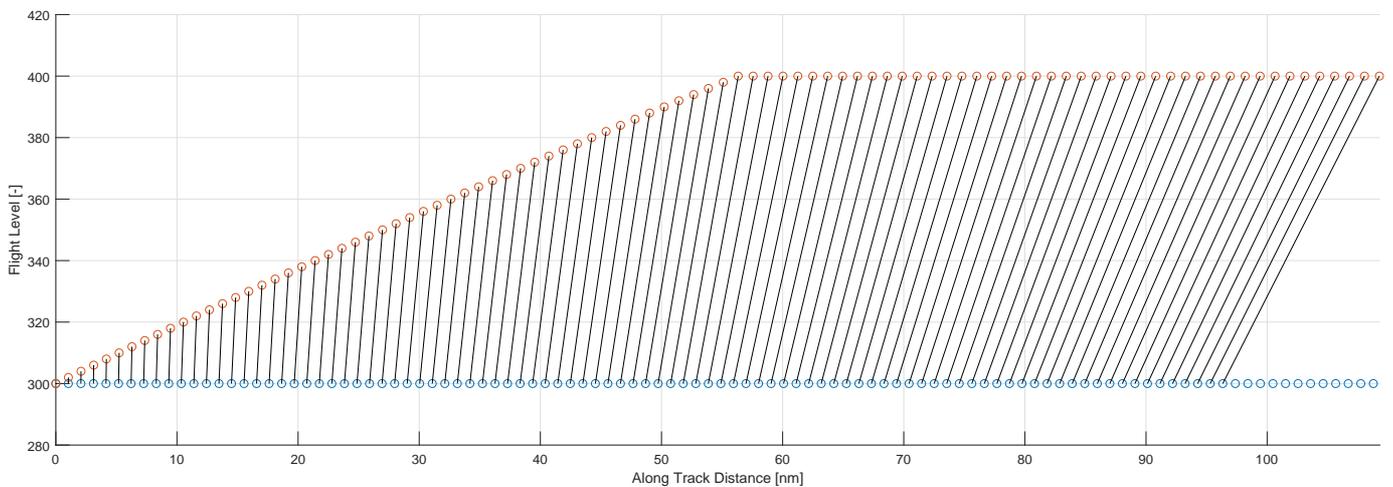


Figure C-4: Two generated aircraft tracks where one climbs and both remain at constant IAS. The black lines connect positions at the same moment in time.

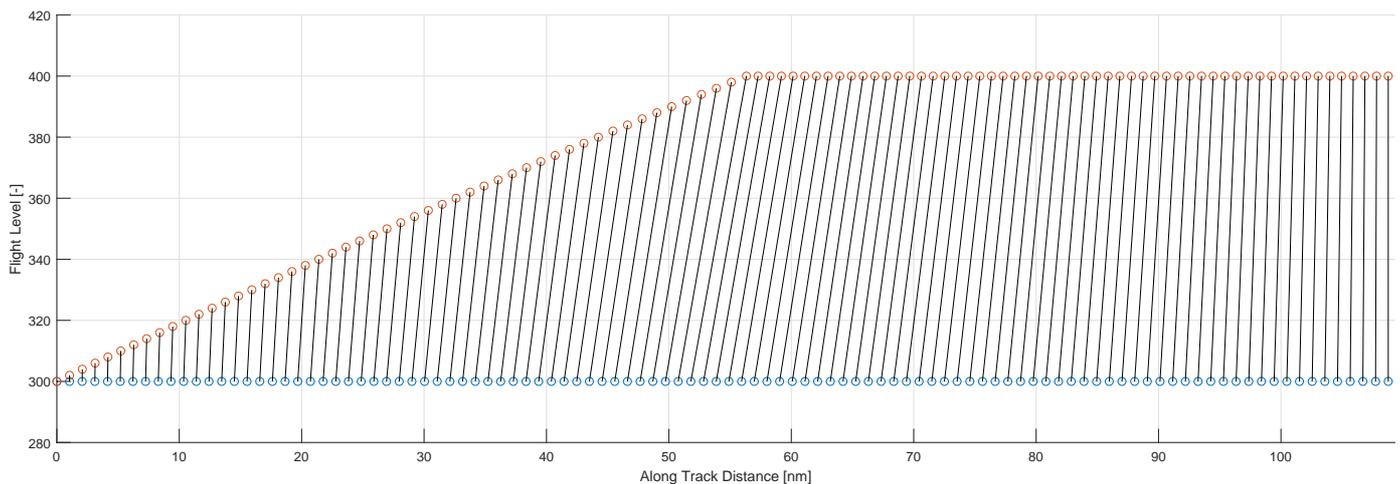


Figure C-5: Two generated aircraft tracks where one climbs and the climbing aircraft adjusts IAS at the top of climb to reach sector exit at the correct time. The black lines connect positions at the same moment in time.

To minimize the changes for the pilot with this new interface, a new indicated airspeed is

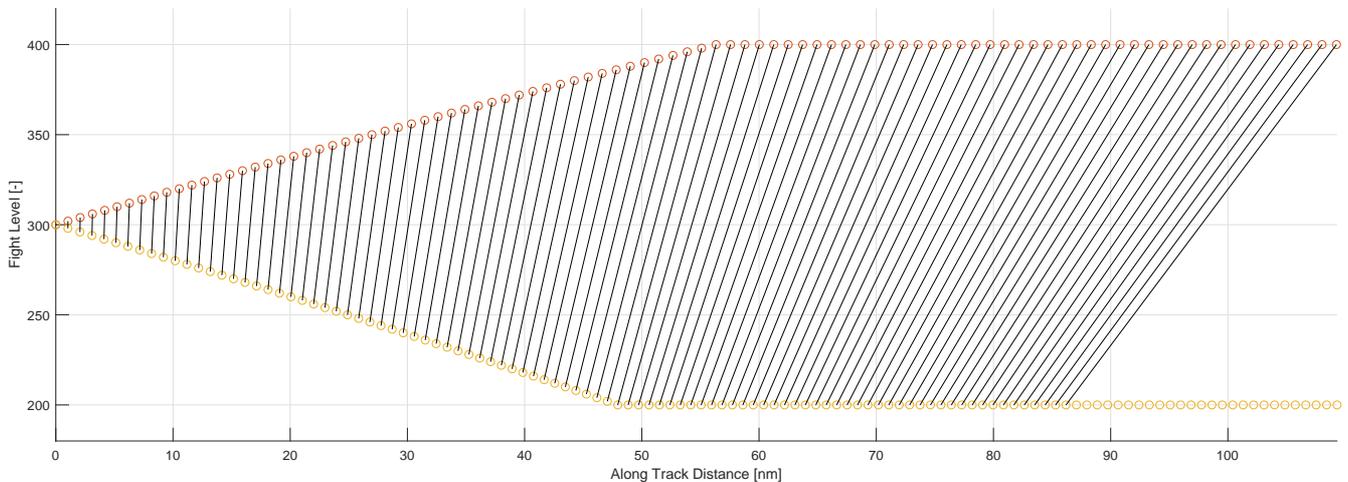


Figure C-6: Two generated aircraft tracks where one climbs and the descends and both remain at constant IAS. The black lines connect positions at the same moment in time.

given to pilots at the end of the climb or descent. The effect of this can be seen in the TSD in Figure D-3 where, during the descent, the TAS decreases until the end of the descent where the aircraft changes speed to arrive at the planned time at the sector exit.

When generating the solution space in altitude, not only does the possible altitude range of the aircraft need to be considered, but also the velocity range at this altitude. If the needed airspeed of the aircraft after a climb is below the stall speed, it is not a possible solution that can adhere to the 4D trajectory. This means cannot be included in the solution space even though the altitude is reachable. When computing a possible conflict at a different altitude, the change in velocity has to be taken into account as well.

To illustrate the change of the speed envelope Figure C-7 shows the minimum and maximum true (Figure C-7a) and indicated (Figure C-7b) airspeeds of an Airbus A321 at flight levels ranging from 150 to 400¹.

As can be seen, as the altitude increases, the minimum required TAS to remain above the stall speed increases. As was determined earlier, when an aircraft is ordered to climb it will need to decrease in TAS to reach the sector exit at the correct time. This makes the minimum TAS an important limiting factor when generating a solution space in the vertical plane.

In the same vein, the maximum TAS can become a limiting factor when the aircraft needs to descend. In the plot 3 parts of the maximum TAS progression can be observed and 2 parts in the IAS plot. First, in the lower portion, maximum IAS is constant, which leads to a rising line in the TAS plot. Here the limiting factor is the absolute maximum IAS of the aircraft in *kts*. Then, around FL 250, the maximum starts decreasing as the altitude increases. Here, the maximum allowable mach number becomes a lower velocity in *kts* than the absolute maximum IAS and must be taken as the limiting factor. Lastly, just above FL 350 and onwards, the maximum TAS remains constant. This is the start of the tropopause where ISA atmospheric conditions remain constant with altitude.

¹Service ceiling of the A321 is usually given between 39000-40000 *ft* but, as this example is for illustration purposes only, the round number of FL 400 was used.

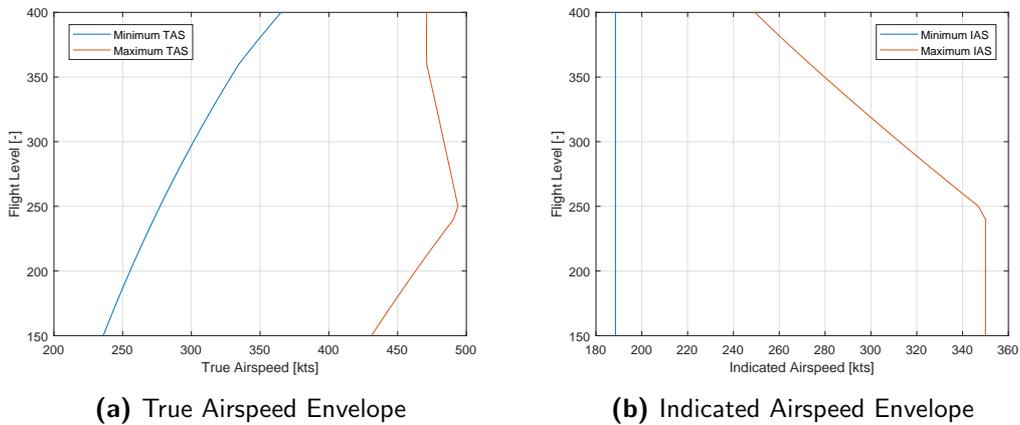


Figure C-7: Speed envelope of an A321 at varying flight levels showing the minimum and maximum possible TAS and IAS.

The effects of altitude on velocity are minor when only applying altitude changes over a small range of flight levels (10-20), but become very relevant when the altitude changes become larger. Because one of the goals is to test the interface with a vertically layered air traffic structure, it is very likely that large altitude changes will be applied. Therefore, these effect cannot be disregarded as insignificant and have to be taken into account.

Appendix D

Final Interface

The interface was expanded on the basis of the findings of the CWA and attempting to remain consistent with the existing elements of the interface. The final layout of the interface is presented in Section D-1 and the rationale behind the design is detailed in Section D-2. How the rate of climb and descent are calculated is explained in Section D-3.

D-1 Interface Layout & Functionality

The full interface with VSD is shown in Figures D-1, D-2, and D-3 including the existing viewscreens. The x-axis is shown on top of the VSD because it represents the same information as the x-axis of the TSD (namely remaining track length) which is above the VSD. The y-axis is on the right as this is the logical direction of flight and consistent with the TSD.

When an aircraft is selected on the plan-view display, the aircraft and track are shown in the VSD as in Figure D-1. The label with aircraft ID is shown next to the y-axis. In this example the selected flight is in conflict with a crossing aircraft, as depicted by the red area. A solution space is generated for a climb or descent starting at the aircraft location.

To solve the conflict, a point on the track is selected to start a decent or ascent. This situation is depicted in Figure D-2. This point is marked with a waypoint and a solution space is shown in green. This includes all the achievable altitudes while still being capable of reaching the sector exit in time, at the right altitude, and without exceeding the maximum aircraft or sector altitude or going below the minimum. The slope of the ascending and descending lines are determined by the aircraft's maximum rate of ascent and descent at the given altitudes. To adjust the altitude the aircraft label can be dragged up or down as depicted in Figure D-3. A second waypoint is placed on the top of climb or bottom of decent, a third is placed where the aircraft starts to return to the sector exit altitude and the new track is generated. If the user is satisfied, this new track can be confirmed.

The new track is also shown in the plan-view display and the TSD with new solution spaces. As can be seen in the TSD the velocity of the aircraft is affected by the altitude change.

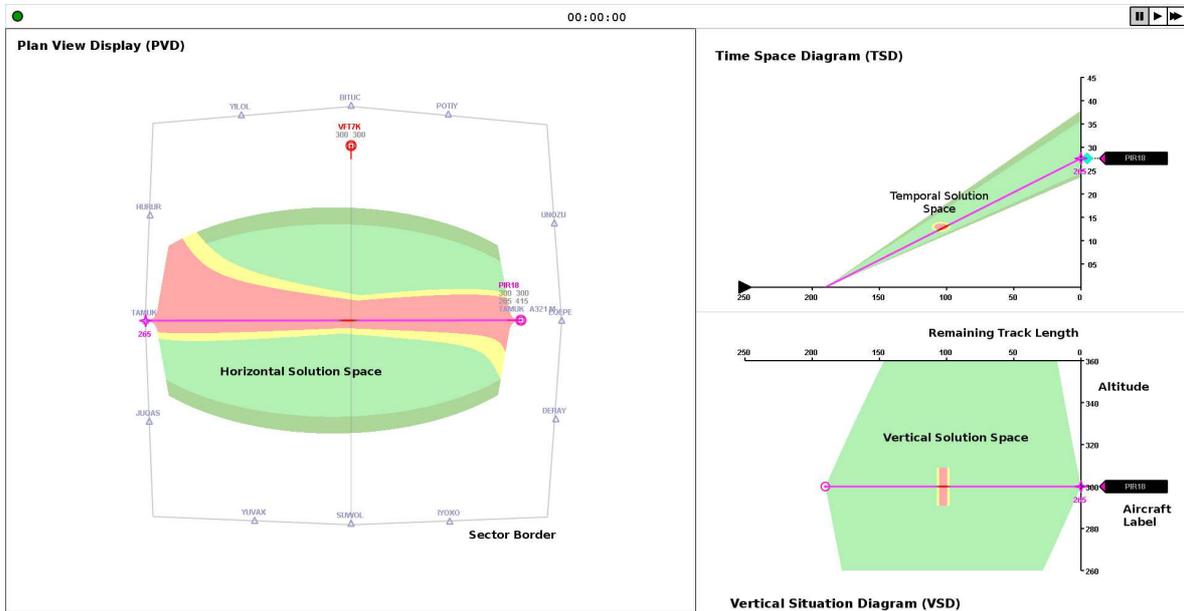


Figure D-1: Final interface with a selected aircraft in conflict with a crossing flight.

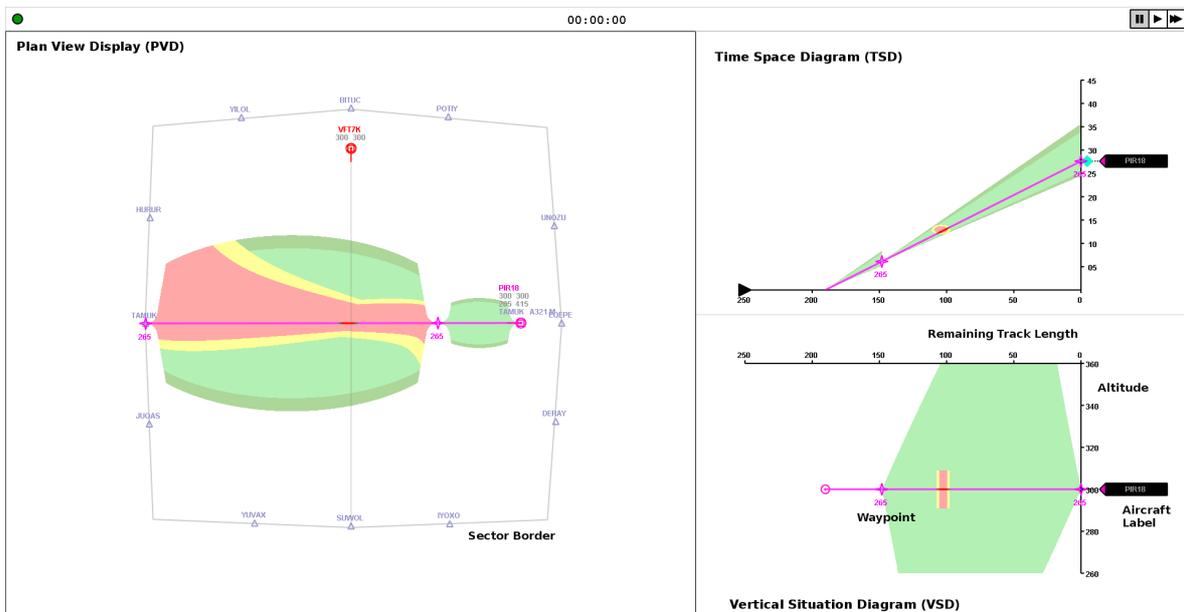


Figure D-2: Final interface with a selected aircraft in conflict with a crossing flight. A waypoint has been placed in the VSD on the track.

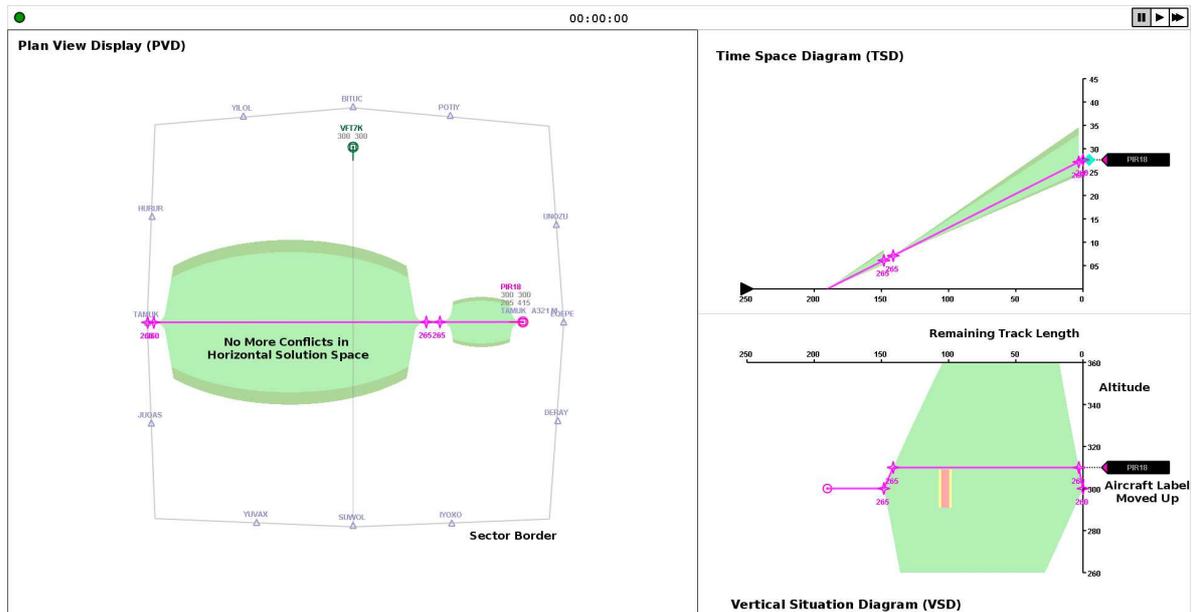


Figure D-3: Final interface with a selected aircraft in conflict with a crossing flight. A waypoint has been placed in the VSD on the track. The label has been moved down to avoid the conflict. A new track is generated and shown in all view screens.

D-2 Design Rationale

In the figures shown in the previous section, the previously existing parts of the interface these being the PVD and TSD are depicted alongside the concept of the new VSD. As much as possible, an attempt was made for the VSD to be observed and used in a similar fashion to the rest of the interface. Due to the nature of ascents and descents, however, the approach differs somewhat. If, like with the other displays, one waypoint could simply be placed anywhere in the altitude solution space, the aircraft could be ascending or descending slightly for very long periods of time which is undesirable for the pilot even when ignoring the fact that the pilot would need to adjust their velocity throughout this climb or descent to remain on schedule. Instead, two waypoints are used marking the start and end of the climb or descent. The pilot can execute the climb or descent at constant indicated airspeed (IAS) as they are used to and the bottom of descent or top of climb a new target IAS is given in order to arrive at the sector exit at the right time.

The main velocity metric used by pilot in the aircraft is the indicated airspeed (IAS). This is a useful metric for the pilots because the aircraft will generally respond to control inputs similarly at a given IAS regardless of the altitude or (constant) wind. For navigation, however, true airspeed (TAS) or groundspeed (=TAS when disregarding wind) indicates the progress along the track. The difference between TAS and IAS is dependent on the pressure and air density outside the aircraft, meaning it depends on the altitude. A certain IAS will result in a higher TAS at a higher altitude than it does on a lower altitude (IAS = TAS at ISA sealevel conditions). (Ruijgrok, 2009)

At low altitudes, the IAS is kept at a constant ideal value during a climb or descent (Ruijgrok, 2009). At a certain altitude (around FL 250-300 in most cases), a crossover point is reached where the ideal climbing Mach number is reached at the current IAS. From this

point upwards, the Mach number is kept constant instead of the IAS because the maximum Mach number of the aircraft now translates to a lower velocity than the maximum airspeed. For the purpose of this research, only constant IAS climbs and descents are used. This can be expanded to use the crossover point at a later stage of development.

What this entails for 4D trajectory management is that any alteration of altitude will need to come with an alteration in velocity to ensure the aircraft will still arrive at its next waypoint at the correct time. This also means this velocity alteration will need to be taken into account when computing the solution space.

The effects of altitude on velocity are minor when only applying altitude changes over a small range of flight levels (10-20), but become very relevant when the altitude changes become larger. Because one of the goals is to test the interface with a vertically layered air traffic structure, it is very likely that large altitude changes will be applied. Therefore, these effects cannot be disregarded as insignificant and have to be taken into account.

To minimize the changes for the pilot with this new interface, a new indicated airspeed is given to pilots at the end of the climb or descent. This means that, for instance, in a descent, the TAS decreases until the end of the descent where the aircraft changes speed to arrive at the planned time at the sector exit. The altitude at the end of the sector is also constrained so, in a descent, there will be a climb back to the required altitude at the end of the sector. The effect of this climb is also taken into account in the TAS change.

When generating the solution space in altitude, not only does the possible altitude range of the aircraft need to be considered, but also the velocity range at this altitude. If the needed airspeed of the aircraft after a climb is below the stall speed, it is not a possible solution that can adhere to the 4D trajectory. This means it cannot be included in the solution space even though the altitude is reachable. When computing a possible conflict at a different altitude, the change in velocity has to be taken into account as well.

Because of the way altitude changes work with this interface, it cannot be assumed the altitude will be the first conflict resolution option considered, like it is with current day air traffic management. Whereas giving an altitude change currently is the easiest and fastest way of resolving conflicts, with this TSR interface, speed and heading changes are just as straightforward. With a short-term conflict, altitude change will still be the fastest solution, but, compared to current ATM, conflict resolutions will mostly be done with more time left before the closest point of approach. Therefore, heading and velocity changes can be more viable as conflict resolution methods compared to current ATM. Because of this the VSD has been given no particular prominence over the PVD or the TSD.

To better show the connection between TSD and VSD, the shared dimension of the x-axis (remaining track length) is shown in close proximity. The physical proximity of this should increase visual momentum when adjusting attention between these displays.

With these three displays the PVD, showing the physical shape of the sector and all the aircraft in it, is bound to be seen as the main display, taking up most of the attention. This is expected and, in itself, is not immediately a problem as it is a very useful display in gathering information on the overall situation and the conflicts that need to be solved. It is also the only display which shows all the aircraft in and around the sector. This makes it a natural starting point when scanning the situation. The remaining displays only show information on a selected aircraft and the conflicts it has. What is important is that these displays do not go ignored completely as they will be vital in reaching the optimal conflict resolutions.

Using the shared dimension of remaining track length, it is easier for the user to shift their

attention to the TSD and VSD and away from the PVD in one go. The altitude is shown on a vertical axis to be immediately understood as it is congruous with the mental picture of altitude. All the conflicts are shown in red and the solution space in green, obviously in line with the other displays. Superfluous information needs to be omitted as much as possible from the TSD and VSD especially as to not discourage the user to shift their attention away from the PVD.

In the CWA, the Abstraction-Decomposition Space has identified the elements that need to be identifiable in the interface. Most of these elements have already been integrated in the existing two displays, what remains are the vertical elements. These are integrated in a manner consistent with how the horizontal elements are visible in the PVD. The vertical flight profile is visualized by the grey trajectory line, rates of climb and descent are visible in the solution space shape with the altitude limits (due to sector limits or time constraints) making up the rest of the solution space limits. Vertical conflicts and waypoints are shown analogous as in the PVD as well.

The control strategies identified in the CWA are also supported in the interface design. Conflicts are easily identified and more information on the conflicting flights can be found by selecting aircraft in conflict. The safe travel space is clearly visualized and the user can use their own judgement when formulating a solution to a conflict. The implications of the chosen solution on the trajectory are shown in all displays before the user confirms it.

D-3 Rate of Climb & Descent

Rates of climb and descent are implemented in the interface in two ways. Which way is used is a setting that can be adjusted in the config file and in the interface itself. The simplest form uses a set value for the rates of climb and descent which can be altered in the settings (this was set to 1000 *ft/min* for climb and 2200 *ft/min* descent in the experiment). This method was used in the experiment to keep what the participants were looking at simple and keep the code in the shaders simple.

The second method uses the Base of Aircraft Data (BADA) to compute the rates of climb and descent (Eurocontrol Experimental Centre, 2013) based on the aircraft altitude and TAS. To do this, the total energy model is used, with the vertical speed as value to be determined (speed and throttle controlled). This is shown in Equation D-1 (assuming ISA). The assumption of ISA means the geopotential pressure altitude, H_p , is assumed the same as the geodetic altitude, h , excluding the need to compensate for this. This assumption is used throughout the computations in the interface and is extended to the vertical computations.

$$ROCD = \frac{dh}{dt} = \frac{(Thr - D) * V_{TAS}}{mg_0} \left[1 + \left(\frac{V_{TAS}}{g_0} \right) \left(\frac{dV_{TAS}}{dh} \right) \right]^{-1} \quad (D-1)$$

In the equation $ROCD$ stands for the rate of climb/descent (in *m/s* in this instance), Thr and D are thrust and drag in N , and V_{TAS} is the true airspeed in *m/s*. For the mass m in *kg*, it was assumed the mass does not change over time and is equal to the reference mass for the specific aircraft given in the BADA. This equations is simplified by defining the last part $\left(\left[1 + \left(\frac{V_{TAS}}{g_0} \right) \left(\frac{dV_{TAS}}{dh} \right) \right]^{-1} \right)$ as the energy share factor $f\{M\}$. This factor represents the

amount of power that is that is used for climbing instead of accelerating and is determined by the type of climb that is used. For the sake of simplicity, one type of climb profile is used for all situations in the interface: a constant IAS climb below the tropopause. Using this climb profile (assuming IAS equals CAS, and again assuming ISA) $f\{M\}$ can be defined as in Equation D-2.

$$f\{M\} = \left\{ 1 + \frac{\kappa R \beta_{T,<}}{2g_0} M^2 + \left(1 + \frac{\kappa - 1}{2} M^2 \right)^{\frac{-1}{\kappa - 1}} \left\{ \left(1 + \frac{\kappa - 1}{2} M^2 \right)^{\frac{\kappa}{\kappa - 1}} - 1 \right\} \right\}^{-1} \quad (D-2)$$

Here, κ is the adiabatic index of air (1.4), R is the real gas constant of air ($287.05287 \text{ m}^2/(K * s^2)$), $\beta_{T,<}$ is the ISA temperature gradient below the tropopause (-0.0065 K/m), and M is the mach number.

To use these equations to calculate *ROCD* at a certain altitude and speed, the thrust and drag need to be known. To compute the thrust during a climb, the maximum climb thrust is computed for the aircraft in question. For jet aircraft, this is shown in Equation D-3.

$$(Thr_{maxclimb})_{ISA} = C_{Tc,1} * \left(1 - \frac{H_p}{C_{Tc,2}} + C_{Tc,3} * H_p^2 \right) \quad (D-3)$$

Here, the C_{Tc} variables are engine thrust parameters specific for a type of aircraft. These values are included in the BADA, and are thus known. As mentioned earlier, it is assumed $H_p = h$, thus the climb thrust can be computed. To find the thrust while descending, the climb thrust is used with a correction factor also included in the BADA.

To compute the drag, the standard method is used as shown in Equation D-4, where the drag coefficient is calculated as in Equation D-5 and the lift coefficient as in Equation D-6. Here, the bank angle is assumed close to zero and thus not a factor for C_L .

$$D = \frac{C_D * \rho * V_{TAS}^2 * S}{2} \quad (D-4)$$

$$C_D = C_{D0,CR} + C_{D2,CR} * C_L^2 \quad (D-5)$$

$$C_L = \frac{2 * m * g_0}{\rho * V_{TAS}^2 * S} \quad (D-6)$$

In these equations, ρ is the density of air at the given altitude in kg/m^3 , S is the wing reference area in m^2 , and $C_{D0,CR}$ and $C_{D2,CR}$ are aerodynamic drag coefficients given for the specific aircraft in the BADA. The wing reference area can also be found in the BADA and ρ can be easily computed using the standard method of computing the temperature and pressure at the required altitude and using Equation D-7.

$$\frac{p}{R * T} \quad (D-7)$$

With the thrust and drag known for climb and descent, and using Equation D-8 to compute the mach number, Equation D-9 can be solved, using Equation D-2 to find $f\{M\}$, to find the rate of climb or descent.

$$V_{TAS}/\sqrt{\kappa * R * T} \tag{D-8}$$

$$ROCD = \frac{(Thr - D) * V_{TAS}}{mg_0} * f\{M\} \tag{D-9}$$

Because *ROCD* is dependent on altitude, it will change during the course of a climb or descent when holding a constant IAS. When drawing a solution space, not only are the *ROCD* at the current and final altitude needed, but also at all the altitudes in between the first and final altitude. To simplify this, it was assumed that *ROCD* changes linearly with respect to altitude, making it possible to use the average of the first and last *ROCD* to determine where and when the top of climb or bottom of descent will be. Additionally, the *ROCD* of a climbing or descending aircraft was given this average value, making every step in altitude equal.

This method is closer to reality than simply using a constant value for *ROCD* across all situations. The simplifications of using a linearly changing *ROCD* and simply using the average *ROCD* throughout the climb or descent don't have a large impact on small changes in altitude but will need to be changed to better reflect reality when further refining the interface, especially when starting to look at larger altitude changes like approaches or climbs from take-off to cruise altitude.

An example of a solution space using this method instead of constant values is shown in Figure D-4. As can be seen, rate of climb decreases with increasing altitude and rate of descent increases but changes less with altitude.

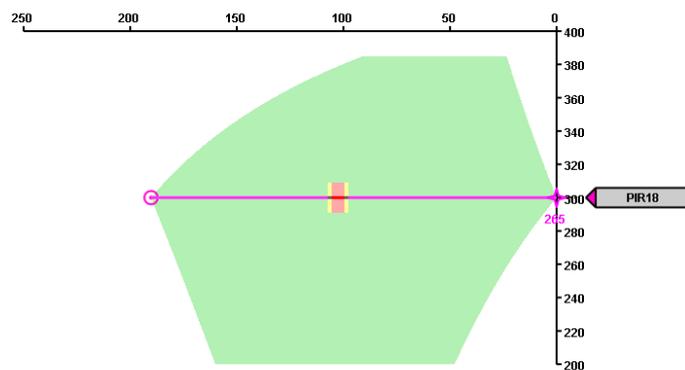


Figure D-4: VSD solution space with *ROCD* computed using BADA

Appendix E

Experiment Design

To validate the interface, explore the influence of the addition of the VSD, and analyse the way it is used, an experiment was performed. Data on safety, efficiency, workload, and user activity was collected.

E-1 Experiment Goal

The goal of the experiment is to validate the functionality of the interface, analyse how the interface is being used. As this was the first experiment performed with the full interface, the interactions of the participants with the interface was also observed to determine if the control strategies defined in the CWA can actually be observed with the completed interface. This experiment was performed under the same conditions as an experiment performed with the interface before the VSD was added. This allows for a low level comparison of the results and to analyse the influence the addition of the VSD has on controller performance and behaviour.

E-2 Conditions

E-2-1 Independent Variables

Two different traffic structures were analysed. All scenarios have two traffic streams: north-south and east-west. The independent variables determine whether these traffic streams are convergent or divergent and whether there is a restricted area in the middle of the sector. Thus, the following 4 scenarios exist:

- Converging, no restricted airspace (C_n)
- Converging, with restricted airspace (C_r)

- Diverging, no restricted airspace (D_n)
- Diverging, with restricted airspace (D_r)

E-2-2 Dependent Measures

To determine which strategies are applied, observations were made about the participant's actions during the experiment. These observations were then discussed with the participants after the experiment to confirm the observed strategies. To provide insight into user activity the mouse position was tracked as well. This can provide insight in where the attention of the participant was focussed.

To get a measure of performance, losses of separation, restricted area intrusions and intrusion times were tracked as a measure of safety. Efficiency was measured by looking at the impact on the trajectory of user actions. Small actions mean the aircraft does not have to divert much from its original trajectory and is therefore more efficient. Total added track miles, the total introduced delay and the average and maximum altitude changes were tracked as a measure of efficiency. Whether a certain altitude change is more efficient than a certain horizontal track change was not considered in this experiment.

During the simulation, prompts were given the user to provide a workload rating on a 0-100 scale. The number of actions in each viewscreen was tracked as well. Besides this notes were made on any unexpected behaviour during the experiment which might have influenced the workload.

E-2-3 Control Variables

The control variables are the test parameters which will be kept consistent throughout every scenario. This will ensure variance in the data will be independent of these parameters. The following have been defined as control variables:

- Sector parameters (size, shape, etc.)
- Traffic density (1 aircraft enters the sector every 90 seconds)
- Aircraft type (A321)
- Scenario duration (1 hour in scenario time)
- Availability of the interface
- Experiment environment

E-2-4 Participants

A 4x4 experiment matrix is shown in Table E-1. The scenario order is different for every participant to prevent any remaining learning effects after the training, emerging from a certain scenario order, from being reflected in the results. The scenarios are also rotated

differently for each participant to ensure the traffic streams can come from different sides for each scenario. With four scenarios, at least 4 participants are needed.

The four experiment participants all have some experience with the basics of air traffic management but are not experts. In addition all had interacted with the interface without VSD before. The control task asked of the participants was to control the sector as safely and efficiently as possible.

Table E-1: Latin square experiment matrix for validation experiment

	Trial 1	Trial 2	Trial 3	Trial 4
Participant 1	$C_r 0^\circ$	$D_n 180^\circ$	$C_n 90^\circ$	$D_r 270^\circ$
Participant 2	$D_n 180^\circ$	$C_n 0^\circ$	$D_r 270^\circ$	$C_r 90^\circ$
Participant 3	$C_n 0^\circ$	$D_r 180^\circ$	$C_r 90^\circ$	$D_n 270^\circ$
Participant 4	$D_r 180^\circ$	$C_r 0^\circ$	$D_n 270^\circ$	$C_n 90^\circ$

E-3 Scenarios

As stated when defining the independent variables, 4 scenarios were tested. All aircraft were of the same type and entered and exited the airspace at FL300. It was up to the participant whether or not to introduce any sort of structure in the vertical space. Each scenario is 1 hour long, run at four times the speed (making each scenario take 15 minutes in real time). Every 90 seconds in, scenario time, an aircraft enters the sector, flying either north-south or east-west (north-south or south-north is determined by the rotation of the sector, also for the east-west stream). Figure E-1 and E-2 show two of the scenarios used during the experiment, the first having converging traffic and a restricted zone present and the second having diverging traffic and no restricted zone.

E-4 Procedure

Before the experiment, participants were provided with a training script which guided them step by step through simple scenarios to familiarize them with the interface and its different viewscreens. After that, six training scenarios of increasing difficulty were run where the final scenarios were comparable in difficulty those of the actual experiment.

Once the participants completed these training scenarios successfully and were comfortable with the interface, the experiment began. The four scenarios of 15 minutes each were run with a few minutes of rest in between should the participant desire this. During the experiment, notes were made to try and define the participant's strategy in each scenario and whether or not they adhered to these strategies. At the end of the experiment, the participants were asked about their experience and what strategies they had in mind themselves.

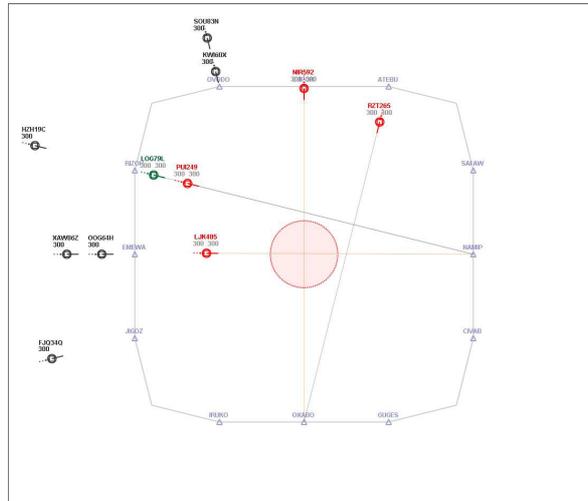


Figure E-1: Plan view display of the interface with the converging traffic scenario with restricted zone present.

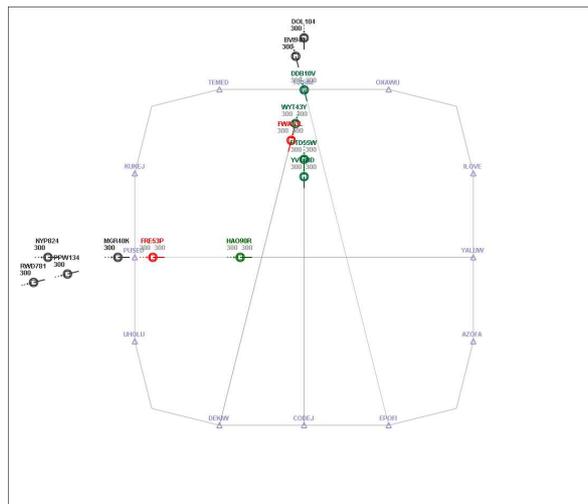


Figure E-2: Plan view display of the interface with the diverging traffic scenario without restricted zone present.

E-5 Hypotheses

Based on the goal of the experiment and the data that would be collected, the following hypotheses were made about the possible results:

- I The applied strategies will not differ noticeably between converging and diverging traffic scenarios
- II The applied strategies will focus more on the VSD in scenarios without restricted areas and more on horizontal actions in scenarios with restricted areas
- III Like with the experiment without VSD, the safety metrics will provide insufficient data

to make any significant statement on safety

- IV The experiment with VSD will result in more efficient solutions, especially in the scenarios with restricted area
- V Workload is expected to be similar for both experiments in the scenarios with restricted area but is expected to be lower for scenarios without restricted areas

It is not hard to imagine the extra degree of freedom of the altitude could make the scenarios significantly easier. It was hypothesized the scenarios without restricted area could be so easy as to become almost trivial if the participant decided to structure traffic in altitude. This would, of course, also greatly reduce the workload. It was expected that participants would mostly structure traffic based on altitude in the scenarios without restricted area.

In the scenarios with restricted area, horizontal trajectory manipulations are always needed. It was hypothesized this would shift focus away from the VSD and TSD to the PVD. Workloads in these scenarios were expected to be comparable to those of the scenarios with restricted area in the experiment without VSD.

Appendix F

Experiment Briefing

The following chapter contains the training script the participants were given before the experiment. This training script was followed while using the accompanying scenarios to learn how the interface worked and get used to interacting with it. Besides the training script, the briefing consisted of discussing the number of scenarios, their length and when to stop them.

F-1 Training Script

F-1-1 Purpose of the Training

In order to have a good understanding of how to perform your role as future air traffic controller in the main experiment, all tools and features that are available to you in the experiment simulator will be described in this training session. The training will be in the form of an interactive step-by-step script that will guide you through a number of scenarios. Each scenario will focus on a specific learning objective. At certain points during the scenario you may be required to answer one or more questions to test your understanding so far.

Your main task in the experiment will be to manage the traffic safely, and to try to adhere as much as possible to the initial traffic structure. That is, to keep any path deviations and delays at the sector exit point as small as possible. This will be explained in more detail during the training.

Please try to talk out loud and try to motivate your reasoning for the decisions you make during the training scenarios. Read all the instructions carefully and don't hesitate to ask questions if something is unclear. During the training you are free to ask questions or ask for help, but in main experiment you will be asked to control the traffic without external interference.

F-1-2 Airspace and Traffic

The controlled airspace used in the training scenarios and in the main experiment are artificial, en-route upper airspace sectors that are designed especially for this experiment. All aircraft resemble a generic type of medium-sized commercial airliner and have equal performance characteristics (equal speed envelope). You will be able to manipulate the route and the speed of the aircraft. All aircraft in this experiment start at the same altitude, so applying vertical separation or structuring traffic based on altitude is up to you.

F-2 Scenario 1

F-2-1 Part 1: System functionality and basic representations

The simulation is paused at this point, so please take the time to carefully read each following step:

- The experiment simulator is built up by three separate screens:
 - PVD (Plan View Display): The screen on the left hand side shows the top-down radar view of the sector, the entry and exit waypoints and all aircraft. The controlled sector in the training session has 12 unique entry and exit points, and in this scenario there is one controlled aircraft (callsign: BMS02N). You will use this screen to manipulate the horizontal route of the aircraft.
 - TSD (Time-Space Diagram): The screen on the top right hand side is a so-called Time-Space Diagram and will visualize information about the trajectory of a selected aircraft in terms of distance and time. A more in-depth explanation will follow later on.
 - VSD (Vertical Situation Diagram): The screen at the bottom right hand side is the Vertical Situation Diagram. It visualizes information about the altitude and the distance to go of a selected aircraft. It will be used to manipulate the vertical route of the aircraft.

Basic information on the PVD

- The heading of BMS02N is indicated by a speed vector that is currently aligned with its route. The tip of the speed vector indicates the position at which the aircraft will be when following the current heading for 60 seconds. A longer speed vector therefore indicates a faster flying aircraft. The aircraft is flying towards exit point TAMUK and its route is indicated by a thin line.
- Highlight BMS02N and its route by hovering over it with the mouse in the PVD.
- Left-click on the highlighted aircraft to select it .
- The selected aircraft and its route will turn cyan and the current indicated airspeed in knots (265 KTS), true airspeed, the planned exit point (TAMUK), and the aircraft

type and weight class appear in the label. The waypoints along the route of a selected aircraft are visualized by magenta star symbols. BMS02N has one active waypoint that is located at the sector exit point. The planned speed towards this point is shown below the star symbol (also 265 KTS).

- The shaded area that has appeared along the route of BMS02N is the so-called Travel Space of the aircraft. The Travel Space shows the area in which the aircraft can be rerouted and will still be able to arrive at the originally planned time at the sector exit point. Note that any deviation from the current direct route to the exit point will lead to a longer trajectory, and as a result, the aircraft will have to fly faster to reach the original exit time. The travel space is therefore bound by the speed envelope of the aircraft. That is, the travel space is bounded by the maximum speed that the aircraft can fly.
- The darker shaded area at the edge of the Travel Space shows the region where the aircraft is required to fly close to its maximum speed. This is less efficient in terms of fuel usage, and therefore should, if possible, be avoided.

Basic information on the TSD

- The TSD (top right screen) shows the time-space representation of the trajectory. Here, the x-axis indicates the distance from the sector exit point along the current trajectory. The y-axis indicates future time. The cyan line represents the trajectory of the aircraft. Observe that at the current time (00:00), the aircraft has approximately 175 nautical miles to fly until reaching the exit point. The arrival time of the aircraft at the sector exit point is approximately at (00:26), and is indicated by the intersection of the line with the time-axis.
- The position of the aircraft label along the time axis in the TSD indicates the current exit time of the aircraft. The cyan diamond along the time axis indicates the originally planned exit time of the aircraft. Note that these are now the same, but in case of a delay they will be different.
- The speed envelope of the aircraft is also represented in the TSD by a shaded area. Similar to the Travel Space, the darker shaded area indicates the less efficient speeds. The intersection of the area with the time axis indicates the possible arrival times of the aircraft at the exit and is now approximately from (00:23) to (00:35). Note that if the aircraft would fly slower than currently (i.e., arrive at a later time), the time-space line will be steeper. Vice versa, a more shallow line indicates a faster flying aircraft.
- Further, the white triangle at the left-bottom of the TSD is a slider that can be used to make a projection of the future aircraft movements. Drag the slider up to see the expected position of the aircraft in future time on the PVD.

Basic information on the VSD

- The VSD (bottom right screen) shows the time-space representation of the trajectory. Here, the x-axis, as in the TSD, indicates the distance from the sector exit point along

the current trajectory. The y-axis indicates the flight level. The cyan line represents the trajectory of the aircraft. The circle represents the current location of the aircraft, currently approximately 175 nautical miles from the sector exit. Note that the flight level is 300 throughout the trajectory.

- The vertical solution space is shown in the VSD. This shows the altitudes attainable by the aircraft while still being able to exit the sector at the correct altitude. As can be seen, from the current distance to go, the aircraft can reach FL260 and FL360. This is what the vertical axis is currently limited to and what will be the full altitude range in the airspace for all the scenarios.
- Deselect the aircraft with a right mouse click on any viewscreen. The time-slider in the TSD will also reset to the initial position.

F-2-2 Part 2: Trajectory manipulation

Route manipulation on the PVD

- The route of an aircraft can be modified in the PVD by adding, moving or deleting waypoints. Please select BMS02N in the PVD.
- Hold CTRL to enter route manipulation mode. A waypoint symbol will be attached to the mouse cursor.
- Hold CTRL and left click on a position inside the Travel Space to insert an intermediate waypoint into the trajectory of the selected aircraft.
- You can see that the route has been split-up into two segments and the aircraft route passes through the newly created waypoint. The two new segments will have an equal speed (check that by the speed indication label under the waypoints).
- Observe in the TSD that the sector exit time of the aircraft has not changed (the label and cyan star coincide). Also observe in the VSD that the flight level has not changed.
- Also notice that the new waypoint is visible in the TSD and VSD, and that as for the Travel Space, the speed/time constraints have been split over the two segments.
- Delete the waypoint by pressing CTRL and right clicking on it when it is highlighted

Route manipulation on the TSD

- Waypoints can also be added, manipulated and deleted on the TSD. Press and hold CTRL when the mouse cursor is in the TSD. A waypoint now appears attached to the time-space line of the aircraft.
- Holding CTRL, left click somewhere on the time-space line of BMS02N to insert a waypoint into the trajectory of that aircraft.
- Move the mouse over the new waypoint in the TSD to highlight it and left click and drag to change the planned arrival time at that waypoint.

- Note that you can manipulate the arrival time of the aircraft at both the intermediate waypoint and at the sector exit point. Also notice how the Travel Space on the PVD is directly influenced by speeding up or slowing down the aircraft. In general, the area of the Travel Space will increase when the aircraft is delayed.
- Delete the waypoint in the TSD by pressing CTRL and right clicking on it when it is highlighted.

Route manipulation on the VSD

- Waypoints can be added in the VSD in a similar manner as in the TSD. Press and hold CTRL when the mouse cursor is in the VSD. A waypoint now appears attached to the track of the aircraft.
- Holding CTRL, left click somewhere on the line of BMS02N to insert a waypoint into the trajectory of that aircraft. This will determine the start of an altitude change in the trajectory. If no waypoint is placed, an altitude change will start at the aircraft location.
- Move the mouse over the aircraft label in at the y-axis and left-click and drag it up or down to make an altitude change in the trajectory.
- Note that two new waypoints are generated: one at the end of the first altitude change and another at the start of the altitude change at the end. The speed of the aircraft is adjusted to compensate for the altitude change (note the speed indication label under the waypoints again), and the sector exit time remains constant.
- So far you have only modified the 'probe trajectory of the aircraft. Any changes made here have not been sent to the aircraft and the aircraft would continue to fly along its original trajectory if the simulator was running.
- Deselect the aircraft by right-clicking on any viewscreen and select BMS02N in the PVD again. As can be seen any unconfirmed changes made to the trajectory have been reset. Deselecting an aircraft will also cause any changes made to the probe trajectory to be reset. You can use this cancel the probe trajectory.
- Because of the way altitude is adjusted by dragging the label, it can always only be adjusted in the last segment of the trajectory. Hold CTRL and left click on a position inside the Travel Space in the PVD to insert an intermediate waypoint into the trajectory of the selected aircraft. Now look at the VSD and note a solution space is visible in the last segment. When wanting to change altitude along the entire trajectory and also wanting to change the horizontal trajectory, remember to first adjust the altitude.
- Manipulate the route of BMS02N (add a waypoint and/or change the timing at that waypoint) and press ENTER to send it to the aircraft. You will notice a message at the top left corner of the PVD that confirms that the trajectory of the selected aircraft has been updated. Manipulated aircraft are shown in a brighter shade of green. You can see this after the aircraft is deselected.
- Deselect the aircraft by right-clicking on any viewscreen.

F-2-3 Part 3: Dynamic traffic

- When the simulator is running, select the aircraft and observe how it maneuvers along the updated trajectory. Also observe how the time-axis moves down as time progresses in the TSD. In accordance, you can see that the along-track distance of the aircraft to the exit point will decrease. Practice adding, manipulating, deleting and sending updated trajectories for BMS02N.
- Every 2nd minute a workload rating scale will appear on the left side of the PVD. Please indicate your experienced workload at that time (0 to 100, low to high) by clicking in this scale.
- Press the fast forward on the right top corner of the simulator above the TSD. The simulator will start running at 4x speed (fast-time). You may continue to the next scenario when you feel comfortable with manipulating the route of the aircraft.

F-3 Scenario 2

F-3-1 Part 1: Conflicts on the PVD

- A red colored aircraft symbol indicates that that aircraft is expected to have a loss of separation at some point in the future. A loss of separation occurs when the lateral separation of the aircraft is less than 5 nautical miles with respect to other traffic.
- Use the time slider in the TSD to investigate where and when the loss of separation will occur (do not yet select an aircraft). The circles around the projected aircraft positions have a radius of 2.5 nautical miles, hence, a loss of separation occurs when these circles overlap.
- Select one of the aircraft on the PVD.
- Notice the red and yellow part of the trajectory of the selected aircraft (not in the Travel Space, but along the trajectory line itself). The red section indicates the location of the projected loss of separation for that aircraft. The yellow portion of the line indicates where the aircraft will have a separation of between 7 and 5 nautical miles (close proximity to a loss of separation).
- Also notice that a large red zone is present in the Travel Space of the aircraft. The red zone or restricted field of travel shows all the locations that are unsafe to place a waypoint in. When a waypoint is placed somewhere in the restricted zone, the new trajectory will lead to a conflict with other traffic.
- The yellow boundary around the restricted field of travel indicates that if a waypoint is placed in that area, the new trajectory will be in close proximity to a loss of separation (5-7 nautical miles separation). The aircraft symbol will color yellow if the separation is between 5-7NM.

- Hover over the restricted field of travel in the Travel Space on the PVD with the mouse to highlight the aircraft that causes this zone. Left click on the highlighted zone to select the other aircraft. You can see how the Travel Space of both aircraft is affected by the other aircraft.
- Add a waypoint somewhere in the restricted field of travel for the selected aircraft and check with the time slider in the TSD that the conflict has indeed not been resolved.
- If possible, add a new waypoint in the yellow area of the travel space to resolve the conflict. If this is not possible, delete the other created waypoint first. Check the validity of this conflict resolution with the time slider in the TSD.
- Please delete all newly created waypoints for both aircraft before continuing to the next part.

F-3-2 Part 2: Conflicts on the TSD

- Select one of the aircraft on the PVD
- Notice the restricted field of travel in the TSD. This restricted area represents the locations in time and distance to go for the selected aircraft that are occupied by other traffic. A conflict will occur if the time-space trajectory of the aircraft passes through such a zone.
- Similar to the Travel Space, the yellow boundary around the restricted field of travel indicates that if the time-space trajectory passes through this area, the trajectory will be in close proximity to a loss of separation (5-7 nautical miles separation).
- Hover over the restricted field of travel in the TSD with the mouse to highlight the aircraft that causes this zone. Left click on the highlighted zone to select the other aircraft. You can also see here how the Travel Space of both aircraft is affected by the other aircraft.
- Solve the conflict by changing the arrival time at the sector exit for one of the aircraft and check the validity of this solution by using the time slider in the TSD.
- In this scenario it is possible to solve the conflict and to let both aircraft arrive at the sector exit point at their originally planned time by adding an intermediate waypoint in the TSD. Experiment with such a solution for a given aircraft and check the solution with the time slider.
- Please delete all newly created waypoints for both aircraft before continuing to the next part.

F-3-3 Part 3: Conflicts on the VSD

- Select one of the aircraft on the PVD

- Notice the restricted field of travel in the VSD. This shows the along track location of the conflict as well as the vertical area. As can be seen, the vertical separation between aircraft needs to be at least 10 flight levels.
- Solve the conflict by dragging the label up or down. The aircraft will either pass below or above the other.
- Please deselect the aircraft to cancel any changes before continuing to the next part.

F-3-4 Part 4: Dynamic conflict resolution

- When the simulator is running, select an aircraft and observe how the restricted fields of travel evolve in the Travel Space, TSD and VSD. Also note that the available control space becomes smaller as the aircraft close in.
- Practice conflict resolution with the simulator running. You could, for instance, try to perform a cooperative resolution in which the conflict is resolved by giving both aircraft a small path deviation (spatial or time), rather than manipulating only one aircraft. This will reduce the relative path deviation for each individual aircraft.
- Press the fast forward on the right top corner of the simulator above the TSD. The simulator will start running at 4x speed (fast-time). You may continue to the next scenario when you feel comfortable with manipulating the route of the aircraft.

F-4 Scenario 3

F-4-1 Part 1: Restricted field interpretation on the TSD

- In this scenario there are six controlled aircraft. Five are currently inside the sector and two aircraft (KLY80 and FRS8K) will enter from point BITUC and SUWOL respectively in the near future. None of the aircraft are in conflict with each other (no aircraft are red). You can check the predicted evolution of the traffic by using the time slider in the TSD.
- Note that restricted fields of travel in the Travel Space and TSD are only shown for aircraft that are inside the controlled sector. The zones caused by KLY80 and FRS8K are therefore not represented yet. Aircraft that enter from outside the sector may have conflicts with other aircraft inside the sector, but will only be flagged once they enter the sector.
- Please select the aircraft VFT7K.
- The shape and location of the restricted fields of travel in the TSD provides additional information about the crossing geometry and relative movements of the traffic.
- All restricted zones that lie under the time-space trajectory in the TSD represent aircraft that will pass in front of the selected aircraft. How many aircraft will pass in front? Check this by hovering over the restricted fields to find out which aircraft they belong to, and by using the time slider.

- All restricted zones that lie above the time-space trajectory represent aircraft that will pass behind the selected aircraft. How many aircraft will pass behind? Check this by hovering over the restricted fields to find out which aircraft they belong to, and by using the time slider.
- The location of a restricted zone along the x-axis of the TSD indicates where along the trajectory the other aircraft will pass. You can see that PLX9Z and BRW29 will cross at around the 100 nautical mile to go mark. PMG5L will pass at a further point along the trajectory at around the 50 mile mark.
- An in-trail aircraft (PIR18) is indicated by a restricted field along the entire trajectory of the selected aircraft. In this case the restricted zone is above the time-space line indicating that the aircraft is in-trail and behind VFT7K. Note that delaying the selected aircraft at the sector exit point will cause an in-trail conflict (overtake) with PIR18.
- Note that in the TSD the labels are also shown of all other aircraft that have the same sector exit point as the selected aircraft. In this case you can see the label of PIR18. Additionally, by clicking on the label you can select the other aircraft.
- Please switch between selecting aircraft VFT7K and PIR18 on the TSD. Because these aircraft fly along exactly the same trajectory, the shape and location of the restricted zones caused by the other traffic remain the same for both aircraft.
- Select one of the in-trail aircraft (VFT7K or PIR18).
- The shape of the restricted zones in the TSD also provides information about the crossing angle of the other traffic. A pure 90 degree crossing (PMG5L) will show up as a circular restricted zone. Check this in the TSD.
- A shallow crossing (BRW29) will result in a forward slanted ellipse-shaped restricted zone. Check this in the TSD.
- A head-on crossing (PLX9Z) will look like a backward slanted ellipse-shaped restricted zone. Check this in the TSD.
- As a direct result of the crossing geometry and the shape of the restricted zone, can you reason whether a head-on conflict or a shallow conflict is harder to resolve with a speed change alone? As a hint: imagine that the ellipses of BRW29 and PLX9Z are located on the time-space line of the selected aircraft.
- Please select the aircraft BRW29.
- By only looking at the conflict zones in the TSD, can you reason how many aircraft will pass in front of the selected aircraft, how many will pass behind, how many crossing points there are along the trajectory, and where and what the passing geometry looks like (shallow or head-on crossing)?
- When KLY80 and FRS8K enter the sector a head-on conflict will occur, could you reason what the shape of a head-on restricted zone would look like in the TSD?

F-4-2 Part 2: Dynamic restricted fields

- In this scenario you are free to manipulate the trajectories of the aircraft and see what the influence is on the conflict zones in the TSD.
- Press the fast forward on the right top corner of the simulator above the TSD. The simulator will start running at 4x speed (fast-time). You may continue to the next scenario when you feel comfortable with manipulating the route of the aircraft.

F-4-3 Part 3: Exercise

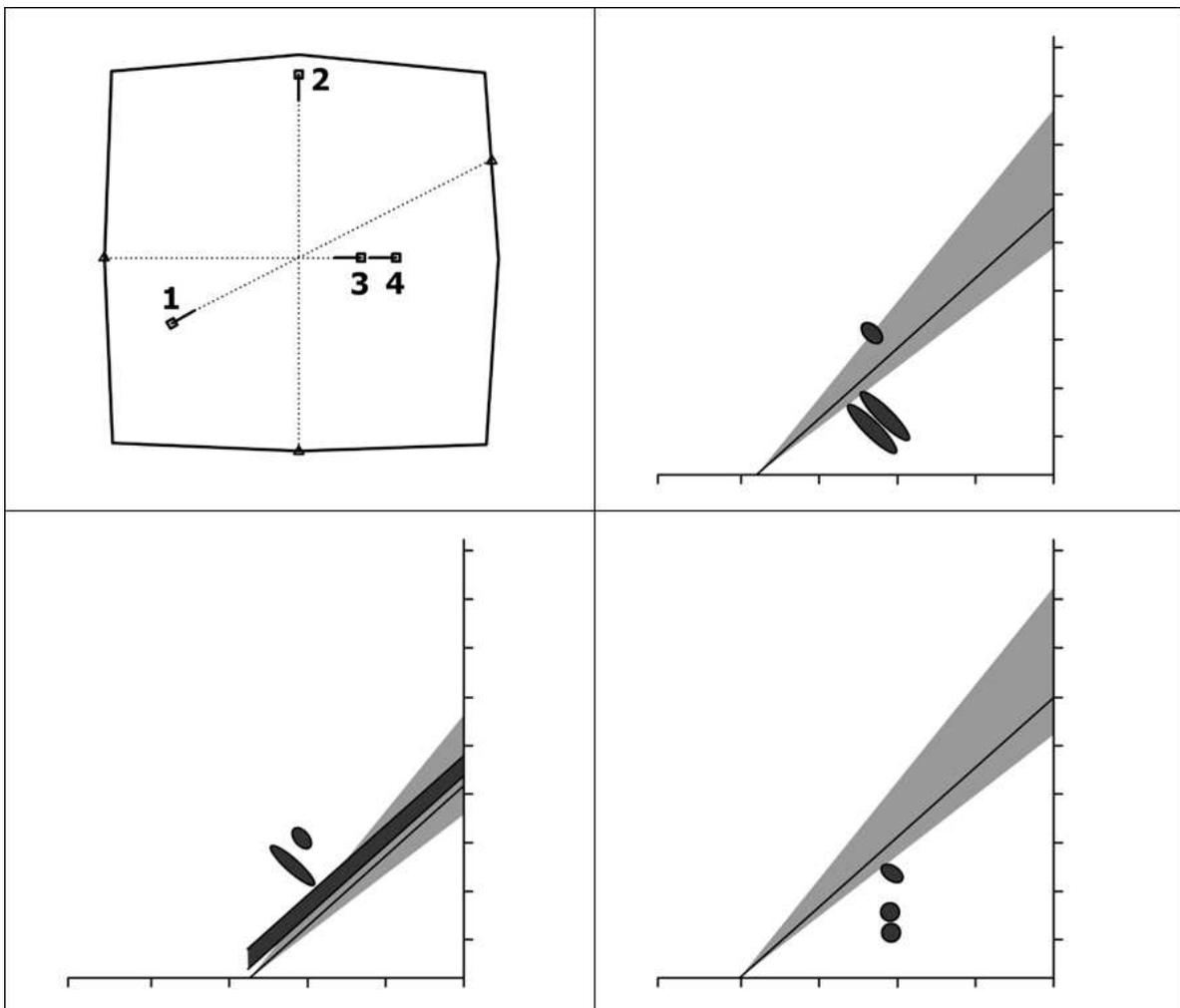


Figure F-1: Exercise Image

- The above picture shows a schematic image of a sector and three TSDs. Each TSD shows the time-space line and restricted zones for a specific aircraft in the sector (1,2,3, or 4). Which TSD belongs to which aircraft?

F-5 Scenario 4

F-5-1 Part 1: Restricted field interpretation on the VSD

- In this scenario there are four controlled aircraft. Two aircraft are flying in trail towards TAMUK and one is going in the opposite direction. The fourth aircraft crosses the trajectories of the others at an angle.
- Select the front of the two aircraft in trail (VFT7K). This aircraft is in conflict with the crossing aircraft, but not with the others. Note on the second line of the aircraft labels that our selected aircraft and the crossing aircraft are at FL300, the oncoming aircraft is at FL280 and the aircraft in trail is at FL320.
- Observe the solution space in the VSD. When highlighting the different red zones you can see which aircraft these possible conflicts are with. The zone at the current altitude belongs to the conflicting aircraft, you can see the trajectory passes through the conflict area. The red zone below belongs to the oncoming aircraft. Note it is more narrow as the time in conflict is shorter with oncoming aircraft.
- The wide area around FL320 belongs to the aircraft in trail. This aircraft is flying above and faster than the selected aircraft. Note in the TSD the PIR18 label is below the VFT7K label, meaning it exists the sector before VFT7K. You can also use the time slider to see it overtake the selected aircraft.
- Drag the label in the VSD towards the different conflict areas and to plausible solutions to see how the travel space changes in the PVD and the TSD. Notice how dragging the trajectory to the lower red zone creates a zone in the TSD that is unavoidable by changing speed, which makes sense considering the aircraft is now in a head-on conflict. Dragging the trajectory to the upper red zone creates a zone in the TSD which can only be avoided in speed if the speed is increased so much the aircraft has to leave the sector too soon, which makes sense considering the overtaking aircraft was supposed to leave the sector before the selected aircraft.

F-6 Scenario 5

F-6-1 Part 1: Restricted airspace and traffic flows

- This scenario features a restricted airspace in the middle of the controlled sector. The restricted airspace represents hazardous weather or a no-fly zone and should be avoided by all aircraft. Trajectories that go through a restricted airspace are shaded orange.
- Currently none of the active aircraft is planned to fly through the restricted zone. However, there is one conflict between PIR18 and FTM6R.
- Please select aircraft PIR18.
- Add a waypoint in the Travel Space on the trajectory of LWB54 and HTZ78, and on a safe location (i.e., merge the routes of the selected aircraft and the two other southbound aircraft). Press enter to send the new trajectory to the aircraft.

- Investigate the TSD of PIR18 to see how the restricted areas in the TSD of a trajectory merge look. It can be seen that from the added waypoint to the sector exit point, the two other aircraft will fly in-trail and behind.
- Also investigate the TSD of HTZ78 and LWB54 to see how the restricted area of an aircraft looks that merges on the trajectory of a selected aircraft.

F-6-2 Part 2: Basic dynamic scenario

- In this scenario you are free to manipulate the trajectories of the aircraft to resolve any further conflicts or restricted airspace crossings.
- Press the fast forward on the right top corner of the simulator above the TSD. The simulator will start running at 4x speed (fast-time). You may continue to the next scenario when all incoming aircraft have entered the sector, are conflict free, and will fly around the restricted airspace.

F-7 Practice Scenarios

- In the previous scenarios you have been shown all the tools and features that are available to you to in the experiment simulator. The following training scenarios are intended as practice, to increase your experience, and to make you feel comfortable with performing your task in this experiment.
- In each scenario you are free to manipulate the trajectories of the aircraft to resolve any further conflicts or restricted airspace crossings during the remainder of the scenario. Try to minimize any path deviations and delays at the sector exit point, and please try to adhere to the scenario traffic structure.
- The difficulty will slightly increase in each subsequent practice scenario.
- You may continue to the next scenario when all incoming aircraft have entered the sector, are conflict free, and will fly around the restricted airspace.
- The difficulty of the scenarios in the main experiment will be at more or less the same level as these practice scenarios.
- At the start of each scenario, press the fast forward on the right top corner of the simulator above the TSD. The simulator will start running at 4x speed (fast-time).

Experiment Results

G-1 Safety

The number of conflicts and their duration for both experiments are shown in Figure G-1 and the number and duration of restricted area intrusions are shown for both experiments in Figure G-2.

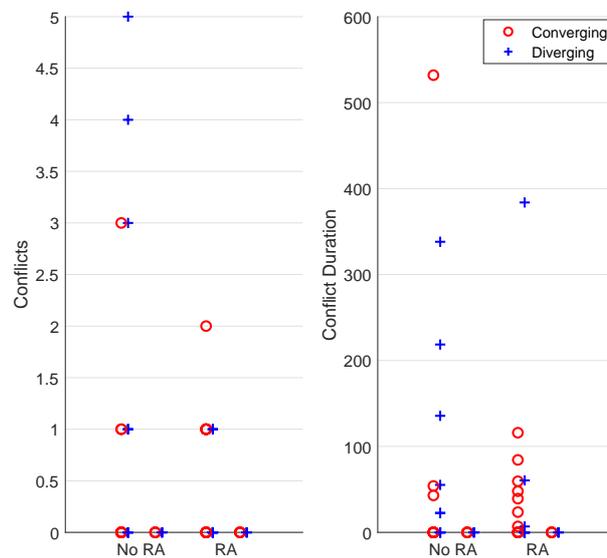


Figure G-1: Results of number of conflicts and conflict duration for both experiments without (left) and with (right) VSD

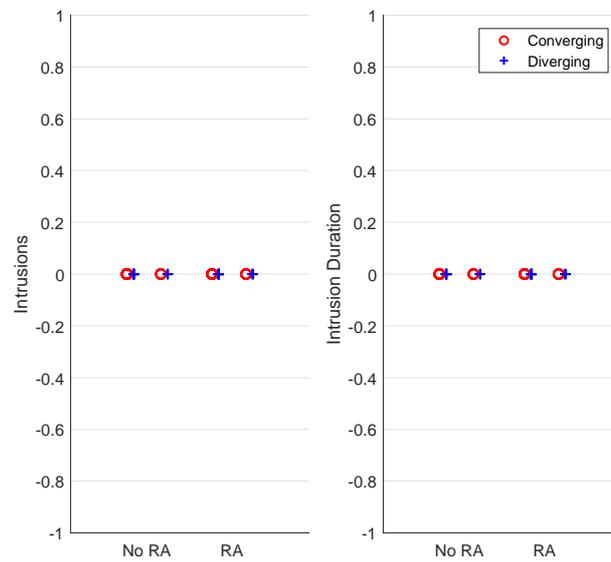


Figure G-2: Results of number of intrusions and intrusion duration for both experiments without (left) and with (right) VSD

G-2 Efficiency

The total added track miles in *nm* for both experiments are shown in Figure G-3. For both experiments the total delay is shown in Figure G-4 and the average and maximum altitude changes are shown in Figure G-5.

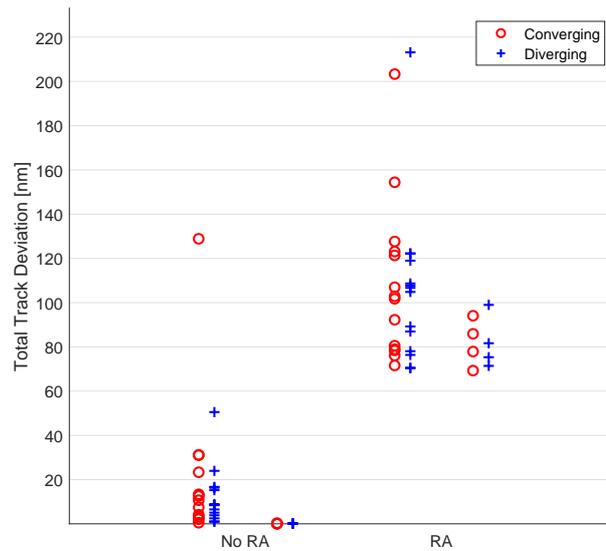


Figure G-3: Results of total added track miles in *nm* for both experiments without (left) and with (right) VSD

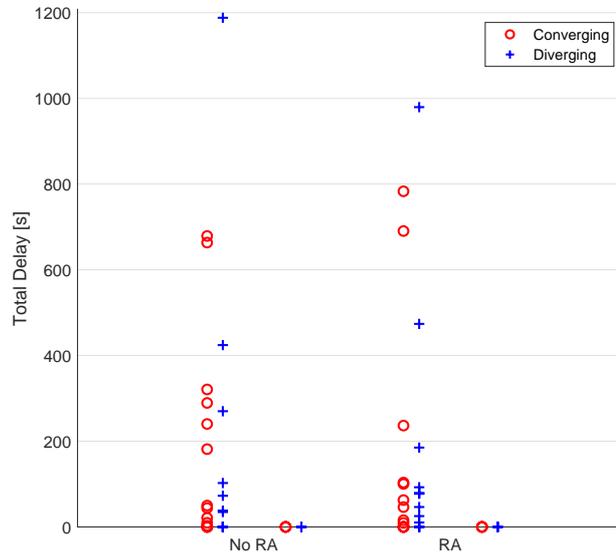


Figure G-4: Results of total delay in s for both experiments without (left) and with (right) VSD

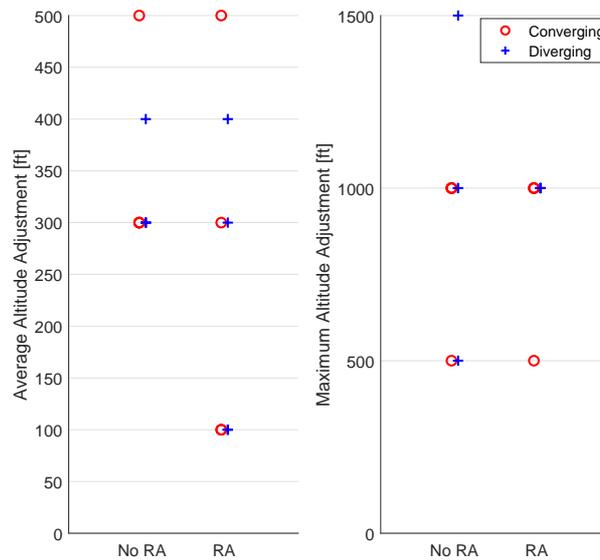


Figure G-5: Results of average (left) and maximum (right) altitude changes in ft for the experiment with VSD

G-3 Workload

The workload ratings for both experiments and their z-scores are shown in Figure G-6. The user activity for the experiment without and with VSD is shown in Figure G-7.

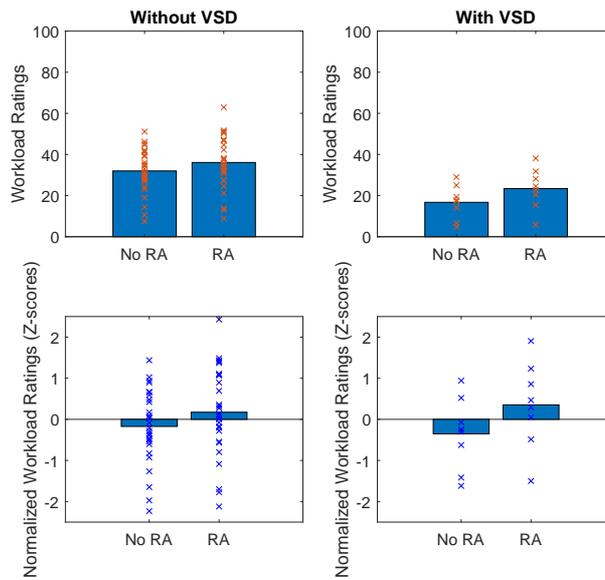


Figure G-6: Workload ratings and Z-scores of both experiments. The crosses indicate the individual values and the bars indicate the mean of each set.

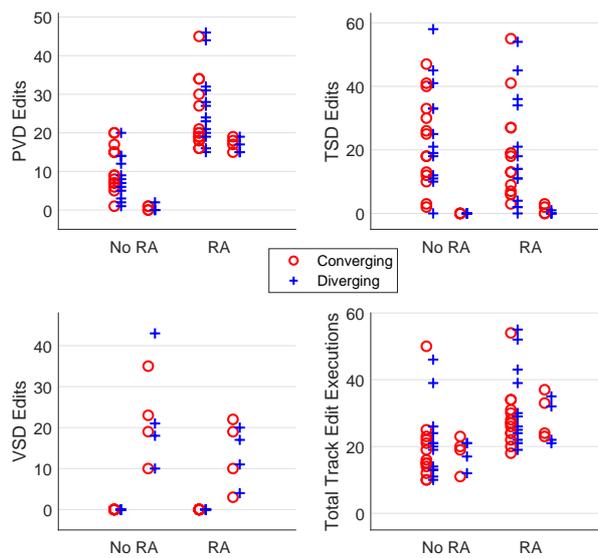


Figure G-7: Results of trajectory edit actions per viewscreen and total executed trajectory changes for the experiment without (left) and with (right) VSD

G-4 Control Strategies

G-4-1 P1

The observed strategy for *P1* was to separate traffic by altitude on sector entry. One traffic stream was chosen to change in altitude (either up or down by $1000ft$) on what seemed to be the least dense at the start of the scenario. In the scenarios with RA the aircraft needing to be routed around the RA were routed as close as possible around the RA. For all scenarios the TSD was unused. The mouse heatmaps of all scenarios for this participant are shown in Figure G-12, Figure G-13, Figure G-14, and Figure G-15.

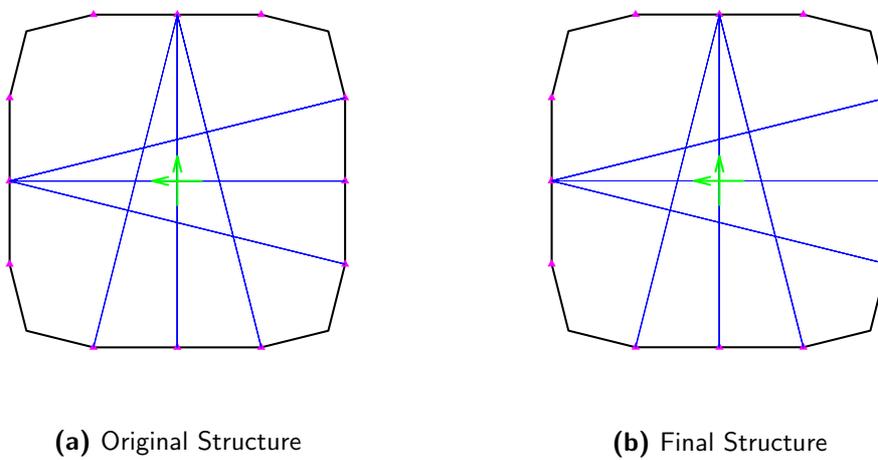


Figure G-8: Horizontal traffic structure of P1 in the Converging scenario without RA

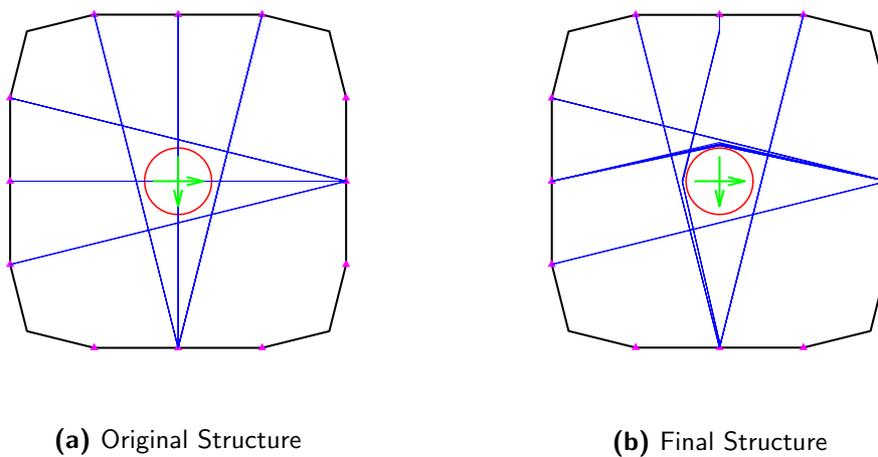


Figure G-9: Horizontal traffic structure of P1 in the Converging scenario with RA

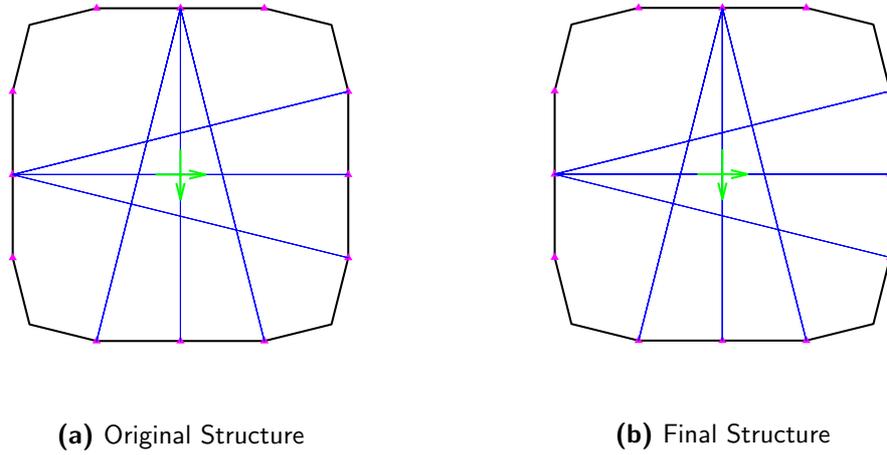


Figure G-10: Horizontal traffic structure of P1 in the Diverging scenario without RA

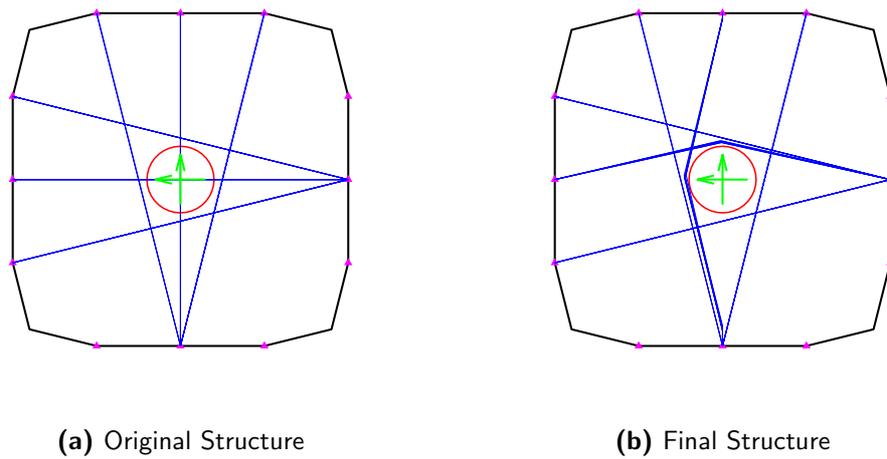


Figure G-11: Horizontal traffic structure of P1 in the Diverging scenario with RA

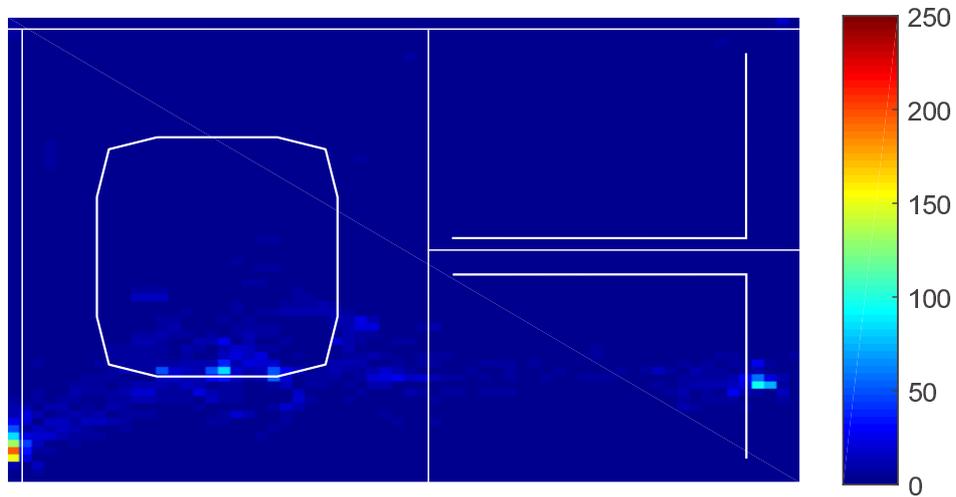


Figure G-12: Heatmap of mouse activity on the interface of P1 in the Converging scenario without RA

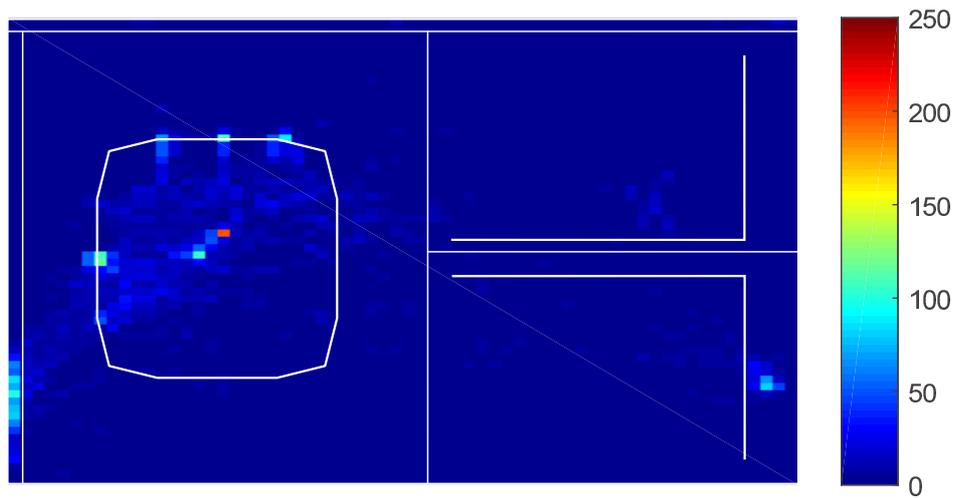


Figure G-13: Heatmap of mouse activity on the interface of P1 in the Converging scenario with RA

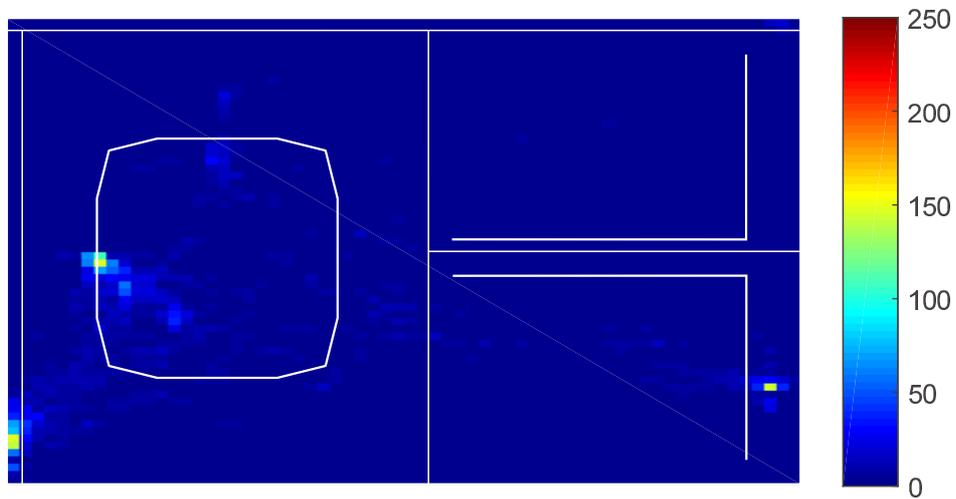


Figure G-14: Heatmap of mouse activity on the interface of P1 in the Diverging scenario without RA

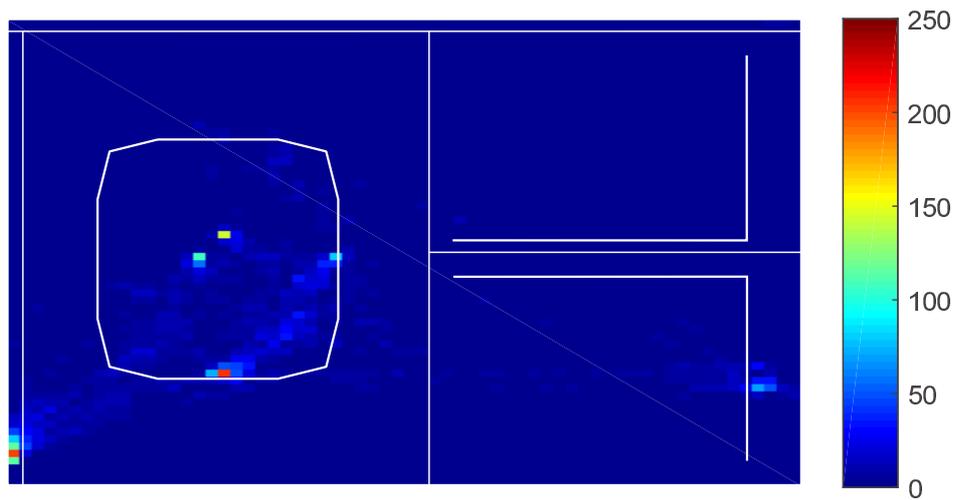


Figure G-15: Heatmap of mouse activity on the interface of P1 in the Diverging scenario with RA

G-4-2 P2

The observed strategy for *P2* was to solve conflicts as they occurred. With no RA present, almost all conflicts were solved in altitude by making aircraft from one (consistent) stream climb 1000 *ft* and descend back down after the aircraft had passed all crossing traffic streams. Small conflicts were occasionally solved horizontally or with the TSD. With an RA present, solving conflicts horizontally was preferred when aircraft were also passing through the RA, but sometimes both horizontal and vertical changes were used. When conflicts occurred with neither aircraft passing through the RA, the same altitude resolutions were usually used as in the scenarios without RA. The mouse heatmaps of all scenarios for this participant are shown in Figure G-20, Figure G-21, Figure G-22, and Figure G-23.

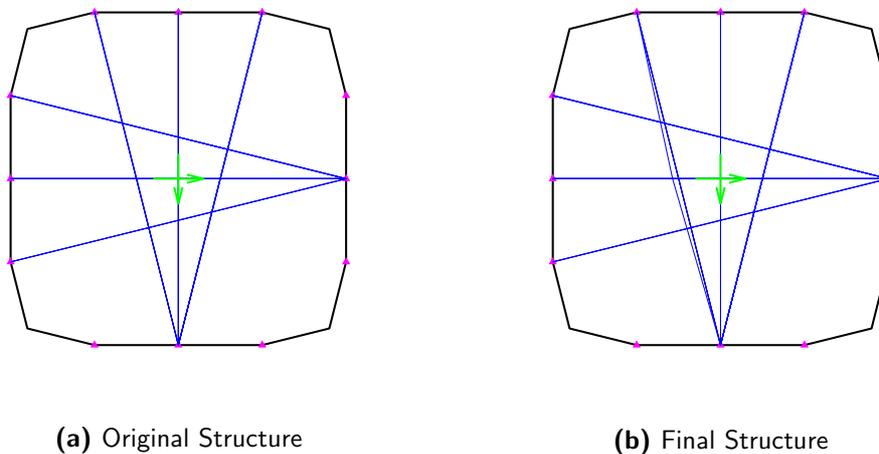


Figure G-16: Horizontal traffic structure of P2 in the Converging scenario without RA

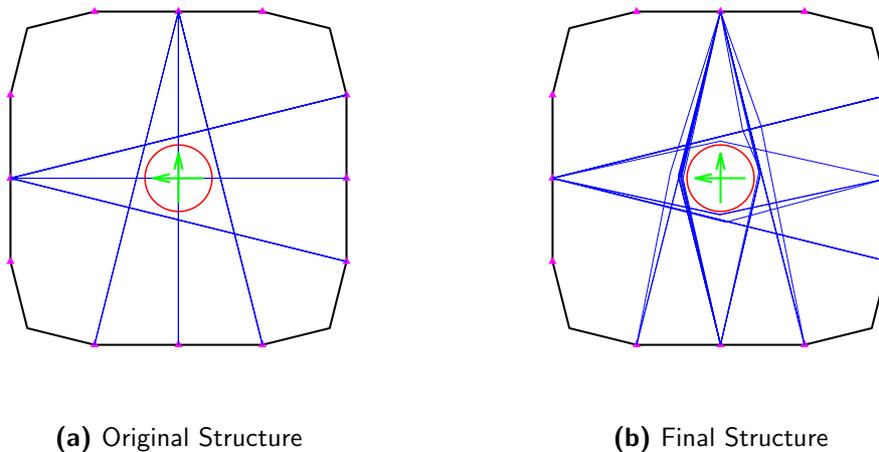


Figure G-17: Horizontal traffic structure of P2 in the Converging scenario with RA

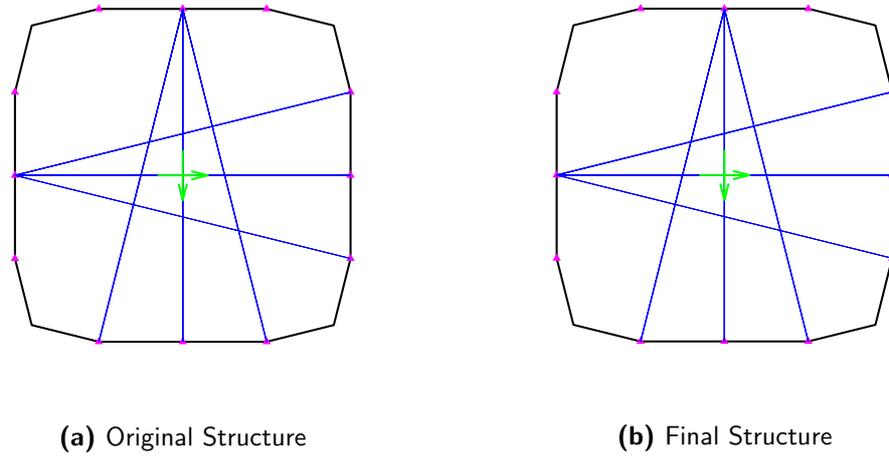


Figure G-18: Horizontal traffic structure of P2 in the Diverging scenario without RA

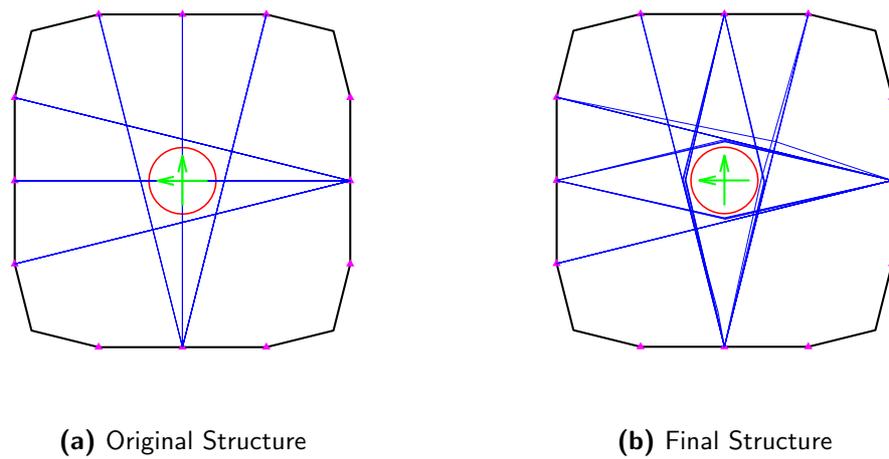


Figure G-19: Horizontal traffic structure of P2 in the Diverging scenario with RA

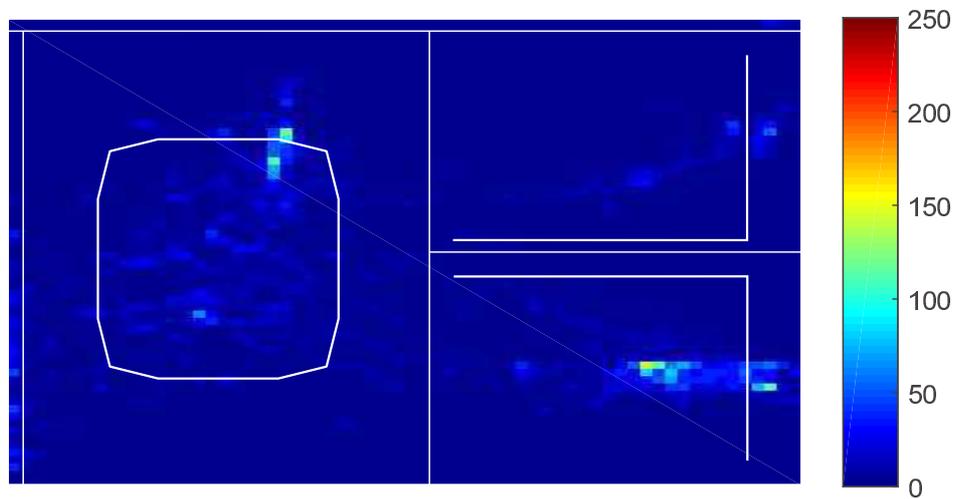


Figure G-20: Heatmap of mouse activity on the interface of P2 in the Converging scenario without RA

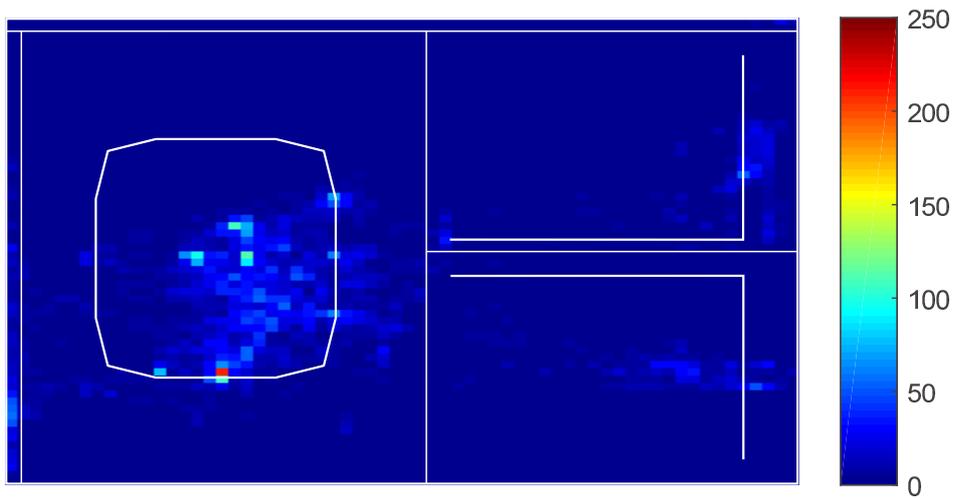


Figure G-21: Heatmap of mouse activity on the interface of P2 in the Converging scenario with RA

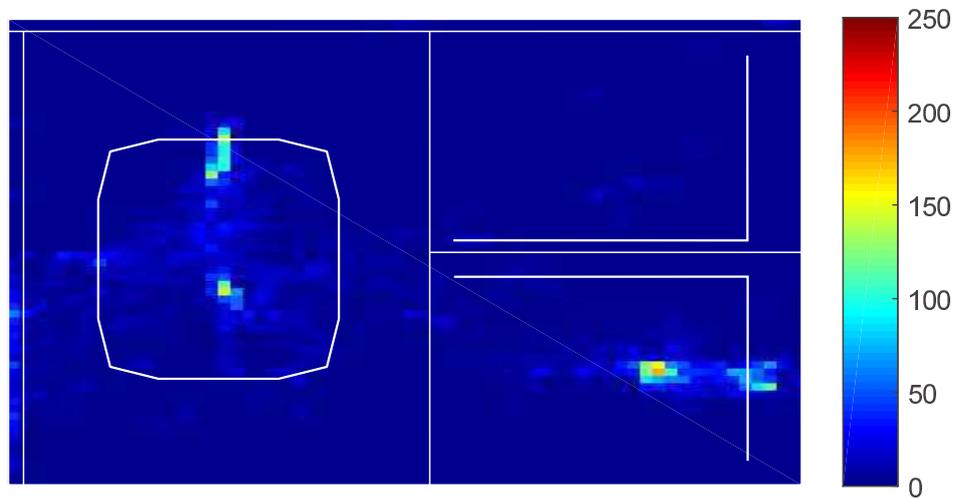


Figure G-22: Heatmap of mouse activity on the interface of P2 in the Diverging scenario without RA

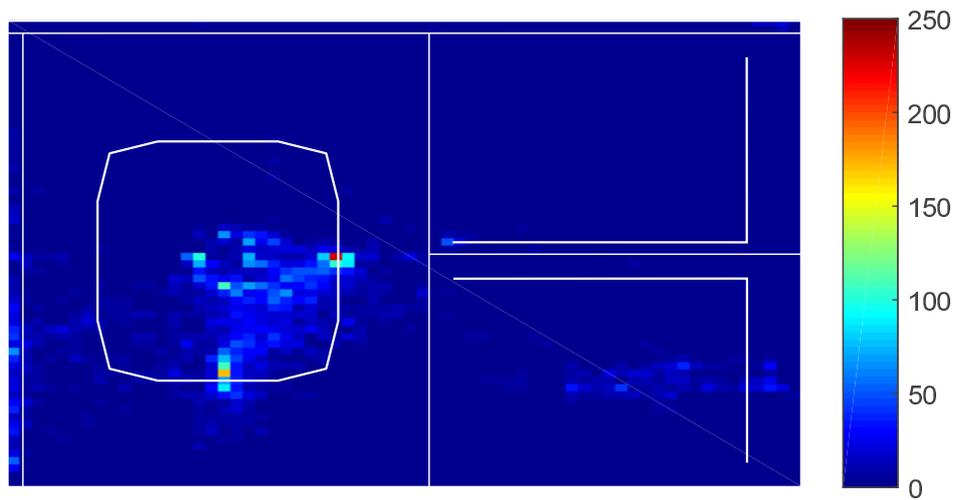


Figure G-23: Heatmap of mouse activity on the interface of P2 in the Diverging scenario with RA

G-4-3 P3

The observed strategy for *P3* was to solve conflicts as they occurred. With no RA present, almost all conflicts were solved in altitude by making aircraft from one (consistent) stream climb 1000*ft*. Occasionally, when the traffic stream that was usually left at the same altitude seemed less dense than the other, conflicts were solved by making aircraft from this stream descend by 1000*ft*. Small conflicts were occasionally solved horizontally or with the TSD. With an RA present, solving conflicts horizontally was preferred when aircraft were also passing through the RA, but sometimes both horizontal and vertical changes were used. When conflicts occurred with neither aircraft passing through the RA, the same altitude resolutions were usually used as in the scenarios without RA. The mouse heatmaps of all scenarios for this participant are shown in Figure G-28, Figure G-29, Figure G-30, and Figure G-31.

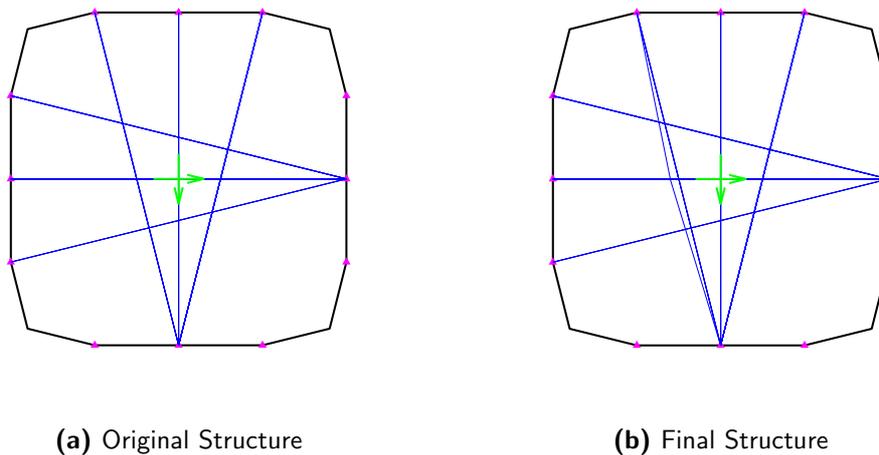


Figure G-24: Horizontal traffic structure of P3 in the Converging scenario without RA

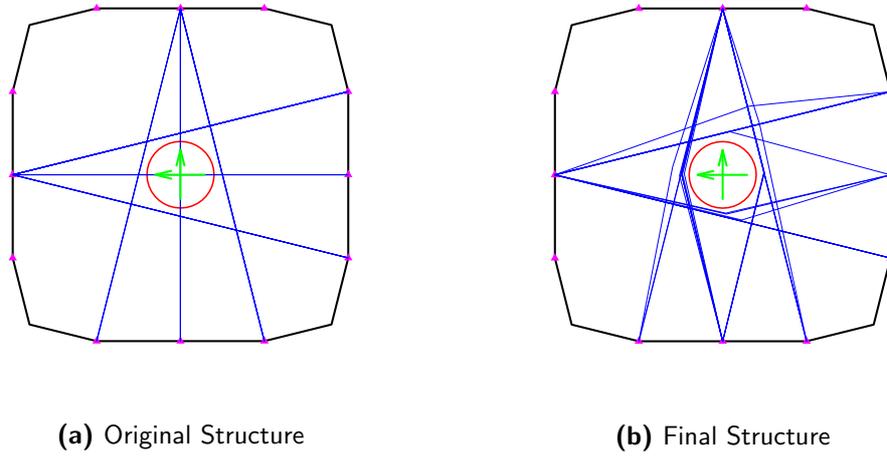


Figure G-25: Horizontal traffic structure of P3 in the Converging scenario with RA

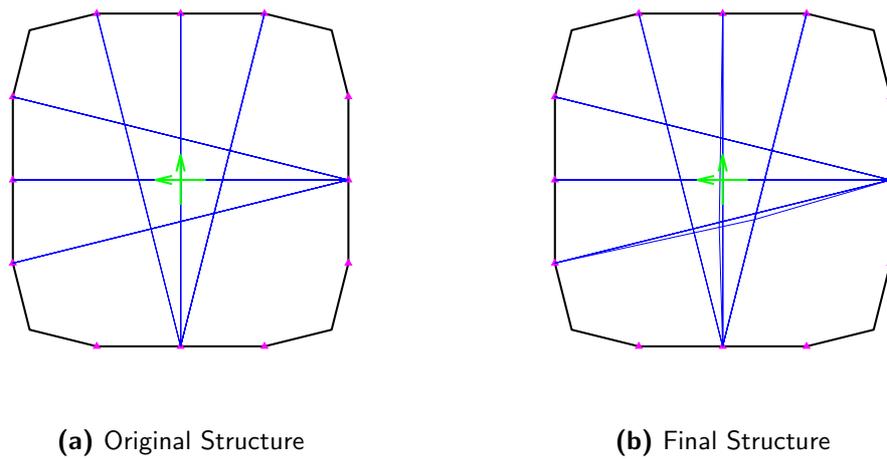


Figure G-26: Horizontal traffic structure of P3 in the Diverging scenario without RA

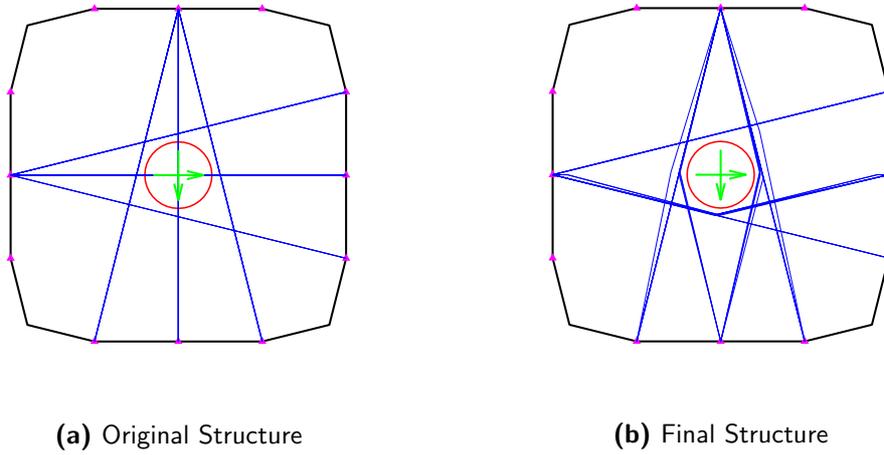


Figure G-27: Horizontal traffic structure of P3 in the Diverging scenario with RA

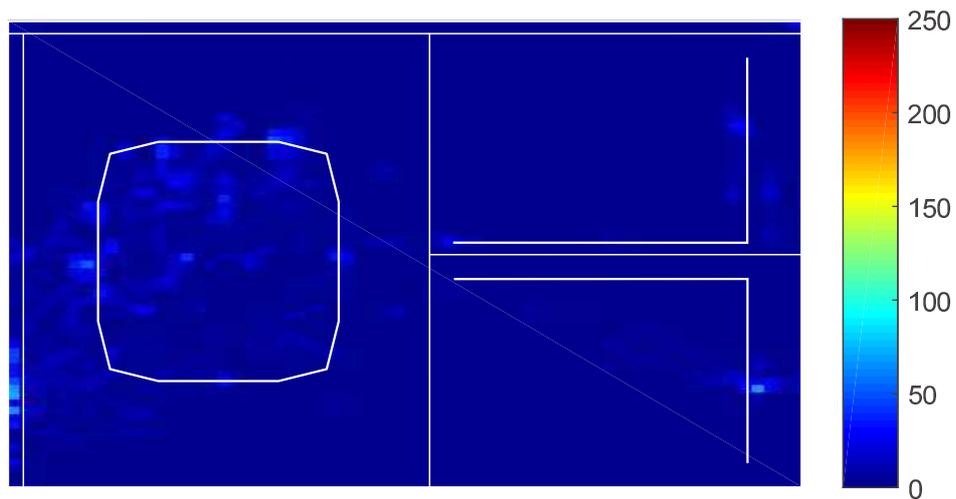


Figure G-28: Heatmap of mouse activity on the interface of P3 in the Converging scenario without RA

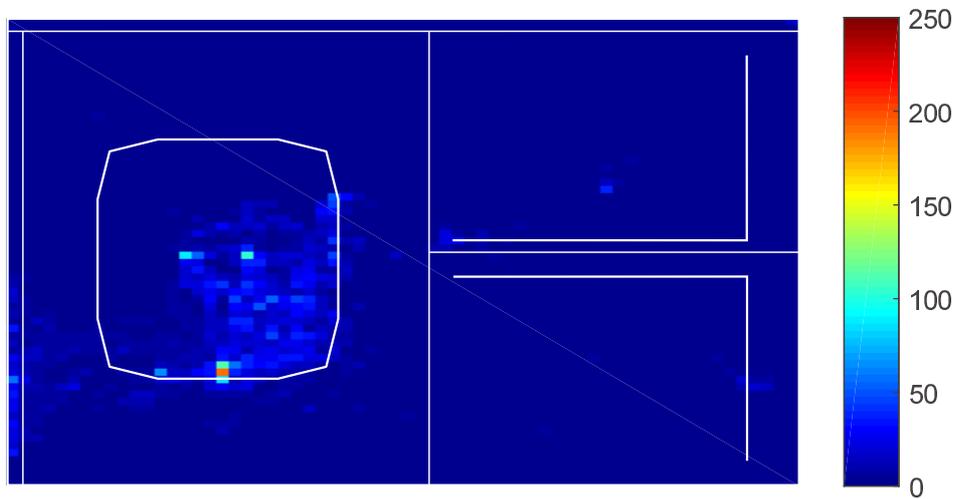


Figure G-29: Heatmap of mouse activity on the interface of P3 in the Converging scenario with RA

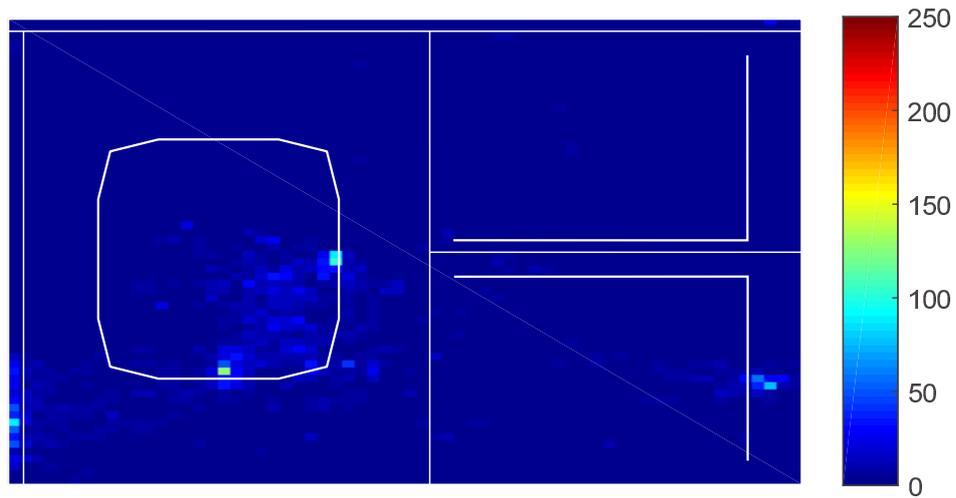


Figure G-30: Heatmap of mouse activity on the interface of P3 in the Diverging scenario without RA

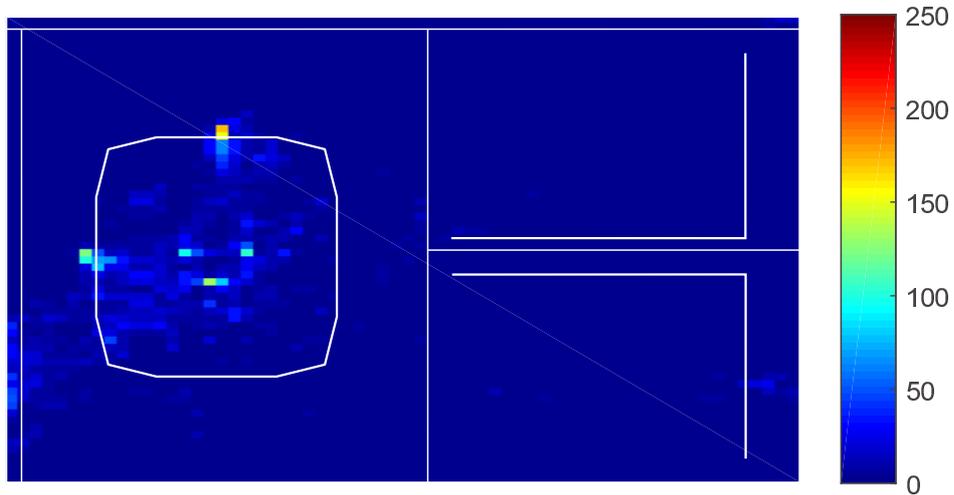


Figure G-31: Heatmap of mouse activity on the interface of P3 in the Diverging scenario with RA

G-4-4 P4

The observed strategy for *P4* was to solve conflicts as they occurred. With no RA present, almost all conflicts were solved in altitude with cooperative solutions by making aircraft from one stream climb $500ft$ and aircraft from the other stream descend $500ft$. Small conflicts were occasionally solved horizontally. With an RA present, solving conflicts horizontally was preferred when aircraft were also passing through the RA, but sometimes both horizontal and vertical changes were used. When conflicts occurred with neither aircraft passing through the RA, the same altitude resolutions were usually used as in the scenarios without RA. With this participant, the most problems occurred when trying to implement both a horizontal and vertical trajectory change. The mouse heatmaps of all scenarios for this participant are shown in Figure G-36, Figure G-37, Figure G-38, and Figure G-39.

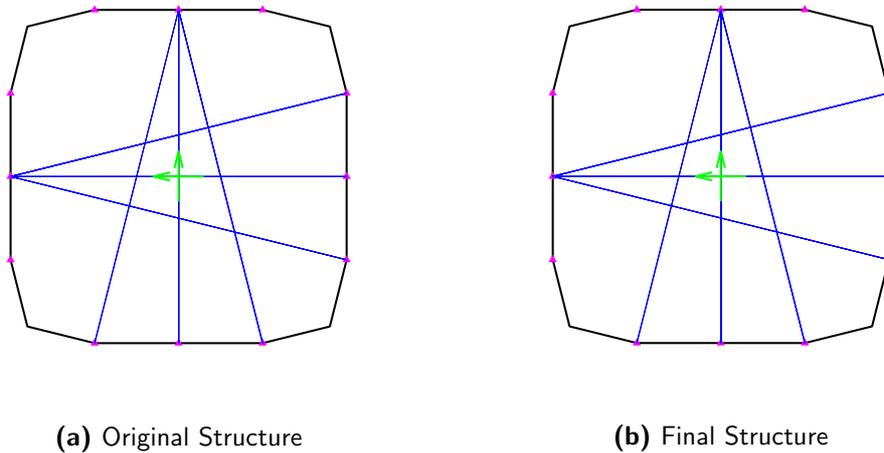


Figure G-32: Horizontal traffic structure of P4 in the Converging scenario without RA

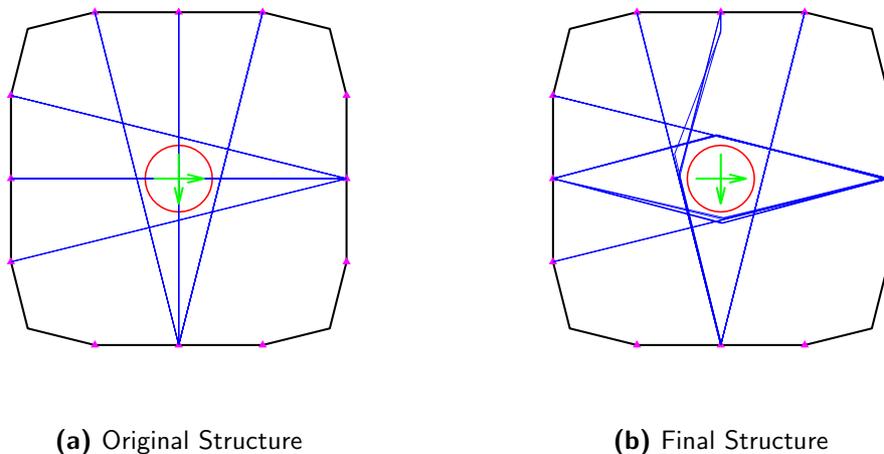


Figure G-33: Horizontal traffic structure of P4 in the Converging scenario with RA

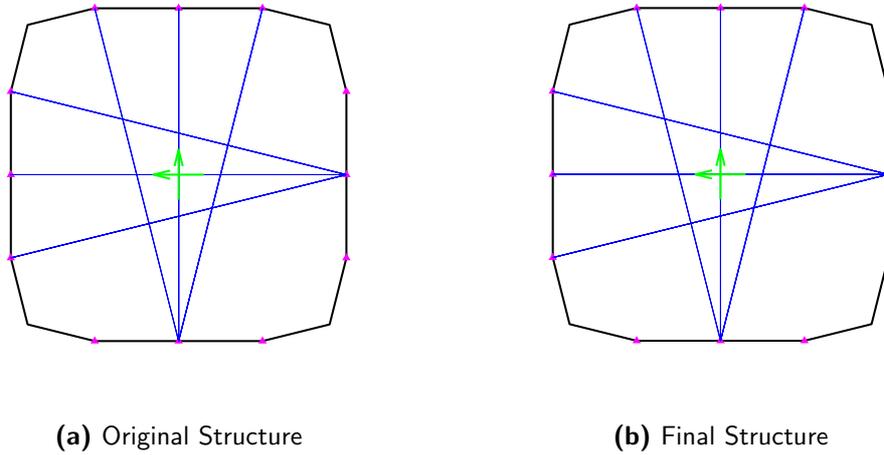


Figure G-34: Horizontal traffic structure of P4 in the Diverging scenario without RA

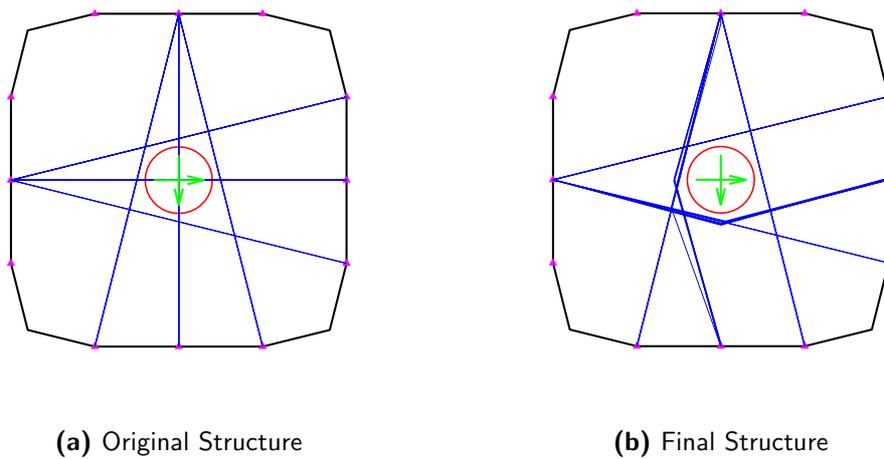


Figure G-35: Horizontal traffic structure of P4 in the Diverging scenario with RA

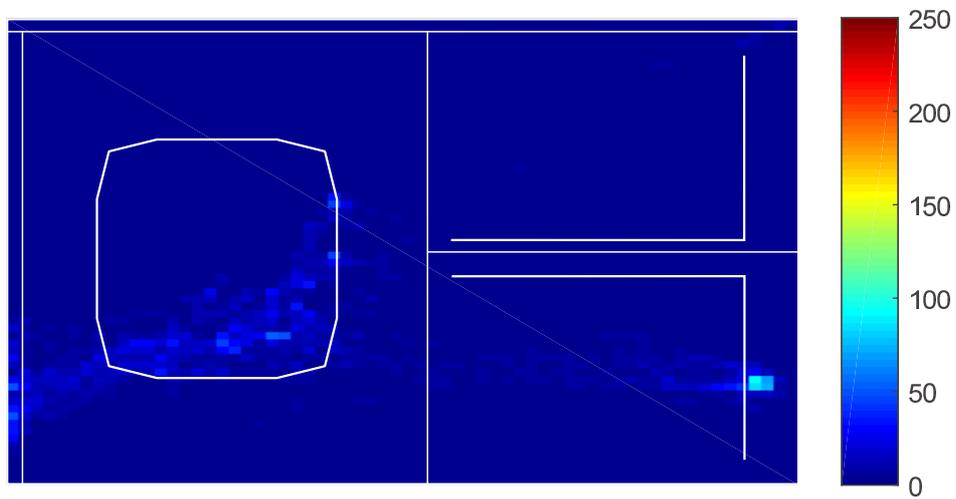


Figure G-36: Heatmap of mouse activity on the interface of P4 in the Converging scenario without RA

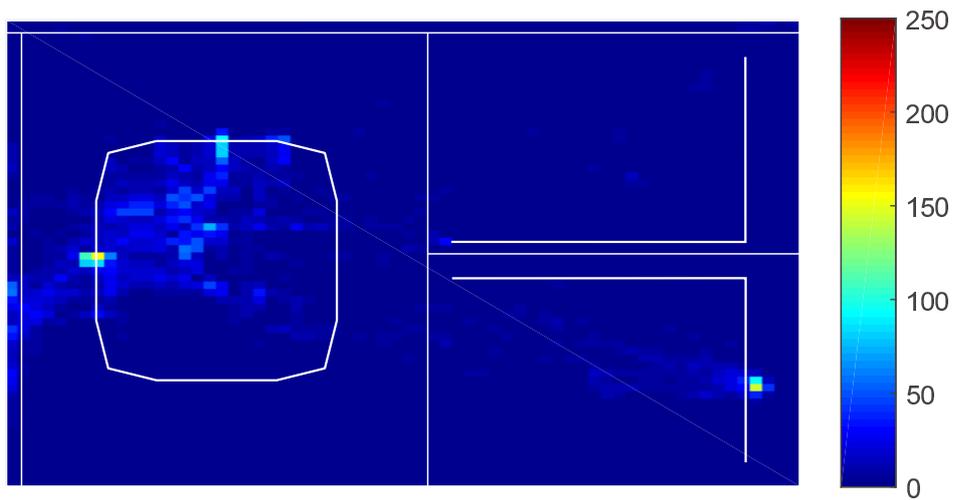


Figure G-37: Heatmap of mouse activity on the interface of P4 in the Converging scenario with RA

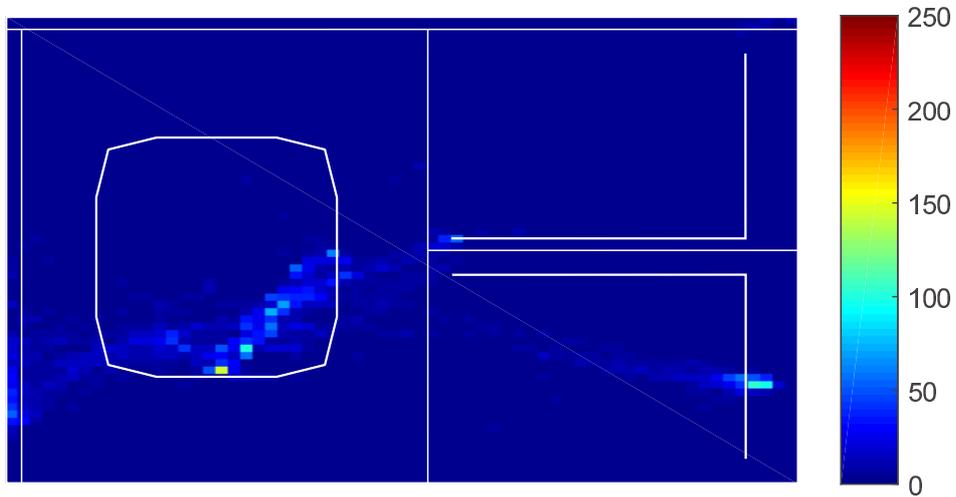


Figure G-38: Heatmap of mouse activity on the interface of P4 in the Diverging scenario without RA

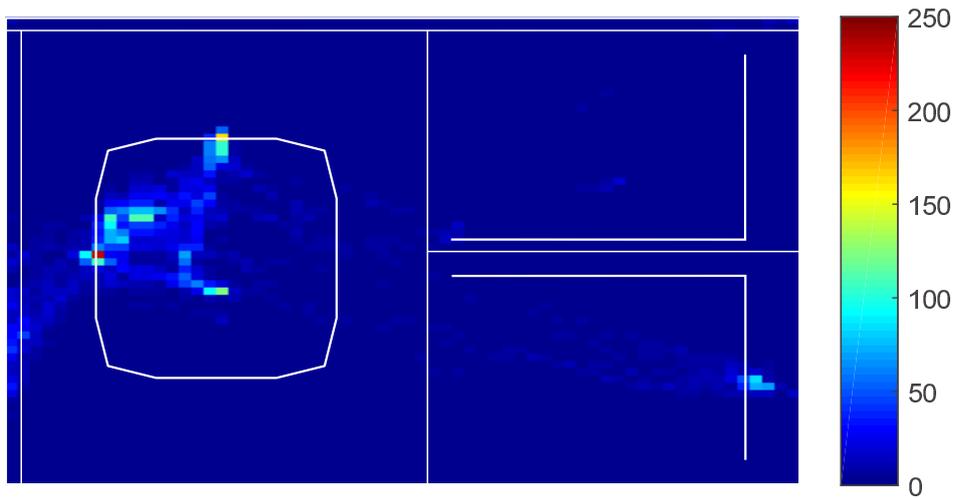


Figure G-39: Heatmap of mouse activity on the interface of P4 in the Diverging scenario with RA

Appendix H

Interface Code

The package structure of the interface code is shown in Figures H-1,H-2, and H-3. Classes that were changed or added are shown in red. The additions and changes are detailed per package in the following sections. Besides the changes in the packages, all the shaders have been edited to account for the altitude when determining conflicts and solution spaces.

H-1 display

- In the display package, the biggest addition was the vsd package, containing everything to display and interact with the vsd. This package was created by copying the tsd package and altering it to, step by step, become the VSD.
- For the other viewscreens, alterations were made to the classes in the aircraft and travelspace/timespace packages. These changes involved adding a second texture to be sent to the shaders which provides altitude information on the trajectories.
- In GLRbt in the radarscreen a check was added to see if a non-selected ac moves through a special use airspace, changing the colour of the trajectory in the viewscreen if it does. This was added because the possibility of special use airspaces being limited by altitude was added, meaning the trajectory going through a special use airspace on the horizontal view does not necessarily mean it will actually pass through this space (because it might be going over or under).
- In GLAircraft in radarscreen, the aircraft label was adjusted to show altitude.
- In DisplayState and GLMasterViewport, the VSD was added as a viewscreen where necessary.
- In GLMasterViewport logging functionality was added to enable logging of the mouse position.

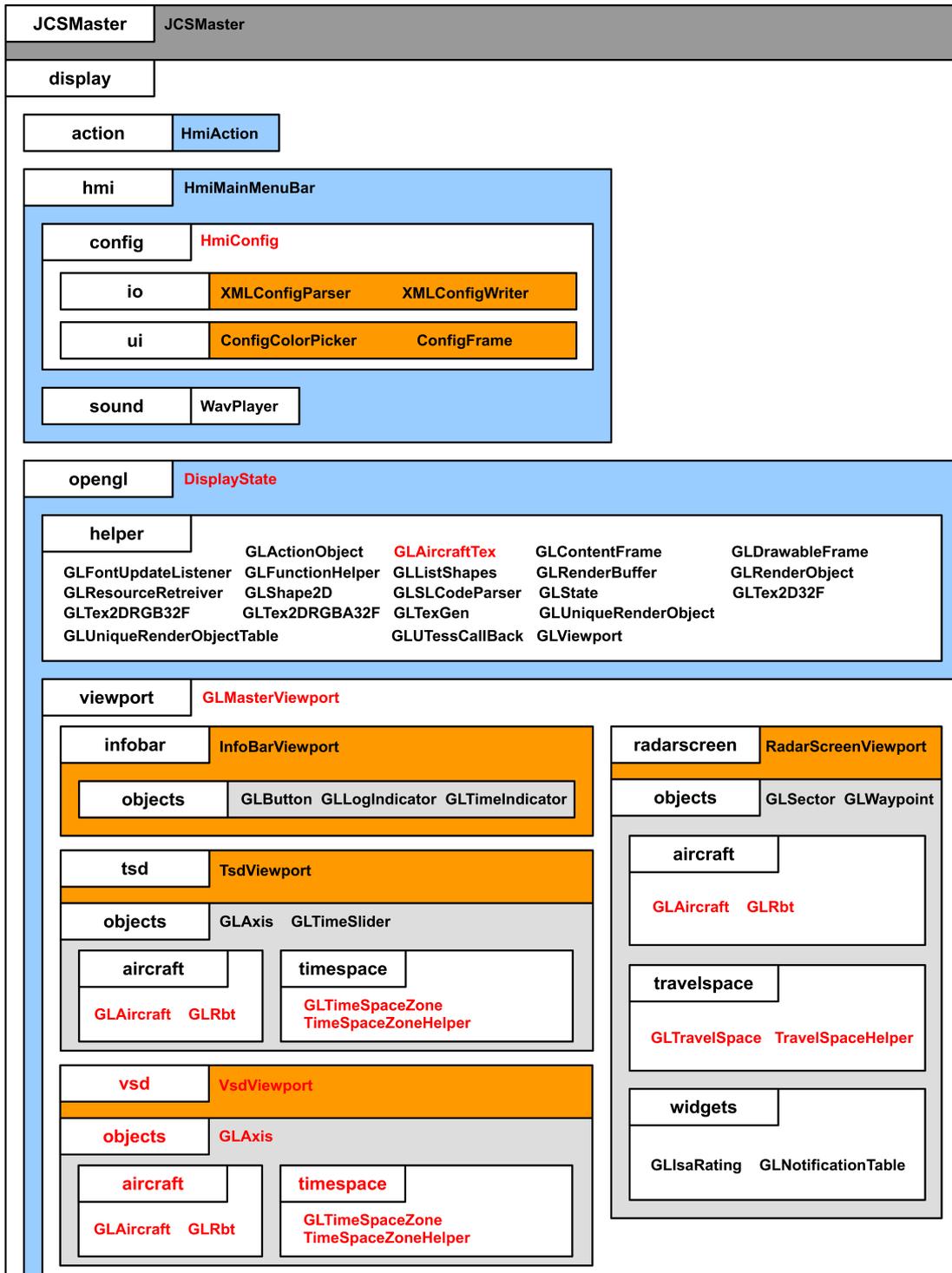


Figure H-1: Package structure of the interface code (1/3)

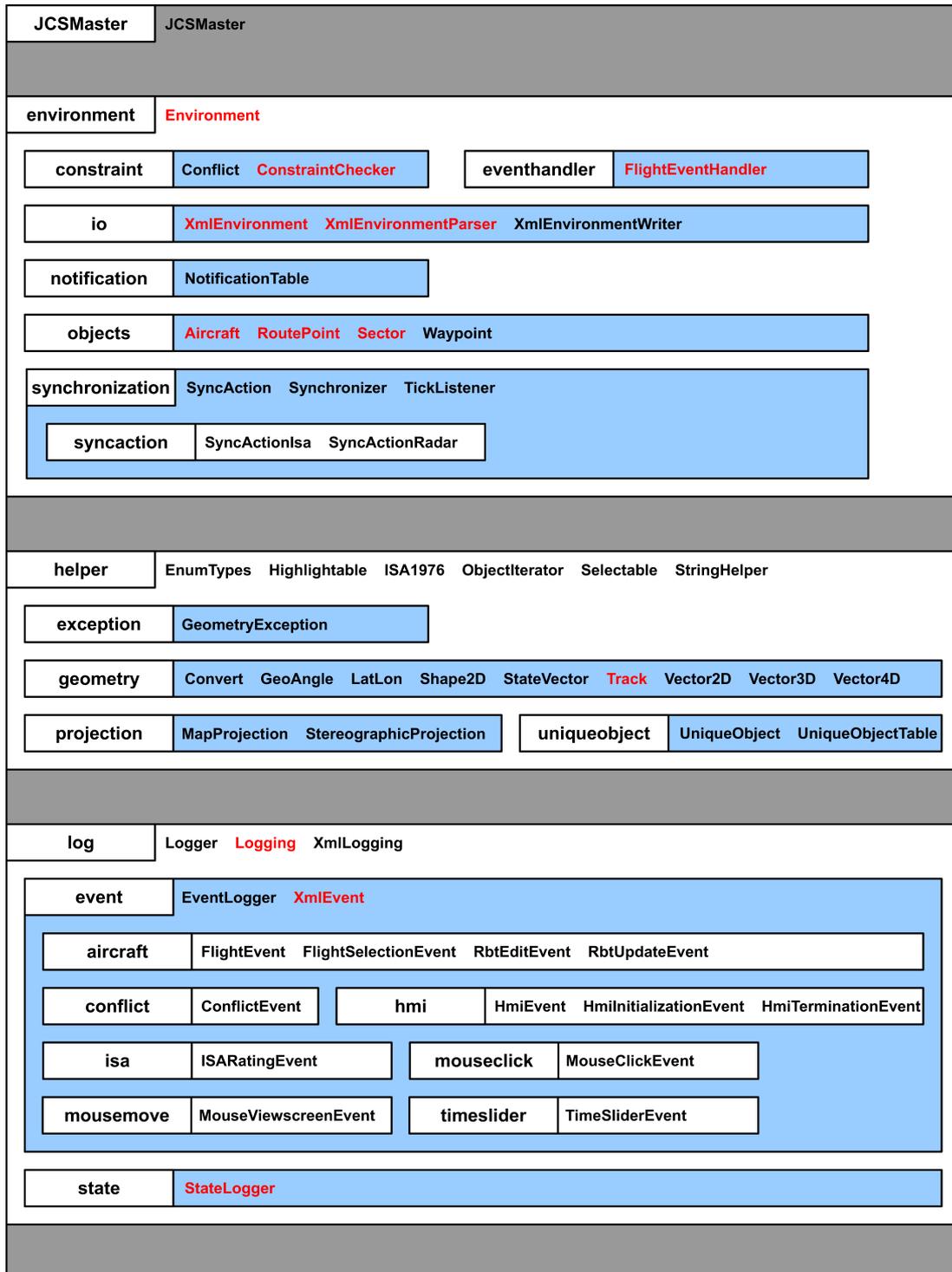


Figure H-2: Package structure of the interface code (2/3)

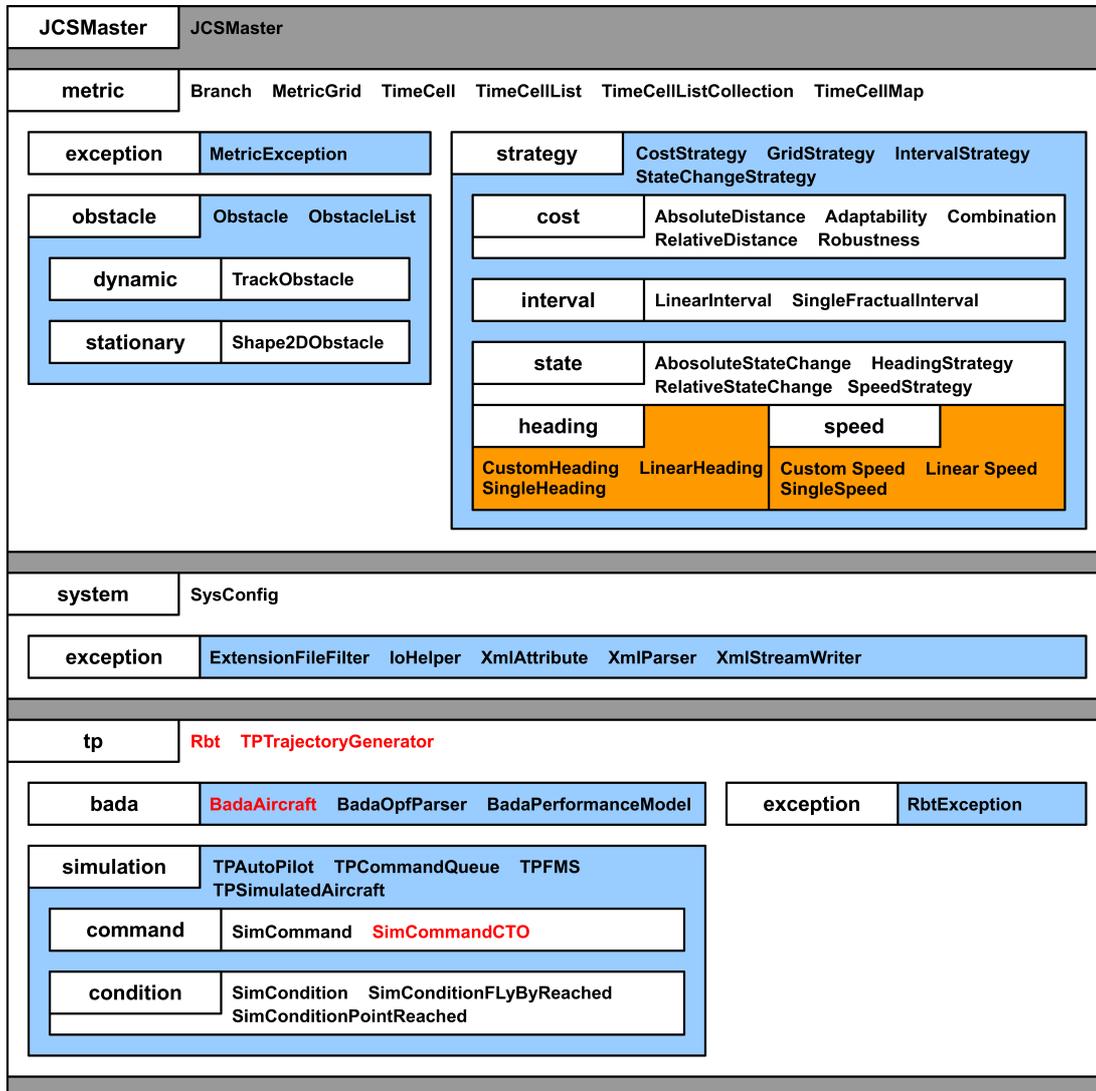


Figure H-3: Package structure of the interface code (3/3)

- GLAircraftTex was altered in the helper package of opengl to add a new AltArray class working the same way as IntentArray but includes altitude data to send to the shaders as a texture.
- Both AltArray and IntentArray (in GLAircraftTex) were given the vsdUpdate functions which allows parts of the array to be removed and the solutions space to be drawn starting at different waypoints. HmiConfig was altered to include config variables for the VSD.

H-2 environment

- In the environment class, the variable `NUM_CLICK_VSD` was added to track the number of clicks in the VSD like in the other viewscreens.
- In `ConstraintChecker`: the function `getCPA_s_nm` now also returns the altitude difference between the aircraft at cpa to help determine conflicts. `getConflicts` now also checks altitude when determining conflicts.
- In `FlightEventHandler`, in `deselectAircraft`, the aircraft's boolean is set `setEdited(false)` to confirm the waypoints are no longer being edited in altitude.
- In `FlightEventHandler`, `addRoutePoint` now also determines the altitude of the waypoint based on the altitude of the other route points
- In `XmlEnvironment`, added `N_ALTS`, `N_ALT`, `A_BOT` and `A_TOP` nodes which adds the option to read sector altitudes from scenario xml files.
- In `XmlEnvironmentParser`: sector altitudes can be read. If no sector altitudes are included in the xml a range of FL200 – 400 is assumed. Special use airspaces are now included in the `SECTOR` object table, as seems to have been intended as the aircraft state update checks the `SECTOR` table to determine if it is inside a special use airspace.
- In `Aircraft`: update next waypoint if it is being edited and if it is an altitude change. Added an altitude check for the special use sector check. `edited` boolean to track if the aircraft is actively being edited or not. `setEdited(false)` when an edit is executed to confirm the waypoints are no longer being edited.
- In `RoutePoint`: Added boolean `PoC` which is true for the first waypoint of the two generated for a climb/descent. This helps identify the correct points for several computations. Added `interpolateAtDtg_s` used to determine x,y position at a certain dtg. Used when dragging the label in the VSD. Added `getAltDistancePositionAtDtg_s` based on `getTimeSpacePositionAtDtg_s` to determine position in the VSD viewscreen.
- In `Sector`, added `bottom` and `top` float values to include an altitude range in sectors.

H-3 helper & logger & tp

- In `Track`, added `altStart` and `altEnd` to help generate the states
- In `Logging`, added `VSD_VIEWPORT` in the mouse click counter.
- In `StateLogging`, added `logMouse` function for mouse position tracking.
- In `XmlEvent`, added `VSD_VIEWPORT` as possible event location
- In `Rbt`, `postProcess` now determines the altitude of states and conforms the speeds in the rbt and the states to the correct values according to the climbs (constant IAS climb and adjust speed when level to compensate)

- In TPTrajectoryGenerator, includes starting and ending altitudes in order to determine the altitude of sates between waypoints.
- In BadaAircraft: `getRoC` and `getRoD` compute the rate of climb or descent with a given altitude and TAS using bada data. `getMaxAlt` and `getMinAlt` compute the maximum and minimum attainable altitude based on sector, aircraft and time constraints
- In SimCommandCTO, `execute()` takes the correct altitude into account

Appendix I

Recommendations and Conclusions

In this chapter conclusions are drawn on the project. Additionally, recommendations are made for the further development of the interface.

I-1 Conclusions

The goal of this project was to extend an existing trajectory management interface to include the visualization of altitude and decision making support to manipulate the trajectory in altitude. This was done by adding a Vertical Situation Diagram to the interface. This would make the interface fully 4D, visualizing all the dimensions of the trajectories and enabling manipulation in all four dimensions. Besides this the interface was validated with a small experiment, the results of which were compared to the results of an experiment without VSD to attempt to say something meaningful about the addition of the VSD.

Using the principles of ecological interface design and the principles of display design, the VSD was designed and implemented into the interface. Special care was taken to ensure that the information presented was consistent and presented in a similar manner as in the existing parts of the interface to optimize visual momentum. The resulting interface allowed for and supported full 4D trajectory manipulation with a limited increase in complexity.

The interface performed as intended during the experiment. Participants applied recognisable strategies to control the scenarios and the VSD was used as intended, though more flexibility in manipulating the trajectories in the VSD could have been beneficial. A comparison with an experiment without VSD hints at a decrease in workload for participants while solving conflicts at least as efficiently, if not more efficiently. No meaningful observations could be made comparing performance in terms of safety, as no significant safety data was found.

I-2 Recommendations

When further developing the interface, some basic improvements to the VSD could improve the performance and flexibility of implementation greatly. As already mentioned in the discussion of the interface, enabling the trajectory to be manipulated in the VSD by dragging the trajectory segments up or down can reduce the complexity for the users and increase performance. In a similar vein, and also mentioned in the discussion, dragging waypoints and properly visualizing the effects of this action in every viewscreen can improve user experience.

Right now the VSD can only implement a standard climb or descent which is the achievable rate for the altitude. Introducing different kinds of climbs and descents for users to implement in the trajectory would likely needlessly add complexity without really improving the interface. However, allowing the interface to work with different sector entry and exit altitudes and also introducing set intermediate waypoints from which climbs or descents are set to start or end will be necessary when looking at realistic scenarios the interface will need to be able to handle.

When considering realistic scenarios, another important thing to consider is the effects of wind and pilots ability to adhere to the trajectories. Currently, the interface assumes there is no wind and the aircraft always follow the trajectory perfectly, meaning it is entirely deterministic. Wind and uncertainty are important factors to deal with properly when wanting to implement this interface in the real world. Besides this, a good way to test the interface would be to see how a more realistic scenario is handled. An existing sector could be implemented in the interface with traffic as it is encountered in the real world (translated to 4D trajectories).

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