Decision Support Tool for Time-Based Separation under Fixed Approach Trajectories in Approach Control

Increasing the Efficiency of Approach Control

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Cover Image: Aircraft Flying in the Sunset by Gerhard Gellinger

Preface

Before the reader lies my master thesis report. The final requirement to graduate as an aerospace engineer at the faculty of Aerospace Engineering, Delft University of Technology. This thesis has been performed in collaboration with LVNL as part of the Centre-of-Excellence programme, which in turn is funded by the Knowledge and Development Centre Mainport Schiphol.

I would like to thank the people directly involved with the thought process throughout my graduation. That includes all the paricipants of the experiment and my supervisors Clark Borst, Max Mulder, René van Paassen and Gijs de Rooij who represented the TU Delft and Ferdinand Dijkstra who provided supervision from the KDC side with a lot of experience in the world of ATM.

Finally, I would like to thank my parents, family and friends who supported me through the good and sometimes tough times here in Delft. Special thanks go to my fellowship friends and roommates with whom I had the pleasure of spending lots of time on our “bankie?”, talking about non-study related topics and allowed me to take my mind of my thesis for a brief moment. Last but not least, I would like to thank all the people who I met during my time at LVNL and iLabs, the conversations we had enabled me to solve problems and nasty bugs.

Stijn van Selling
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Thesis Paper

Decision Support Tool for Time-Based Separation under Fixed Approach Trajectories in Approach Control

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Abstract—**The Dutch Air Traffic Control has implemented fixed approach trajectories within approach control during night operations when traffic density is low. During the day, when traffic density is higher, vector-based operations are used. The Dutch Air Traffic Control aims to implement fixed approach trajectories when traffic density is high. This shift from the current vector-based operations will allow aircraft to perform a continuous descent and fly around inhabited areas,reducing the emissions and noise. To improve the capacity of the landing runway in strong headwind conditions, time-based separation is envisioned. Separating aircraft on time will result in a constant runway capacity in all wind conditions. However, to make these changes possible, additional decision support tools are required to assist controllers and reduce their workload. This paper discusses the use of a new toolset, centered around a time-space diagram which shows the expected arrival time and distance-to-go to a selected reference waypoint. Results of an experiment with eight professional air traffic controllers show that the added tools allowed future conflicts to be solved sooner and with fewer instructions. Aircraft followed the fixed approach trajectories better in the latter stages of the approach when compared to current vector-based operations. Although a slight increase in runway capacity was observed with the new toolset, it was not statistically significant. The workload of the controllers did not show a difference when using the new toolset. In conclusion, the added tools enabled the controllers to combine fixed approach trajectories with time-based separation. However, to reduce perceived workload, future designs should aim to integrate the time-space diagram on the main radar screen such that controllers do not need to switch attention between screens.**

Index Terms—**Air Traffic Management, Time-Based Separation, Fixed Approach Trajectories, Air Traffic Control, Decision Support Tool, Time-Space Diagram**

I. Introduction

THE Air Traffic Management (ATM) system is expected to change in the coming years to accommodate new airspace users and address environmental concerns [1, p. V-VI]. Air Traffic Controllers (ATCOs) are envisioned to change their role with the use of Decision Support Tools (DST) from a tactical to a more strategical approach [2]. Within approach control, the two most notable changes at Amsterdam Airport Schiphol (AAS) are the desire to implement Time-Based Separation (TBS) in combination with fixed approach trajectories in the Terminal Maneuvering Area (TMA). Fixed approach trajectories lead aircraft from the Initial Approach Fix (IAF) to the Final Approach Fix (FAF), where the Instrument Landing System (ILS) is intercepted. With the introduction of these two concepts, safety, productivity and efficiency are expected to be improved, while reducing controller workload.

TBS is envisioned to replace the currently used Distance-Based Separation (DBS) operations [1, p. 70], where aircraft are separated based on distance. When a strong headwind is present on final approach, maintaining a fixed distance between landing aircraft considerably decreases the landing capacity. TBS is envisioned to eliminate these losses. Separating aircraft based on time allows the distance between aircraft to reduce safely in strong headwind conditions, enabling more aircraft to land within the same time interval.

The main issue with TBS is that with the current tooling available to approach controllers, TBS is very difficult to obtain from a 2D radar screen. Hence, additional tooling is required. Such tooling has been successfully implemented at Heathrow with use of the Intelligent Approach (IA) tool [3]. In the near future IA will also be used at AAS. The main limitation of IA is that it is not yet compatible with fixed approach trajectories. ATCOs are still required to vector aircraft onto the extended centerline, aided by the IA tool.

Fixed approach trajectories allow aircraft to descend more consistently and predictably. Furthermore, the trajectories can be placed such that they lead aircraft around cities and villages, reducing noise pollution in populated areas. Currently, fixed approach trajectories are already in use during night operations at AAS. Flightpath uncertainties and the limited maneuvering space available when adhering to fixed approach trajectories currently require an increased separation between arriving aircraft, lowering the runway capacity. A reduced runway capacity at night is accepted as capacity demand is low. During the day, however, capacity demand increases, and fixed approach trajectories can not be used with the current toolset available. Aircraft are vectored onto the extended centerline to intercept the ILS. This adds uncertainty to the flightpath of an aircraft, and because the amount of track miles flown to the runway are unknown, a continuous decent is not possible. If a fixed approach trajectory is flown, however, the pilots and the FMS of the aircraft can anticipate the amount of track miles to fly and adjust their descent profile accordingly.

With the introduction of fixed approach trajectories, speed and altitude instructions are preferred to merge the traffic and guarantee sufficient separation. Identifying future conflicts as soon as possible is therefore important. Currently, approach controllers merge traffic close to the FAF. This is no longer possible when aircraft fly on the same approach trajectories. It is difficult for a human operator to foresee the effect of a speed change 5-10 minutes in the future, including effects of the wind, descent profile and variations in aircraft performance. Therefore, a new DST needs to be designed to support the controllers in their control task. With the correct use of such a DST, controllers can make better informed decisions. Predicted trajectories will include uncertainties caused by variations in wind speed and direction, pilot behavior, aircraft performance, etc. [4]. The DST should therefore enable controllers to take uncertainties into account when making decisions.

This research aims to implement TBS and fixed approach trajectories in approach control. In Section II more background on the problem is provided. Next, the newly designed DST elements are presented in Section III. The experiment performed to evaluate the DST is explained in Section IV, of which the results are presented in Section V. These are discussed in Section VI after which the conclusion follows in Section VII.

II. Background

Aircraft descending towards their destination airport fly through different sectors. Each sector is controlled by a different ATCO. The task of the ATCOs is to guide the aircraft towards the sector exit point, which could be a waypoint, direction or runway. Sometimes flightpaths of different aircraft cross, causing a conflict which can lead to a Loss Of Separation (LOS) if insufficient action is taken. ATCOs bear the responsibility of maintaining sufficient horizontal and vertical separation between aircraft. Separation is primarily maintained to avoid a midair collision, and secondary to avoid wake turbulence caused by a leading aircraft. In approach control, all arriving traffic is put in sequence towards the active runway(s). Aircraft follow each other and effects of wake turbulence must not be neglected.

A. *Concept of Operations*

The proposed improvements of the ATM system include the concepts of TBS and fixed approach trajectories [1, p. 70,XI].

1) Time-Based Separation: TBS has proven to increase runway capacity at Heathrow and is envisioned to be beneficial at AAS [3], [5]. TBS has been operational at Heathrow since March 2015 with the use of the Intelligent Approach (IA) tool [3]. IA adds moving markers on the extended runway centerline as can be seen in Figure 1. This marker is used as reference for controllers to aim at. Aircraft are put as close as possible behind the moving markers. If the aircraft passes the moving marker, insufficient separation is maintained. The IA margin indicator is only available on the extended centerline. At Heathrow, IA has proven to increase the tactical capacity on average by two aircraft landings per hour in all wind conditions and saves on average 1,410 seconds of arrival spacing every day which is equivalent to extending

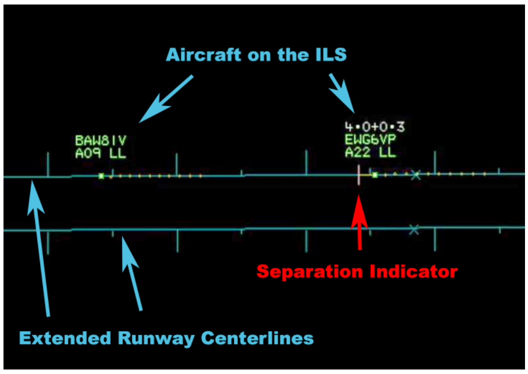


Figure 1: Intelligent Approach Screenshot [8]

the operating day with 23.5 minutes [3]. TBS separates aircraft based on time, allowing the runway to be used to its full capacity in all weather conditions. Different aircraft types are taken into account according to the RECAT wake turbulence categorization [6]. Using the RECAT aircraft types, the TBS separation used at Heathrow were deemed too small to be used at AAS by LVNL. Alternative separation minima were used [7], see Table I. For the empty leader/follower combinations, a required separation minima of 80 seconds is used.

Table I: Time Based Separation (TBS) minima, light category excluded [7]

Leader \ Follower		Super Heavy A	Upper Heavy B	Lower Heavy C	Upper Medium D	Lower Medium E
Super Heavy	A		100s	120s	140s	160s
Upper Heavy	B				100s	120s
Lower Heavy	C				80s	100s
Upper Medium	D					
Lower Medium	E					

When TBS is implemented correctly, it is possible to use the runway at a higher capacity in strong headwind conditions. Therefore, less holding or delays will be required. As aircraft spent less time in the air, less fuel is consumed and the produced noise and emissions are reduced. This also improves the life cycle of aircraft as less time in the air reduces stress and fatigue on the airframe and engines, allowing airlines to operate their fleet more efficiently. Due to the benefits regarding efficiency and the environment, TBS makes aircraft operations more efficient.

2) Fixed Approach Trajectories: Combining TBS with fixed approach trajectories will allow the runway to be used to its full capacity while at the same time increasing efficiency, reducing noise and pollution effects and reducing controller workload. This can be explained as follows:

- **Environmental effects:** If the aircraft follows a predefined route, pilots know the amount of track miles to the runway. This enables them (and the onboard automation) to plan a continuous descent. This saves fuel and reduces the amount of noise produced.
- **Societal effects:** Due to the position of the fixed approach trajectories, the aircraft can be flown in-between cities and densely-populated areas.

- **Controller workload:** By knowing which route to fly, the ATCO does not need to tell each aircraft when to turn, reducing the amount of instructions per aircraft. This could reduce their workload, allowing them to handle unforeseen situations such as a go-around, diversion or emergencies better.

When spacing gets tighter than expected, or if bad weather is present on the fixed approach trajectory, minimal deviation from the fixed approach trajectory might still be required. Hence, the DST should assist the controller to make these alterations to the approach trajectory efficiently. Using future Controller-Pilot Data Link Communication (CPDLC) capabilities, it is assumed that flightpath alterations can be uploaded to the aircraft and executed by the pilots directly [1].

B. *Uncertainty*

The concept of operation requires accurate predictions of the future position and time separation of all aircraft.

Prediction uncertainty has multiple causes, such as environmental uncertainties, pilot behavior and aircraft performance [4]. This research does not include pilot behavior or differences in aircraft weight. It is assumed that by flying the fixed approach trajectories with the autopilot engaged, the lateral and vertical flightpath of the aircraft are not influenced by pilot delay. The aircraft performance does add uncertainty, especially the weight of the aircraft, however it was not considered during this research. The uncertainty caused by wind is taken into account. In approach control, aircraft descend from about FL100 to 2,000 feet. During this descent the wind can change, adding to the uncertainty. Approaching aircraft spend around ten minutes in the TMA. With the use of future trajectory predictors, which take the flight plan and aircraft performance into account, LVNL expects the uncertainty of predicting the arrival time at the FAF when aircraft enter the TMA to be within tens of seconds.

III. Display Design

This section presents the newly designed decision support tools. The added tools are envisioned to aid the controller in merging traffic on the fixed approach trajectories while maintaining sufficient (time) separation. To understand the newly designed toolset, the conflict probability is explained first. After which the radar screen and the wind visualization are presented. Next, the Time-Space Diagram (TSD) is introduced, followed by the introduction of the Delay-Space Representation (DSR). Finally, the Touch Input Device (TID) used during the experiment is explained.

A. *Conflict Probability*

Throughout the new toolset, conflict probability is used to color trajectories and aircraft labels. It is therefore important to understand how this conflict probability is obtained and what the colors represent. The conflict probability is calculated with the implementation obtained from [9]. This implementation calculates the probability of a LOS, when the vertical separation between two aircraft is less than 1,000 feet, and the lateral separation is less than 3NM. This is calculated for each segment of the predicted trajectory for all aircraft. Additionally, aircraft are given a “maximum conflict probability” property. This property has the same value as the highest conflict probability present along the trajectory of the corresponding aircraft. If insufficient time margin (less than zero seconds) is present at the selected waypoint, the maximum conflict probability property is set to 100%.

The elements that make use of the conflict probability are colored according to the following scheme:

- **Base color:** Every display element has its own base color, used when the probability of a LOS is very low (0-5%).
- **Yellow:** Low probability of a LOS (5-50%).
- **Orange:** Medium probability of a LOS (50-90%).
- **Red:** High probability of a LOS (90-100%).

B. *Radar Screen*

The main source of information for ATCOs is the radar screen. It is therefore very important that the radar screen is readable and provides the controller with the required information needed to build a mental model of the current and future state of the system. To make the results representative, the simulation has been made as realistic as possible. This includes recreating the radar screen that they are familiar with. All colors, icons and information shown are obtained from the actual approach control radar screen used at the Dutch ATC control center. The radar screen used during this research is shown in Figure 2. In this figure the most noticeable features are labeled. The features highlighted with blue markers are always available to the controller, for both display configurations. These features include the following:

1. **Interaction area:** Contains information regarding the current selected aircraft and display setup like current radar range and time.
2. **TMA:** TMA sectors one to six of AAS are shown [10].
3. **CTR:** The Control Traffic Zone (CTR) boundaries of AAS and Rotterdam The Hague Airport.
4. **Runway extended centerlines:** Set to 10NM with markers every 2NM [10].
5. **Fixed approach trajectories:** The trajectories leading from the IAF to the FAF [10].
6. **Waypoints:** Idle waypoints are shown in green. When hovering with the mouse over a waypoint, the ID of the waypoint is displayed next to the waypoint.
7. **Selected aircraft and corresponding label:** The information shown in the aircraft labels is the same as provided by the labels on the LVNL approach radar screen. These include from top left to bottom right: callsign, current altitude, cleared altitude, aircraft type, inbound waypoint or current heading when vectoring, ground speed and cleared IAS. When using the DST configuration, more information is added to aid the ATCO. The distance-to-go is added to the current inbound waypoint in yellow (waypoint (AM)606, 15NM) and the distance-to-go to the current selected waypoint is shown in magenta. The distance-to-go information is only added to the label of the current selected aircraft. Finally,

when the DST configuration is used, the commanded IAS value in the aircraft label is colored according to the maximum conflict probability property as was explained in Subsection III-A. The base color is the same as the color of the selected aircraft label color.

8 **Inbound aircraft and their corresponding labels:** Similar to selected aircraft, only a different color is used and no distance-to-go information is shown.

All display elements listed up until this point are enabled during both display configurations. When the DST configuration is used, the commanded IAS value in the aircraft labels is colored according to the maximum conflict probability property as was explained in Subsection III-A. Only the IAS value is colored to suggest a speed change to solve the conflict. The base color is the same as the color of the aircraft label color. The new elements added to the radar screen when using the DST configuration are marked with red labels in Figure 2. These elements include the following:

9 **Current selected waypoint:** Waypoints are selected by using a left mouse click on the waypoint, which is similar to selecting an aircraft. Deselecting a waypoint is possible by a left mouse click on the already selected waypoint. When a waypoint is selected it turns magenta. If the current selected aircraft contains this waypoint in their flightplan, the time-to-go and expected altitude are displayed next to the selected waypoint. In this case the selected aircraft (BEE4VP) is expected over AM608 in nine minutes and five seconds at an altitude of 2,000 feet.

10 **Ghost aircraft:** Aircraft symbols are projected at their predicted location in the future. The implementation of this feature is further explained in Subsection III-D.

11 **Trajectory:** The predicted trajectory of the selected aircraft, with the color of the trajectory indicating the chance of a LOS on each segment as explained in Subsection III-A. The base color of the trajectory is blue.

12 **Margin indicator:** Explanation will be provided in Subsection III-F.

Finally, important waypoints are highlighted in Figure 2. These important waypoints include the three IAFs (ARTIP, RIVER and SUGOL), NIRSI, NARIX and the FAF which is waypoint AM621 when landing on runway 18R.

C. *Wind Visualization*

To get an understanding of the wind experienced by the aircraft, a wind visualization overlay can be projected on the radar screen, as can be seen in Figure 3. This visualization uses Gridded Binary (GRIB) files which contain 4D wind information (latitude, longitude, altitude and time), these files were provided by LVNL. Currently, ATCOs do not make use of GRIB wind information. The visualization implementation is obtained from Ottenhoff et al. [9], it adds moving particles on the radar screen indicating the direction and speed of the wind. The altitude layer shown is either FL100 (the altitude at which aircraft normally approach the IAFs at), or the altitude of the selected aircraft. This visualization can be helpful for approach controllers in understanding the information provided by the new tools. When aircraft are approaching from opposite directions, wind has a large effect on their arrival times at the merging points. By showing the controller the dynamic windfield using this visualization, a better understanding of the problem can be obtained, and a better solution can be found.

D. *Time-Space Diagram*

To visualize the time separation to the approach controller, a TSD is added. The TSD used in this research was inspired by Tielrooij et al. [11], but has been modified such that a waypoint needs to be selected before any information with respect to the selected waypoint is displayed. The TSD with its elements labeled is shown in Figure 4. This diagram is portrayed on a separate display and can be manipulated with touch inputs.

The labels in Figure 4 represent the following:

1 **Selected waypoint:** At the top of the TSD, the ID of the selected waypoint (AM608) is shown. In the same color as the selected waypoint on the radar screen.

2 **Time axis:** The vertical axis of the TSD represents the time axis in minutes. As time passes, this axis moves down. The range is set to 15 minutes.

3 **Flight label:** Along the time axis, aircraft passing the selected waypoint are shown. In the label, the callsign of the corresponding flight is shown, as well as a single character to identify the IAF from which this aircraft approaches (**A**RTIP, **S**UGOL and **R**IVER). The color of the label is used to indicate different states of the aircraft:

- **Gray:** Aircraft not yet under our control.
- **Black:** Aircraft currently under our control.
- **Gold:** Aircraft currently selected.

These colors act as the base colors of the flight label. If the conflict probability rises above 5% anywhere along the trajectory of an aircraft, the flight label is colored according to the color scheme presented in Subsection III-A. The conflict probability is only calculated for aircraft that are taken under control, in order to limit the computing power of the simulation.

4 **Selected aircraft:** When an aircraft is selected, the label color changes to gold. In addition, the separation indicator of the selected aircraft and the aircraft in front are shown. These indicators show the time margin that an aircraft should have relative to aircraft in front and behind. This is displayed with a dotted line along the time-axis and a horizontal bar. The color of the separation indicator is based on the difference between the specific standard deviation (σ_s) and separation margin (s) for each aircraft. After consulting with LVNL, the general standard deviation was set to 1.2 seconds per minute. By multiplying this value with the time remaining to the selected waypoint, the specific standard deviation is obtained. With the specific standard deviation known, the color of the horizontal bar is defined as follows:

- If $s < 1.0\sigma_s$, the separation indicator turns red.
- If $s < 1.5\sigma_s$, the separation indicator turns orange.

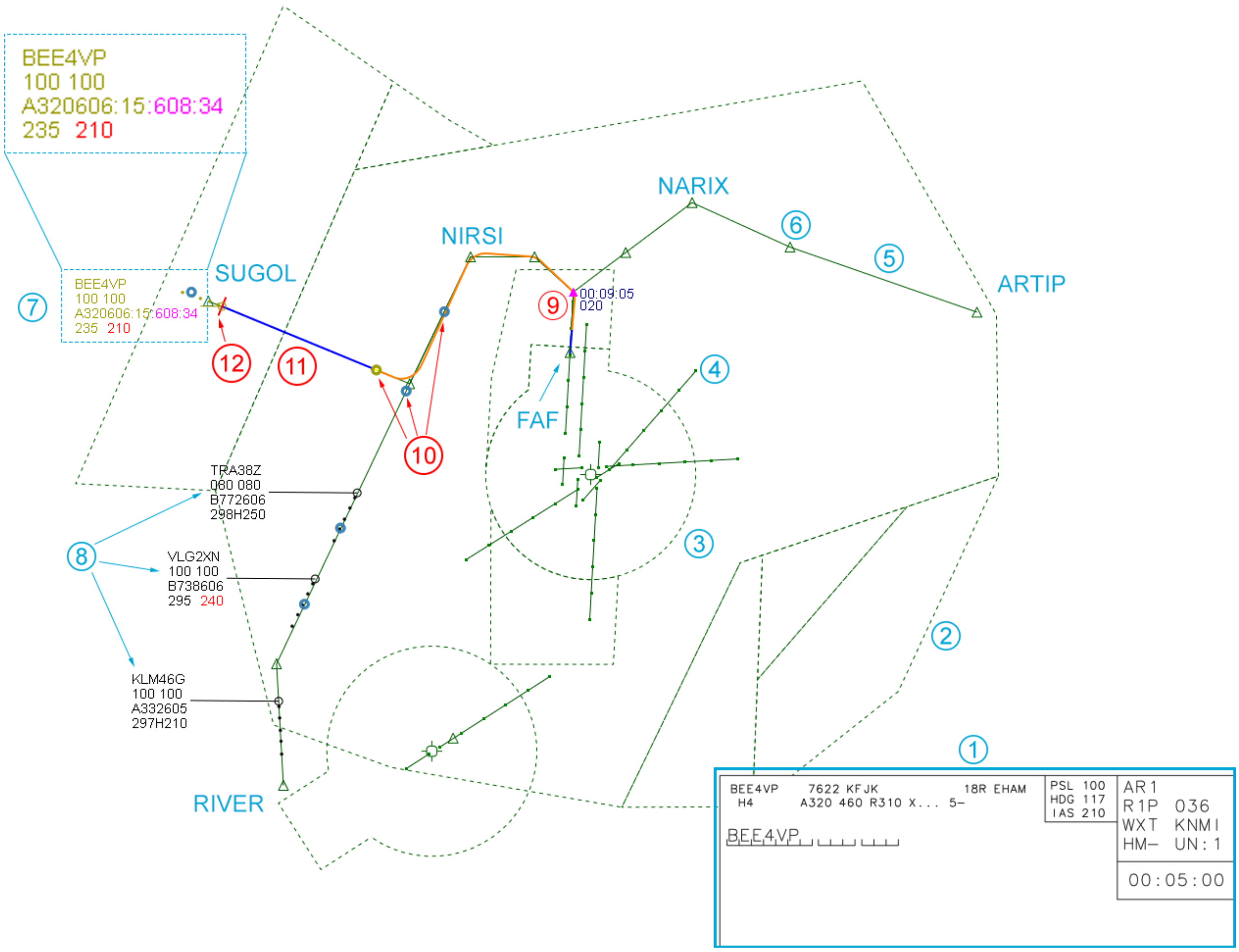


Figure 2: Radar screen (colors adjusted), red markers show elements that are only enabled during the DST display configuration

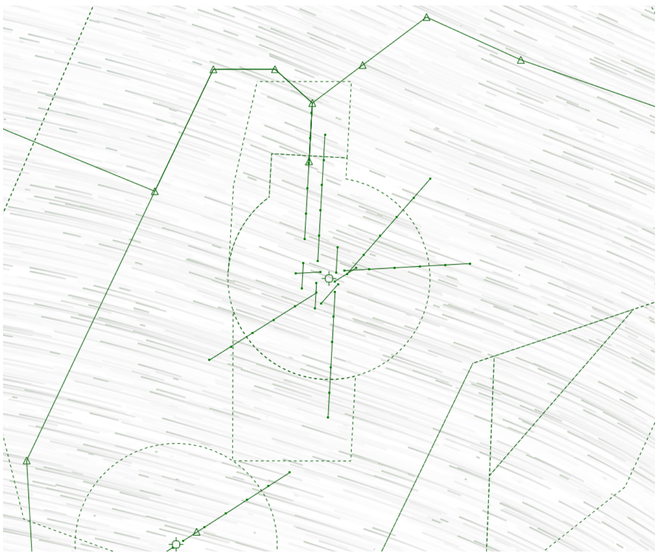


Figure 3: Wind visualization (colors adjusted)

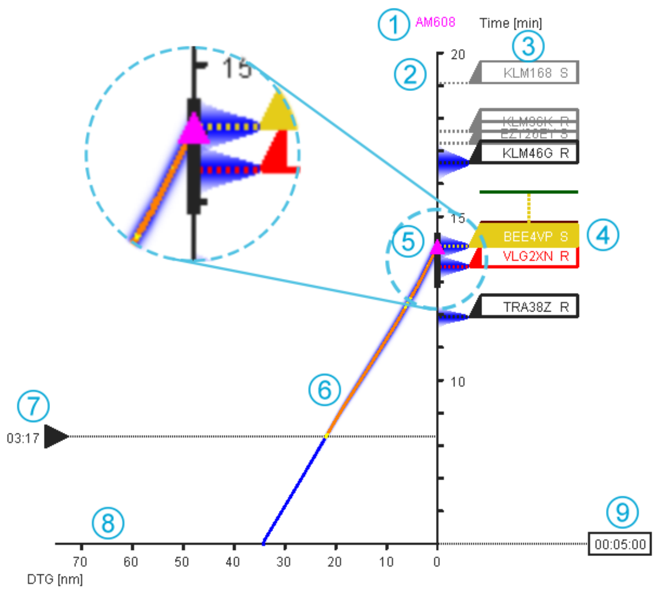


Figure 4: Time-Space Diagram (TSD) (colors adjusted)

- If $s < 2.0\sigma_s$, the separation indicator turns yellow.
- If $s \geq 2.0\sigma_s$, the separation indicator turns green.

5 Multiple elements are shown here:

- **Thick vertical axis line:** Arrival time range with a speed range of 200 to 250 knots. The upper speed limit was set to 250 knots as that is the speed limit below FL100. The lower speed of 200 knots was set to allow the controller a broad range of control, while not extending the range too low, causing the speed to drop below the clean airspeed of most aircraft. The top of the thick line represents the predicted latest arrival time and the bottom the earliest.
- **Magenta triangle:** Representation of the selected waypoint. The position of this triangle on the time-axis represents the predicted arrival time of the selected aircraft at the selected waypoint.
- **Blue normal distribution on the time-axis:** The blue normal distribution shows the probability that the aircraft will arrive at a specific point in time. This implementation was inspired by Tielrooij et al. [12]. The blue normal distribution shows the probability range at which the aircraft is expected at the selected waypoint. The spread of the normal distribution becomes smaller when the look ahead time becomes smaller. This is visible when comparing the KLM46G distribution with the TRA38Z distribution. The normal distribution has a mean of zero and uses the general standard deviation. By multiplying this value with the time to go, the specific standard deviation is obtained.

6 **Time-space trajectory:** The trajectory shows the distance against the time which the selected aircraft has to travel with respect to the selected waypoint. The color of the trajectory indicates a potential LOS along the trajectory. As can be seen, about 3.5 minutes in the future a potential LOS (in distance) is identified. Similar to the colors of the aircraft labels in the TSD, the implementation of the conflict visualization on the trajectory (on the radar screen and the TSD) is obtained from Ottenhoff et al. [9]. The normal distribution on the time-axis is translated to the time-space trajectory, with the standard deviation equal to zero at the current time, and increasing to the specific standard deviation at the time-to-go to the current selected waypoint.

7 **Time slider:** The triangle shown can be dragged up, resulting in ghost aircraft to be drawn on the radar screen at the predicted position corresponding to the time slider setting. As can be seen in Figure 2, the ghost projection of the selected aircraft has the same color as the selected aircraft color which helps to identify the future position of the selected aircraft. The relative time is shown when the triangle is dragged up, showing how far in the future the time slider is set.

8 **Distance-to-go axis:** The horizontal axis of the TSD shows the distance-to-go in nautical miles. As aircraft approach the selected waypoint, the distance-to-go reduces, hence the blue line of 6 shifts to the right. A range of 80NM is used, which is sufficient as aircraft normally do not cover more than 80 nautical miles in the TMA.

9 **Current time:** Finally, the current (simulation) time is shown. This is done in a hh:mm:ss format.

The last element, which is not shown in Figure 4, is a variation of the wind visualization. This is shown on the TSD when an aircraft and waypoint are selected while the wind visualization is enabled. This allows the controller to see where along the trajectory aircraft experience a head and/or tailwind. Finally, if no waypoint is selected, only the time axis, distance-to-go axis, current time and time slider are visible on the TSD.

E. Delay-Space Representation

There are scenarios in which an aircraft needs to deviate from the fixed approach trajectory. Such scenarios include insufficient separation with respect to other aircraft when using speed instructions only or bad weather on the approach trajectory. In these cases shortcuts or additional track miles can be added using the Delay-Space Representation (DSR).

In Figure 5a and Figure 5b it can be seen how changing the trajectory of BEE4VP is visualized on the radar screen. This is done by holding the right mouse button on the radar screen which shows a preview of the suggested trajectory. A waypoint is inserted at the mouse location if the aircraft can reach the waypoint and continue the route. Turn angles larger than 110 degrees result in a rejection of the inserted waypoint. When the turn angle is too large, existing waypoints are removed from the suggested trajectory until the turn angle is below the threshold of 110 degrees. If all waypoints are removed from the flightplan the suggested trajectory is rejected. If a valid trajectory is found, the suggested trajectory is shown on the radar screen, accompanied by the change in track miles and the corresponding change in arrival time at the selected waypoint (+4.3NM and +73 seconds in Figure 5b). By using the left mouse button, the trajectory is fixed. This gives the controller the chance to inspect the effects of the suggested trajectory.

Figure 5c and Figure 5d show the effect of the modified flightpath on the TSD. By altering the trajectory of BEE4VP, the conflict between BEE4VP and VLG2XN has been resolved. Using the time slidert,this can be visualized with the ghost projection. To execute the trajectory command, the Touch Input Device (TID) is used. This display will be explained in Subsection III-G. Shortcuts to a waypoint that is already a part of the aircraft flight plan can be obtained in similar fashion, a right mouse click on a waypoint shows a preview of the trajectory when the aircraft is instructed a direct to the waypoint.

F. Margin Indicator

On the predicted trajectory, a margin indicator is shown. This margin indicator was inspired by the IA tool [3]. The margin indicator used in this research is shown on the entire trajectory of a selected aircraft, as can be seen in Figure 5a and Figure 5b. The margin indicator represents the time margin available at the selected waypoint with respect to the aircraft in front. The margin indicator is projected on the trajectory at the point where the current selected aircraft would be if the time margin with the preceding aircraft equaled zero.

The controller has to keep the margin indicator ahead of the selected aircraft, as is shown in Figure 5b. The color of the margin indicator is the same as the separation indicator on the TSD. Figure 5a shows that there is insufficient time margin at the selected waypoint. With the added track miles and a delay of 73 seconds, sufficient margin is created, as is shown in Figure 5b. This implementation translates time separation margin information from the TSD to the radar screen.

G. Touch Input Device

The last screen that is used during the experiment is the Touch Input Device (TID), shown in Figure 6. This display is used to send instructions to aircraft or to change display elements. Approach controllers will be familiar with this display as it looks similar to what they use normally. However, approach controllers currently use the TID to change the values in the aircraft label as a memorization tool. The actual commands are issued by use of radio transmission between the controller and the pilots. Within the simulation, all commands are sent and executed using the command display. No pilot delay is implemented, commands are executed immediately. It was assumed that in the future, aircraft would have the capability to receive commands via datalink, hence allowing nearly instant execution of a command issued by ATC. The commands are listed as follows:

- **UCO:** Take aircraft under control.
- **TOC:** Transfer of control to other controller.
- **EXQ:** Execute the selected instruction.
- **HDG:** Initiate a heading instruction, followed by a number entered using the numpad (disabled in the DST configuration). Can also be used to fly direct to a waypoint.
- **EFL:** Initiate a change in altitude, followed by a number entered using the numpad.
- **SPD:** Initiate a change in indicated airspeed, followed by a number entered using the numpad.
- **APP:** Clears an aircraft which is on a heading for the approach. The aircraft will intercept the ILS on the cleared heading. Aircraft on the fixed arrival routes do not need to be cleared for the approach.
- **CLR:** Clears current command from the command line.
- **ERA:** Clears current command from the command line and deselects the selected aircraft.
- **48:** Changes the range of the radar to 48NM, after which the button changes to 36, which can be used to revert to a range of 36NM if desired. These ranges are commonly used by approach controllers at LVNL.
- **WIND:** Toggles the wind visualization overlay (disabled in the baseline configuration).

IV. Experiment

To test the newly designed decision support tools, an experiment was conducted. This experiment was approved by the TU Delft ethics committee under application HREC 2606.

A. Experiment Goal

The goal of the experiment is to test the effects of the newly designed decision support tools. The experiment is performed to gather data, obtained from logfiles created by the simulation software and questionnaire results, to test the hypotheses. The results should answer the question if TBS in combination with fixed approach trajectories is possible within the approach control domain when the new decision support tools are implemented.

B. Apparatus

The setup used during the experiment can be seen in Figure 7. Participants interacted with the simulation through the mouse and two 15-inch full HD touch displays (TID and TSD). The keyboard was only used during the open questions of the Qualtrics questionnaire. The main radar screen used was a 42.5-inch monitor with a 4K resolution.

The simulation made use of a Java-based medium-fidelity ATC-simulator called SectorX built by TU Delft. Furthermore, A BADA 3 aircraft performance model was used [13].

C. Participants

Eight professional and operational tower/approach controllers from LVNL participated during the experiment. All participants signed a written informed consent form. The participants age and experience are listed in Table II.

Table II: Participants age and experience

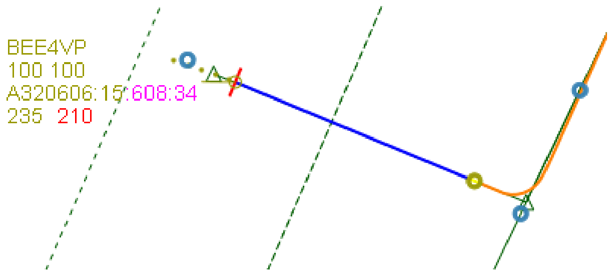
Start Configuration	Age (years)	Experience (years)
Baseline	M = 28.7, SD = 2.5	M = 6.7, SD = 2.5
DST	M = 35.8, SD = 7.4	M = 13.5, SD = 8.6

D. Procedure and Participant Tasks

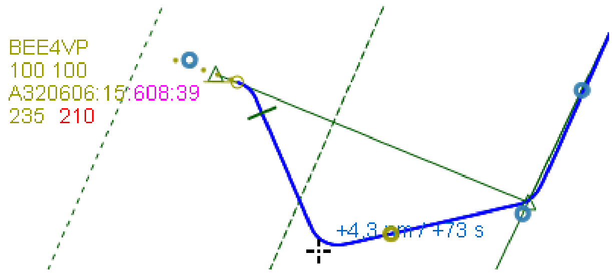
At the start of each display configuration (at the start of run one and five) participants were briefed about 10 minutes on the used configuration. This included a simple static scenario with which the participants could try each element of the used configuration. After the briefing the experiment started. Each participant had a different scenario and/or display type order, as can be seen in Table III. The experiment was designed around six controllers. Therefore, P7 and P8 followed the same experiment structure as P1 and P4, respectively.

During runs four and eight the same scenario was used for each participant. This was done to compare the results between the two display configurations. The last run for each display configuration was used to reduce any learning effects present. By allowing the participants to experiment with the first three training runs, this learning effect was dampened. By changing the display order, the baseline and DST configuration could be compared fairly. It should be noted that all flight labels were randomized between the two display configurations, to avoid participants remembering a scenario from the previous run.

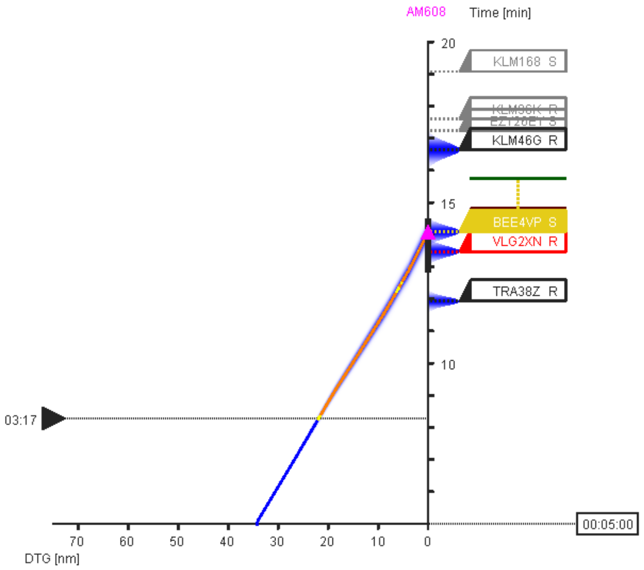
Participants were required to guide aircraft safely to the ILS using directional (heading or trajectory), speed and altitude commands. Additionally, participants were asked to use the fixed arrival routes whenever possible.



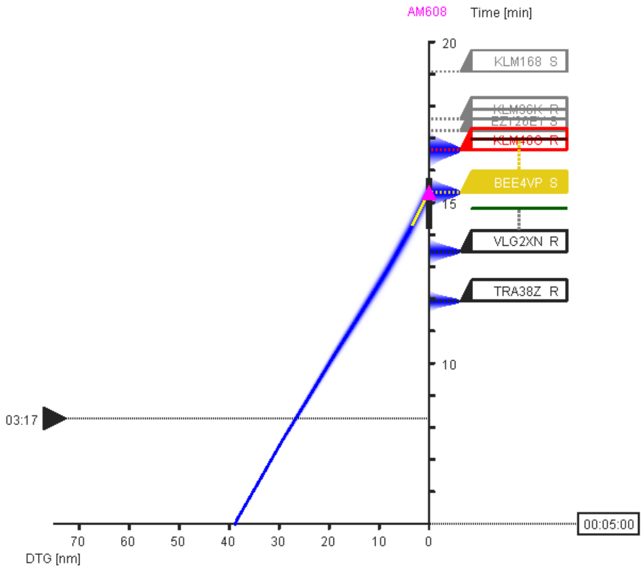
(a) Radar screen, conflict present on trajectory of BEE4VP



(b) Radar screen, conflict resolved using the DSR



(c) TSD, conflict present between BEE4VP and VLG2XN



(d) TSD, conflict resolved using the DSR

Figure 5: Delay Space Representation (DSR) visualized on the radar screen and TSD

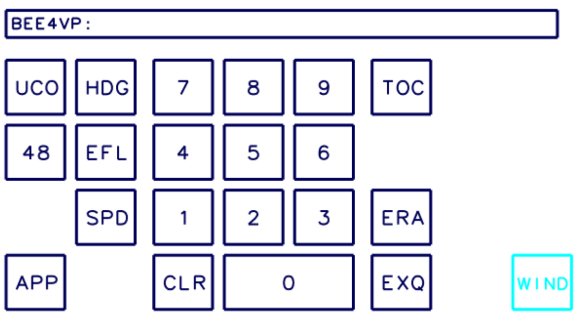


Figure 6: Touch Input Device (TID) used in the experiment

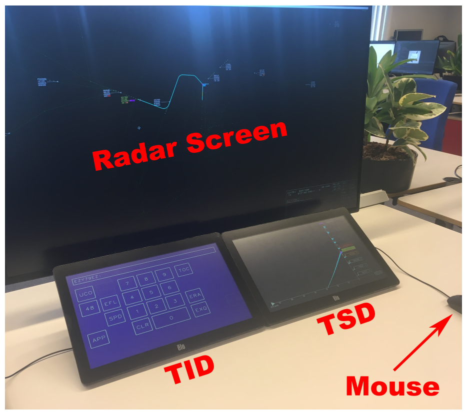


Figure 7: Test setup used during the experiment

Table III: Experiment design matrix, **B**aseline, **D**ecision Support Tools, **T**raining runs, **M**easurement runs

ATCo \ Run	T1	T2	T3	M4	T5	T6	T7	M8
P1/P7	B, 1	B, 2	B, 3	B, 4	D, 2	D, 3	D, 1	D, 4
P2	B, 3	B, 1	B, 2	B, 4	D, 1	D, 2	D, 3	D, 4
P3	B, 2	B, 3	B, 1	B, 4	D, 3	D, 1	D, 2	D, 4
P4/P8	D, 2	D, 3	D, 1	D, 4	B, 1	B, 2	B, 3	B, 4
P5	D, 1	D, 2	D, 3	D, 4	B, 3	B, 1	B, 2	B, 4
P6	D, 3	D, 1	D, 2	D, 4	B, 2	B, 3	B, 1	B, 4

E. Traffic Scenarios

Four scenarios were selected. These scenarios, presented in Table IV, were selected to allow participants to get familiar with the tool in different situations. Scenarios one, two and three were used for training purposes. The fourth scenario was used for analysis. Scenario one was an evening peak where runway 18R and 18C were the active landing runways, all traffic arriving from the east (ARTIP) was directed to 18C by a second approach controller, hence only traffic arriving form SUGOL and RIVER was included in scenario one. Scenario two included an evening peak with traffic arriving from all three IAFs. The third scenario simulated the morning peak of 17-02-2022 which included storm "Eunice". Runway 27 was the only active landing runway due to the strong wind from the west. The fourth and final scenario included a busy morning peak with aircraft arriving from ARTIP and SUGOL.

The scenarios were created using real radar data of the corresponding day and time. Aircraft already inside the TMA were put on the fixed approach trajectory such that within the first five minutes no conflicts were present. All other aircraft were placed on the standard terminal arrival routes with the fly-over time at the IAF matched with the radar data. Within the simulation, an actual windfield and a predicted windfield were present. All information provided to the controller was based on a predicted windfield which was simulated by the wind of one hour prior to the start time of the scenario. Meanwhile, the simulated aircraft experienced the actual wind which was present on the time and day of the scenario. The scenarios ran at twice the normal speed to save time and allow longer training. Little effect on the results was expected as no voice communication was needed, reducing controller workload.

Table IV: Scenario specifications

ID	1	2	3	4
Date	11-07-2019	18-07-2019	17-02-2022	01-07-2019
Time (UTC)	17:00-17:15	16:00-16:15	08:00-08:15	08:00-08:15
Runway	18R	18R	27	18R
# of aircraft	12	12	16	16
Aircraft types	D,E	B,D	B,D,E	B,D
Wind at 2,000ft above Schiphol	156/8 kts	219/13 kts	280/49 kts	275/13 kts
IAF mix	SUGOL, RIVER	ARTIP, RIVER, SUGOL	ARTIP, RIVER, SUGOL	ARTIP, SUGOL

F. Independent Variables

The independent variables were the display type and display order. Two display types were used, the baseline configuration and the DST configuration. All participants performed the same scenarios twice, which would make the display type a within-participants variable. However, not all participants started with the same display configuration to avoid learning effects, which would make the display order a between-participants variable. Hence, the experiment had a mixed-design structure. Therefore, the between-participants display order effect will need to be analyzed first and show no differences, before the display type influence can be analyzed.

The baseline configuration was similar to what the ATCOs use currently. In the DST display configuration, the decision support tools were enabled. This setup allowed the effect of the decision support tools to be compared with current operations.

G. Control Variables

The control variables during the experiment were the traffic scenario and configuration parameters. The configuration parameters included settings on font size, values, flags, and colors of the different elements on the display. All these parameters, except the independent variable remained constant.

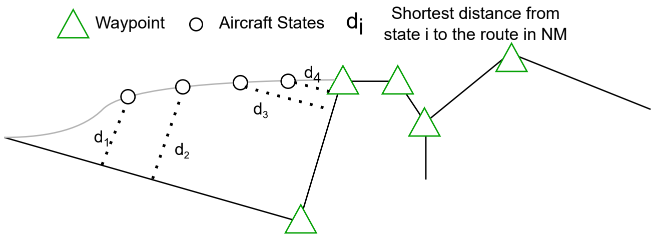


Figure 8: Track deviation metric visualization

H. Dependent Measures

During the experiment safety, productivity, efficiency and controller workload were measured. Safety was measured by counting the number of LOS and investigating the time separation at the FAF, in the past and in the future.

To measure the productivity of the system, the runway capacity was analyzed. Time separation between aircraft should be as close to the minimum required time separation (as defined in Table I) as possible. A larger time separation results in a capacity reduction. Hence, by summing the surplus time separation per ATCO, the capacity loss can be defined. This analysis only included flights that had arrived at the FAF.

Efficiency was measured by recording the ground tracks and where the instructed commands to aircraft were issued. The ground tracks gave an indication on how accurate the fixed approach trajectories were flown.

To quantify the fixed approach trajectories adherence, the Track Deviation Metric (TDM) per ATCO is calculated, defined by Equation 1. In this equation d_i is the closest distance from an obtained aircraft state to the fixed approach trajectory, as is visualized in Figure 8. The TDM was defined as a summed distance in NM, with a lower value corresponding to closer following of the fixed approach trajectory.

To quantify the locations of commands, the Command Distance Metric (CDM) per ATCO was calculated using Equation 2. Once again, d_i is a distance in NM, but the distance is taken from the command location to waypoint AM608. This is visualized in Figure 9.

$$TDM = \sum_{aircraft=1}^{\#Aircraft} \left(\left(\sum_{state=1}^{\#States} d_i \right) \frac{1}{\#States} \right) \quad (1)$$

$$CDM = \left(\sum_{Command=1}^{\#Commands} d_i \right) \frac{1}{\#Commands} \quad (2)$$

Controller workload was obtained after each run using the RSME (0-150) rating scale [14]. Furthermore, the number of commands and flight selections were recorded. The individual commands were separated into the different command types, such as altitude, speed, heading and trajectory commands.

Data were obtained from log files created during each experiment, including the state of the aircraft and simulation, inputs from keyboard and mouse and events (such as flight selections,

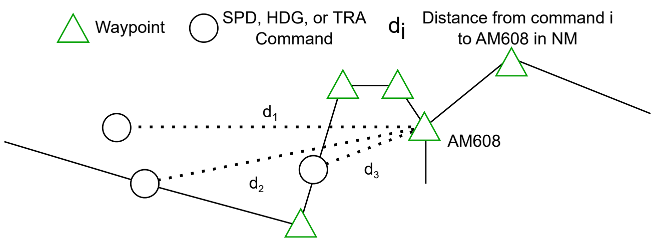


Figure 9: Commands distance metric visualization

flight commands, selected waypoints, etc.) happening within the simulation.

After each display configuration simulation, participants were asked to fill in a questionnaire containing 5-point Likert-scale questions regarding the simulation realism, ease of control task and decision support tool usefulness. Each category included an open question for additional feedback.

I. Hypotheses

The following hypotheses were tested:

H.1 The DST will increase safety. Measured by:
- a) Number of LOS.
- b) Insufficient time separation at the FAF, in the past and in the future.

H.2 The DST will increase productivity. Measured by the capacity loss.

H.3 The DST will increase efficiency. Measured by:
- a) Track deviation by use of the TDM.
- b) Command locations by use of the CDM.

H.4 The DST will reduce controller workload. Measured by:
- a) The Zijlstra workload rating.
- b) The number of commands issued.
- c) The number of flight selections.

V. Results

The experiment was performed by eight professional tower/approach controllers. However, due to a software problem encountered during the measurement run of the first participant, the simulation data from P1 is not deemed comparable to the simulation data of the other participants. Therefore, the simulation data of P1 is not taken into account. The questionnaire data, however, is deemed comparable, therefore the questionnaire includes the results from all eight participants.

Since only three and four samples are present for the display order groups, tests for normality of the data such as Kolmogorov-Smirnov and Shapiro-Wilk tests have only limited statistical power. Therefore, the normality assumption required to perform an independent t-test could not be made. The non-parametric Mann-Whitney U Test is performed on all dependent measures [15]. This showed that the display order did not have a statistically significant influence on the results, allowing the data to be analyzed without taking the display order into account. The results presented with the use of boxplots still differentiate the two display order groups by marking the group starting with the baseline configuration with an “x” symbol and marking the group starting with the DST configuration with a “+” symbol.

To analyze any differences between the baseline and DST display configurations, a two-pair Wilcoxon Signed-Rank Test was performed for each dependent measure. Once again, due to the limited number of samples, it was opted to only consider non-parametric tests.

A. Safety

During the experiment, no LOS occurred. Regarding distance separation, all aircraft were separated by at least 3 NM laterally or 1,000 feet vertically. Regarding time separation at the FAF, the runway utilization is shown in Figure 10. Aircraft are shown as blue and green rectangles with their corresponding aircraft ID. The aircraft depicted with solid rectangles have passed the FAF, while open rectangles indicate aircraft yet to pass the FAF at the predicted times after the scenario ended at 900 seconds. These predictions use the predicted windfield. Insufficient time margins (in seconds) are indicated in red. From these figures it can be seen that there are more predicted conflicts at the FAF in the baseline configuration compared to the DST configuration (25 conflicts in the baseline and 12 in the DST configuration). Furthermore, in the baseline there are four conflicts in the next two minutes (P3,P4,P5,P6), while with the DST it can be seen that only P2 and P6 have a LOS in the next two minutes.

By summing the future insufficient time margin in bins with a time range of 30 seconds, the intensity of future conflicts can be visualized. As is shown in Figure 11, the DST configuration allows controllers to solve future conflicts much sooner, up to almost ten minutes in the future (from t=900 to t=1,450).

B. Productivity

By summing the margins present between the aircraft which passed the FAF as shown in Figure 10, the capacity loss can be obtained. Figure 12 shows the capacity loss boxplots, hinting at a decrease for the DST configuration. No statistically significant difference was found between the baseline (Mean Rank = 5.0) and the DST (Mean Rank = 2.0) configuration, Z = -0.943, p = 0.345.

C. Efficiency

The ground tracks of the baseline and DST configuration are shown in Figure 13, for all aircraft and all participants. These figures show how participants deviated from the fixed approach trajectories near the FAF using the baseline configuration. With the use of the DST, the required delay was obtained before the NIRSI and NARIX waypoints.

The deviation from the fixed approach trajectories was quantified using the TDM, as explained in Subsection IV-H. There was not a significant difference between the baseline and the DST configuration when investigating the whole trajectory from IAF to FAF. However, this changed when the last and most important part of the approach trajectory was investigated, more specifically from NIRSI and NARIX to the FAF, of which the results are shown in Figure 14a.

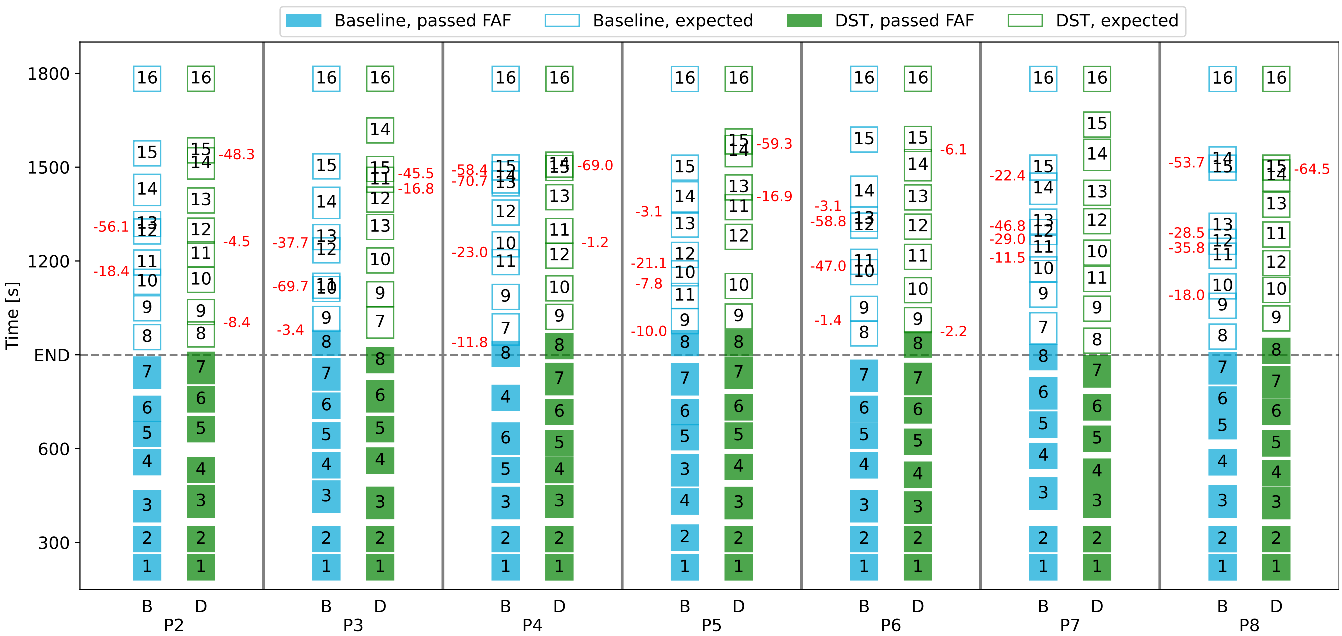


Figure 10: Runway utilization

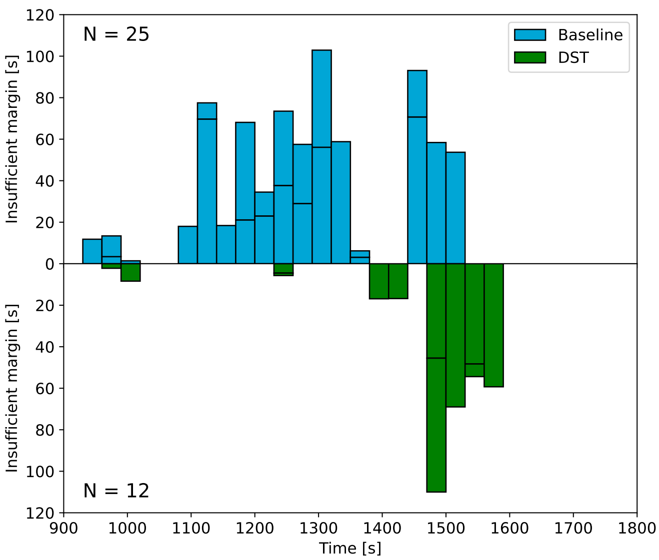


Figure 11: Insufficient time separation in the future

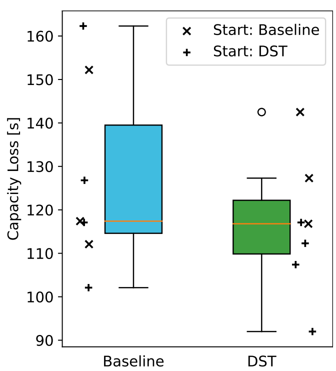
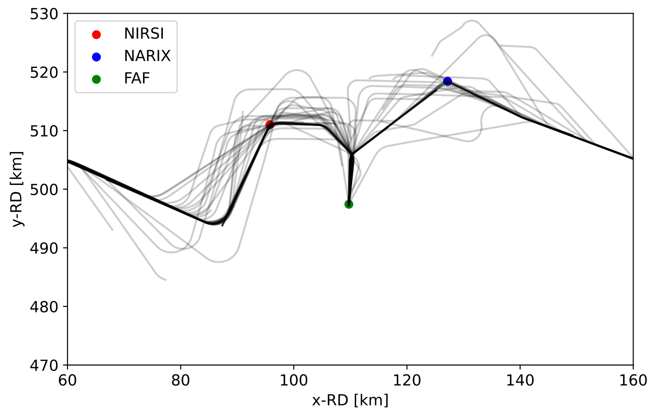
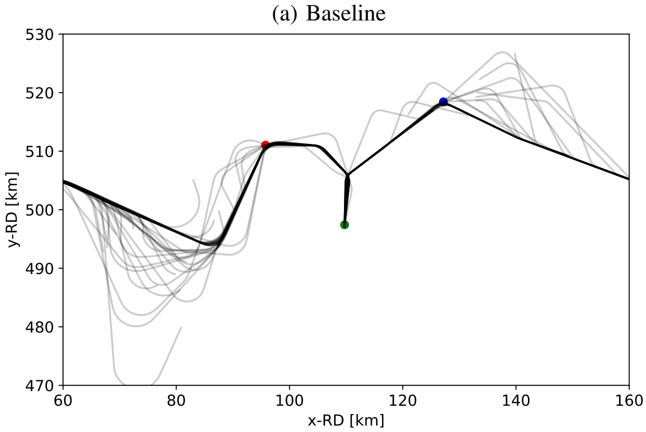


Figure 12: Capacity loss

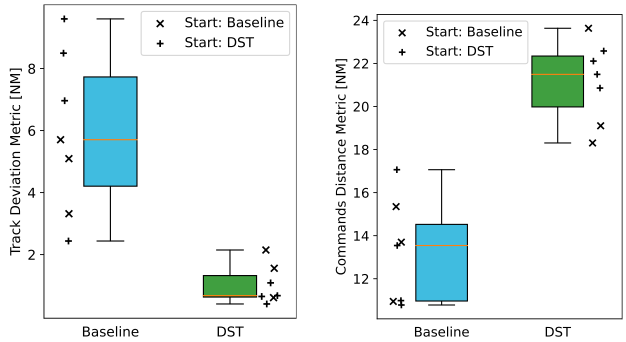


(a) Baseline



(b) DST

Figure 13: Ground tracks of all aircraft and all participants



(a) Track deviation, from NIRSI and NARIX to the FAF

(b) Command distance metric, trajectory from IAF to the FAF

Figure 14: Track deviation metric and command distance metric

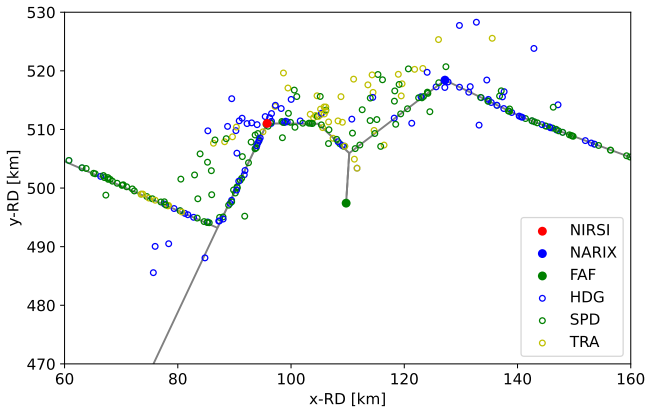
Wilcoxon Signed-Ranks Test shows a statistically significant difference regarding the track deviation metric between the baseline (Mean Rank = 4.0) and the DST (Mean Rank = 0.0) configuration, Z = -2.366, p = 0.018.

The locations of the instructed SPD, HDG and TRA commands were analyzed. Altitude commands were not taken into account in this analysis since an altitude command does not have a large effect on the arrival time of aircraft at the merge points. The command locations are plotted in Figure 15. Using the DST only six commands were issued between NIRSI/-NARIX and the FAF, while in the baseline configuration 112 commands were issued. This difference gives a clear indication that conflicts were solved well before reaching NIRSI or NARIX in the DST configuration. To quantify the command locations, the CDM, as explained in Subsection IV-H, was used. This analysis took the whole trajectory from IAF to FAF into account. The resulting boxplots are presented in Figure 14b. A Wilcoxon Signed-Ranks Test showed that a statistically significant difference regarding the commands distance metric was present between the baseline (Mean Rank = 0.0) and the DST (Mean Rank = 4.0) configuration, Z = -2.366, p = 0.018.

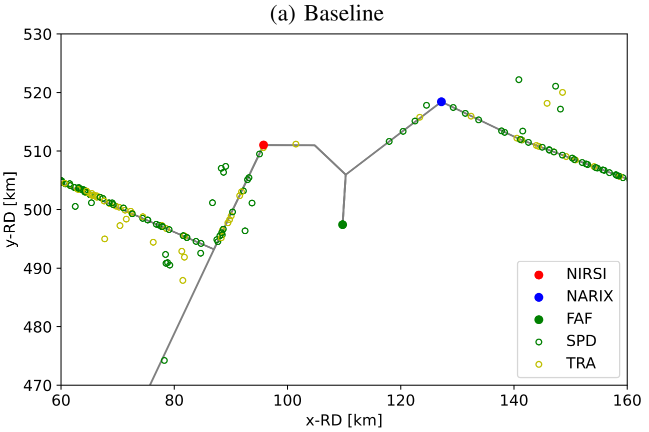
D. Controller Workload

The workload of the participants is obtained using the RSME rating scale, shown in Figure 16 [14]. As expected from a visual inspection between the baseline and DST configuration, no significant difference regarding workload was present between the baseline (Mean Rank = 4.0) and the DST (Mean Rank = 4.0) configuration, Z = -0.339, p = 0.735. The one outlier corresponds to P6, who gave the baseline configuration a higher workload score after having completed the DST configuration first.

The number of flight commands and flight selections are used as other indications of controller workload. Figure 17 shows a reduction in both when using the DST configuration. Regarding the number of flight commands, a statistically significant difference was present between the baseline (Mean Rank = 4.0) and the DST (Mean Rank = 0.0) configuration, Z = -2.371, p = 0.018, r = 0.90. It should be noted that Figure 17a shows two clusters of data within the DST boxplot.



(a) Baseline



(b) DST

Figure 15: Command locations (altitude commands excluded)

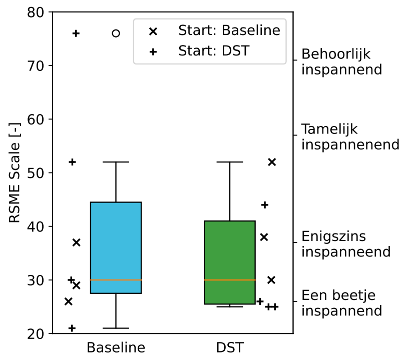
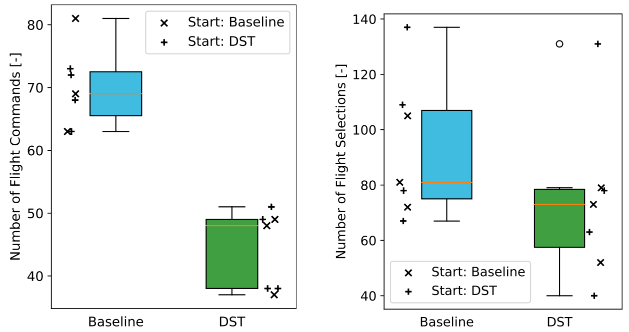


Figure 16: Workload rating, with Zijlstra RSME scale labels on the right y-axis [14]

These two clusters did not correspond to the different display order groups. The participants that issued around 40 flight commands in the DST configuration were participants P5, P7 and P8. From Figure 10, it is visible that P7 and P8 were among the controllers that were able to make the best use of the DST.

Regarding the number of flight selections, no statistically significant difference was present between the baseline (Mean Rank = 3.8) and the DST (Mean Rank = 2.0) configuration, Z = -1.782, p = 0.075. In Figure 17b, the samples shown around 135 in the baseline and 130 in the DST configuration



(a) Flight commands (b) Flight selections

Figure 17: Number of Flight commands and flight selections

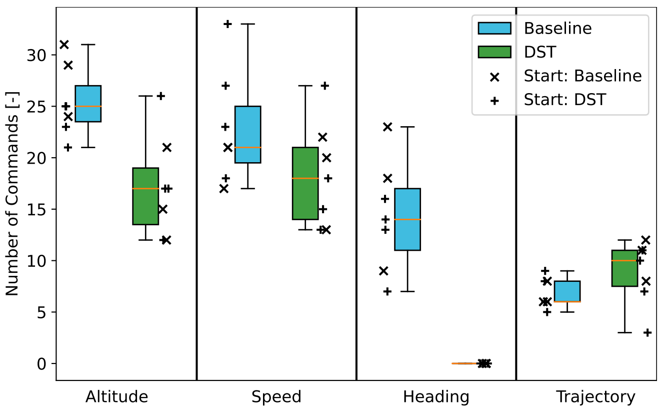


Figure 18: Number of flight commands per command type

are related to the same participant.

The total number of flight commands can be separated into the following categories: altitude, speed, heading and trajectory, shown in Figure 18. During the DST configuration no heading commands were allowed, hence, it is obvious that heading commands showed the largest decrease when using the DST configuration (Mean Rank = 0.0) when compared with the baseline configuration (Mean Rank = 4.0), Z = -2.366, p = 0.018. When looking at trajectory commands (in the baseline configuration, a "direct to waypoint" was recorded as a trajectory command), it is observed that the mean is higher in the DST configuration, compensating the absence of heading commands. No significant difference was found regarding trajectory commands between the baseline (Mean Rank = 4.0) and the DST (Mean Rank = 3.4) configuration, Z = -1.378, p = 0.168.

Finally, the altitude and speed commands show a decrease with the DST enabled. The altitude commands show a statistically significant difference between the baseline (Mean Rank = 4.5) and the DST (Mean Rank = 1.0) configuration, Z = -2.201, p = 0.028. The speed commands, however, do not show a significant difference between the baseline (Mean Rank = 3.8) and the DST (Mean Rank = 2.0) configuration, Z = -1.782, p = 0.075.

E. Questionnaire

Some elements of the DST were found very useful by some participants, while other participants found the same

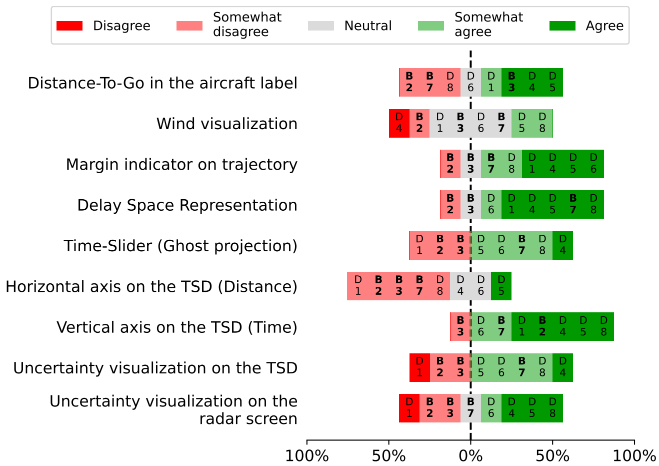


Figure 19: Questionnaire results, DST, "The following display elements were useful:"

element not useful at all, as shown in Figure 19. In this figure (and Figure 20), D and **B** indicate the display order groups, the group starting with the DST and baseline configuration, respectively. The number indicates each individual participant.

This division between the participants reflects the personal preferences of ATCOs. Most participants found the margin indicator, DSR and vertical axis on the TSD to be very useful. Contrarily, the horizontal axis and wind visualization did not aid the participants in their control task. The open questions of the questionnaire included the following observations regarding the DST:

- "*The TSD could give a false sense of safety*", when the TSD does not indicate any conflicts, controllers tend to lean back and get the feeling that no additional work is required. However, the system still needs monitoring as the predictions on the TSD contain uncertainties and are subject to change.
- "*When solving conflicts on the TSD, less attention is put into the radar screen*", which resulted in the participants being afraid that they might miss important events happening on the radar screen.
- "*The new tools are intuitive, with a few training days this would become second nature. Allowing us to become more efficient with the tools*", each participant had about 30 minutes to get up to speed with the new tools. This feedback shows they still required more training to use the tools to their full potential. As an example, the DSR did sometimes cause some problems. Occasionally (more frequent during the training phase) participants forgot to press the execute button on the TID to confirm and execute the trajectory command. After the training phase these mistakes did become less frequent.

Figure 20 shows that controllers were indeed familiar with the simulation and the traffic scenarios. As was clear from the open questions, the TID was slightly different. Finally, aircraft performance was different from real operations as aircraft descended a bit faster. However, the participants agreed that it was sufficient for the purpose of the experiment.

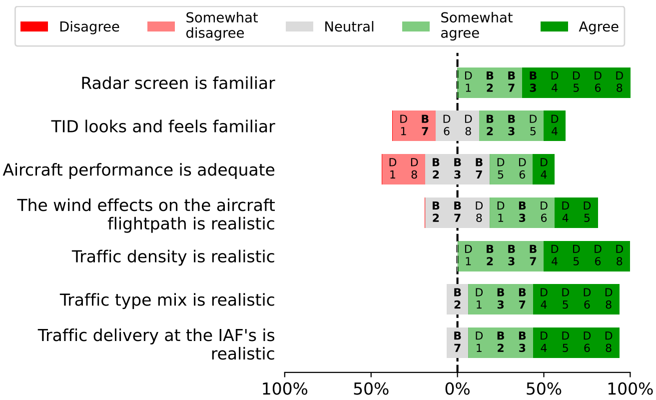


Figure 20: Questionnaire results, simulation realism

VI. Discussion

The results obtained contain interesting patterns. This section will discuss patterns and observations that are of interest. First the simulation realism is discussed, after which the hypotheses set in Subsection IV-I are answered with the obtained results. Finally, recommendations are made.

A. Simulation Realism

The simulation was made as realistic as possible, as it would allow controllers to execute their normal control strategies and practices during the experiment. The questionnaire results regarding simulation realism showed that participants deemed the simulation similar to what they are used to. It should be noted that the TID was slightly different compared to the real TID. This caused some mis-clicks and different interpretations regarding combining ALT, SPD and HDG commands. These minor differences to the real TIDs were noted by the participants, as they were not able to use the TIDs blindly like they are used to.

Finally, since the data were collected within a controlled environment, no changes were allowed to the display settings and display setup. This caused some participants to note that normally they would have the TID on the right display, have the coastline of The Netherlands projected on their screen, have longer runway extended centerlines and the use of a trackball instead of a mouse. These are examples that show how customizable the work environment is, and how controller preference is present in approach control. Therefore, within a controlled environment in which limited flexibility is allowed, some controllers will not be using their preferred setup.

B. Hypotheses

Using the obtained results, the hypotheses set in Subsection IV-I can be answered. Table V summarizes the answers to the hypotheses. A "y" or "n" indicate whether the found trend proved the hypothesis right or not, respectively. When a significant effect was observed, a bold "yes" or "no" is used.

Table V: Summary of hypotheses results including dependent measures

Safety (H.1)		Prod. (H.2)	Efficiency (H.3)		Workload (H.4)		
LOS	*Time sep. at FAF*	*Capacity loss*	*Track deviation*	*Command location*	*Workload rating*	*# of commands*	*# of flight selections*
n	y	y	**yes**	**yes**	n	**yes**	y

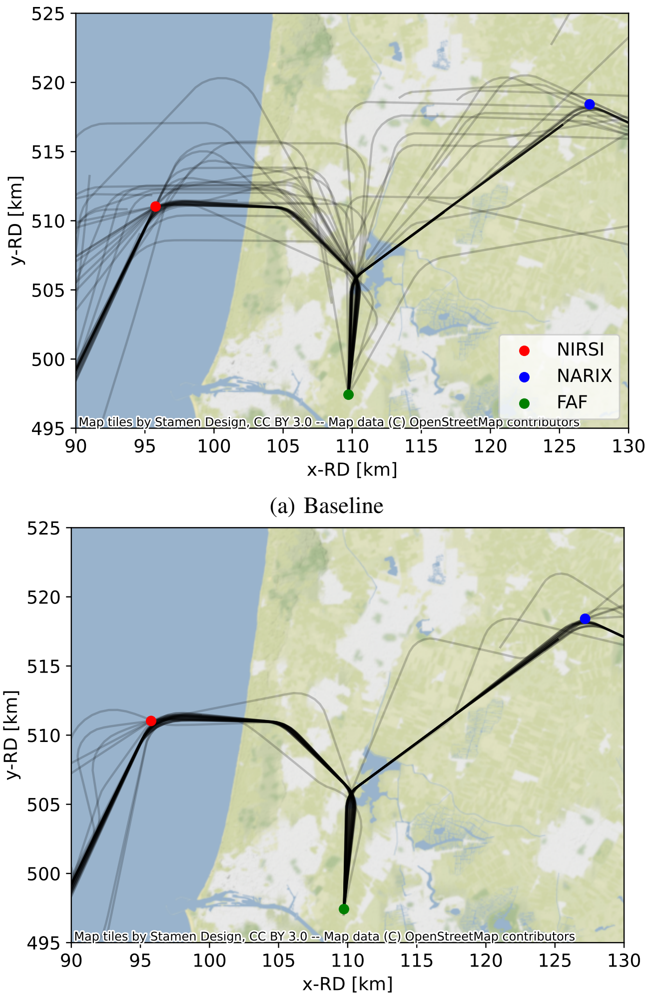
1) The DST will increase safety: No change in the number of LOS was observed (both equal to zero). The hypothesis is therefore rejected. However, the DST configuration did show an improvement when looking at the number of insufficient time margins at the FAF in the future. The next significant conflicts occurred almost ten minutes in the future. This shows how the DST aided controllers to change their behavior from an ad-hoc approach to a much more strategic approach. This would allow controllers much more time to react to unexpected pilot behavior or emergencies, which could increase the safety of the system.

2) The DST will increase productivity: Using the capacity loss metric, no significant difference between the arrival times of the aircraft at the FAF was observed, causing this hypothesis to be rejected. This confirms the high skill-level of the professional participants when vectoring aircraft to the runway. Aircraft delivery to the runway could be improved by additional training with the new tools, this was also noted by participants in the questionnaire. Furthermore, controllers were not allowed to separate aircraft closer than the required time separation indicated by the TSD. This resulted in additional separation on top of the required time separation. Additionally, aircraft were kept on the fixed approach trajectories, hence, aircraft were not able to arrive earlier with the use of shortcuts to fill a gap in the sequence in front. Finally, TBS will have a larger effect when stronger winds are present on final approach, hence with stronger wind conditions the effect of TBS should have a stronger positive influence on the capacity.

3) The DST will increase efficiency: The DST configuration showed more consistent route following after the waypoints NIRSI and NARIX than when using the baseline configuration. The final part of the approach trajectory leads aircraft around inhabited areas, as can be seen in Figure 21. Hence, it is important to follow the approach trajectory at this stage of the approach to reduce noise effects on the ground.

The reason why only the latter stages of the approach are better tracked using the DST configuration could be the fact that the TSD allows the ATCOs to solve conflicts much sooner. Hence, the arrival time at the FAF can be adjusted sooner, resulting in less last-minute course corrections to guarantee sufficient separation.

When using the DST configuration, flight commands were issued earlier than during the baseline configuration. This can be explained by the fact that the TSD enabled the participants to look further ahead, enabling them to identify future conflicts sooner, and solve them by using the space on the time-axis of the TSD. In an ideal world, aircraft delivered to approach



(a) Baseline

(b) DST

Figure 21: Ground tracks on map, zoomed in, gray areas represent villages and cities

control by area control would merge perfectly in the TMA. However, solving merge conflicts in the TMA, when aircraft are yet to start their decent, is very difficult due to the longer time range, increasing the uncertainty.

4) The DST will reduce controller workload: From the data collected it can be concluded that there is no significant workload difference between the two display configurations. This could be explained by the fact that the baseline scenario did not require much effort from the participants, as the participants were well-trained for the baseline scenario. An outlier was observed as workload rating of P6 in the baseline configuration was much higher. The ground tracks of P6 showed fewer track deviations when compared to other participants, resulting in the lowest TDM in the baseline configuration. This was achieved by instructing the most speed commands (33), the fewest heading commands (7) and more flight selections (137) than any other participant in the baseline configuration, as can be seen in Figure 18 and Figure 17b. Additionally, the questionnaire showed that P6 found the DST elements useful. Showing that without the use of the DST, the workload increased if the same performance was pursued.

After the experiment, the participants noted the scenario to be busy, but not any different from day-to-day peak hours. This was to be expected as the scenarios were based on real traffic. Combining this with the fact that the tools used during the DST configuration were new, which required the participants to change their workflow. Instead of determining the order of landing aircraft very close to the runway, this decision could already be made much earlier. This change of workflow would have likely increased their perceived workload. Since no difference was observed in the workload between the two display order groups, it can be concluded that the participants did not memorize the scenario used.

Additionally, the introduction of the TSD as a secondary information source required the participants to divide their attention between the radar screen and the TSD. The participants stated that this increased their workload and reduced the quality of their mental model of the system. Normally, the participants are able to interact with the TIDs blindly and can therefore focus fully on the radar screen while executing their control task. The slightly unfamiliar TID in combination with an additional information source increased the workload.

Fewer commands were given by the controllers, most noticeable is the reduction in altitude commands. This can be explained by the fact that the controllers trusted the trajectory predictions. This resulted in them feeling comfortable giving aircraft descent clearances at once without intermediate altitudes, enabling continuous descent operations that produce less noise and emissions. Next to the differences in the number of altitude commands, the number of directional commands (heading and trajectory commands combined) showed a significant reduction between the baseline and the DST configuration. This can be explained by the fact that by using the new tools, the controllers were able to solve conflicts with speed commands. It should be noted that a single trajectory command consists of two "normal" commands, namely a heading and a direct to waypoint instruction. Using the new tools, the effect of the new path can be seen directly hence allowing the controller to instruct the aircraft to fly the exact amount of track miles required to merge the aircraft safely onto the ILS. Finally, a reduction in the total amount of commands might not have lead to a decrease of controller workload, the workload of pilots might decrease as they have to perform fewer instructions issued by ATC.

C. Recommendations

To address issues raised by the participants and solve other issues found during the analysis of the data, some changes to the DST should be made.

From the questionnaire results and logged simulation data it was found that certain elements were not used as often as others. Hence, the unused elements can be removed, or have their implementation altered. The most noticeable elements are the wind visualization and the horizontal axis of the TSD. Participants stated that as long as the predictions made by the computer took the wind information into account, they did not require additional information regarding the wind. The horizontal (distance-to-go) axis did not provide participants with a better understanding of the system, as they felt more useful information was available on the vertical (time) axis. Additionally, Figure 19 showed that the group starting with the baseline configuration found the DST less useful. This may be caused by the control strategy used by this group. Using their "old strategy" with the DST configuration results in the DST being less effective.

Another improvement can be made by integrating the information provided by the TSD on the main radar screen. By removing the horizontal axis, as previously explained, a single time axis could be placed on the radar screen. This would allow the controllers to have all the required information on a single screen, eliminating the need to divide their attention between two screens. Interacting with the time-axis on the radar screen would require changing the user interface as the radar screen does not have touch capabilities. In order to aid the controllers further, more flexibility regarding display and hardware setup could be implemented.

Due to time limitations, the experiment only included short 15-minute scenarios. It could be interesting to investigate what happens when the simulation duration is extended. By adding departures and a second (parallel) landing runway, the system can be tested according to real operations.

Finally, although the workload of the participants did not show a significant difference between the baseline and DST configuration, it could be interesting to perform the same experiment with novice ATCOs. The baseline scenario would become more challenging for the participants, as they are not well-trained. It is hypothesized that with the DST configuration, these people will be able to control the traffic safely and efficiently while experiencing a lower workload.

VII. Conclusion

The addition of the DST enabled controllers to solve future conflicts more proactively. This enabled the aircraft to follow the fixed approach trajectory better in the latter stages of the approach. Furthermore, fewer commands were required when using the DST to solve conflicts, and these were issued earlier. The self-perceived workload did not decrease with the use of the DST. This could be related to the limited available training time. No LOS in time or distance was observed, proving that the safety of the system did not decrease when using the DST. The landing capacity of the system became slightly higher with the DST enabled. No significant change was observed compared to the baseline configuration, which also shows the professionalism of the participants.

Acknowledgment

The author would like to thank all parties involved with this research. That includes LVNL and Ferway for providing their expertise and data to create a realistic experiment. Furthermore, the author would like to thank all participants who took part in the experiment, their contribution extends beyond only performing the experiment, as the discussions post-experiment were found to be really insightful.

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Part II

Thesis Appendices

A Experiment Plan

A.1. Goal

The research question to be answered during this experiment is: "How can traffic merging in approach control be implemented, while time-based separation and fixed approach trajectories are used?". Hence, the goal of the experiment is to determine if the proposed solution to this research question is resulting in the predicted results.

A.2. Hypothesis

With the use of the added decision support tools, it is expected that this will lead to the following hypothesis:

Hypothesis

- H.1 The DST will increase safety.
- H.2 The DST will increase productivity.
- H.3 The DST will increase efficiency.
- H.4 The DST will reduce controller workload.

A.3. Independent Variables

The independent variables during this experiment are the display configuration and display order. During the experiment a baseline and a Decision Support Tool (DST) display configuration is used. The baseline configuration will be similar to what the ATCOs use currently, meaning the ATCOs will have to give vectors to guide the aircraft to the ILS. In the DST configuration, the decision support tools will be activated. The starting order of these display configurations will be altered between the participants.

A.4. Control Variables

The control variables during the experiment are the configuration parameters that are used for each scenario. This includes settings on font size, values, flags, and colors of the different elements on the display. All these parameters, except the independent variables will remain constant.

A.5. Dependent Variables

The experiment will measure the safety, productivity, efficiency and controller workload. The safety will be measured by looking at the minimum separation between aircraft, based on distance and based on time. The performance will be measured by looking at the amount of aircraft that can be landed within a certain amount of time. The efficiency will be measured by investigating the ground tracks on deviations from the fixed approach trajectories and if commands are given sooner due to the use of the DST. Finally, the workload of the approach controllers will be measured by looking at the number of commands given, the number of flight selections and by asking ATCOs after each run to give a 0-150 Zijlstra rating of their perceived workload [24].

A.6. Participants

Qualified approach controllers will participate during the experiment. These controllers are working for LVNL as Schiphol tower/approach controllers. The aim is to recruit approximately 6 controllers, which fits the experiment structure as can be seen in Table A.2.

A.7. Structure

The experiment will be based around four scenarios. These scenarios are shown in Table A.1. With the wind field loaded from the same date and time for the propagation of the aircraft. The DST makes use of a “predicted” wind field which is one hour behind the current time.

The first three scenarios are used for training while MP2 is used for taking measurements. The experiment design matrix is displayed in Table A.2. Here it can be seen that the first three participants start with four runs with the baseline scenario, after which they will switch to the decision support tool scenario. For the last three participants this is reversed, first the decision support tools scenario, after which the baseline scenario is performed. This experiment follows a factorial, within participants design structure. As can be seen, the order of the training scenarios is varied for all participants. Also, in order to reduce the risk of participants recognizing scenarios during runs 5-8, the aircraft callsigns will be randomized.

Table A.1: Scenario specifications

ID	**1**	**2**	**3**	**4**
Date	11-07-2019	18-07-2019	17-02-2022	01-07-2019
Time (UTC)	17:00-17:15	16:00-16:15	08:00-08:15	08:00-08:15
Runway	18R	18R	27	18R
# of aircraft	12	12	16	16
Aircraft types	D,E	B,D	B,D,E	B,D
Wind at 2,000ft above Schiphol	156/8 kts	219/13 kts	280/49 kts	275/13 kts
IAF mix	SUGOL, RIVER	ARTIP, RIVER, SUGOL	ARTIP, RIVER, SUGOL	ARTIP, SUGOL

Table A.2: Experiment design matrix, Baseline, Decision Support Tools, Training runs, Measurement runs

ATCo \ **Run**	T1	T2	T3	M4	T5	T6	T7	M8
P1	B, 1	B, 2	B, 3	B, 4	D, 2	D, 3	D, 1	D, 4
P2	B, 3	B, 1	B, 2	B, 4	D, 1	D, 2	D, 3	D, 4
P3	B, 2	B, 3	B, 1	B, 4	D, 3	D, 1	D, 2	D, 4
P4	D, 2	D, 3	D, 1	D, 4	B, 1	B, 2	B, 3	B, 4
P5	D, 1	D, 2	D, 3	D, 4	B, 3	B, 1	B, 2	B, 4
P6	D, 3	D, 1	D, 2	D, 4	B, 2	B, 3	B, 1	B, 4

A.8. Experiment Briefing

A separate document containing the briefing is sent to all participants. This separate document is added to this report in Part V. It explains the experiment goal, concept of operations and the new decision support tools. Before the experiment, this briefing document is further explained if any questions are still present. After which the participants start with the training. For the baseline training not much explanation is required as it’s very similar to what the controllers are used to. For the decision support tools scenarios, additional briefing is put in place to explain the limitations and use cases of the decision support tools further. Additionally, a static training scenario is made. This way, the controllers can play with the new tooling, change trajectories using the DSR, use the TSD and provides the researcher the change to explain the newly added tools while the controllers are actually able to interact with them. Which gives them a better feeling of the tools than from a picture on a sheet of paper.

A.9. Questionnaire

This section shows the questions used during the experiment. After each scenario run, the participants are asked to fill in the corresponding questionnaire. After the baseline scenario, the questions posted in Section A.9.1, after the decision support tools the questions from Section A.9.2 are used.

Questions of the same category are grouped together and asked simultaneously. For each question, 5 options are available. The options are:

- Agree (or easy for the group called “Element rating”)
- Somewhat agree (or somewhat easy for the group called “Element rating”)
- Neutral
- Somewhat disagree (or somewhat difficult for the group called “Element rating”)
- Disagree (or difficult for the group called “Element rating”)

After each block, an open question is provided in order to allow the participants to explain their answers.

A.9.1. After Baseline

The groups and questions used:

- Intro:
  - Age and experience
- Realism of simulation:
  - Radar screen looks familiar
  - Touch input device looks and feels familiar
  - Aircraft performance is realistic
  - The wind effects on the aircraft flight path was realistic.
  - Traffic density is realistic
  - Traffic type mix is realistic
  - Traffic delivery at the IAFs is realistic
- Ease of control task:
  - It was clear and easy to select an aircraft
  - It was easy to change the aircraft label position
  - it was easy to change the speed using the TID
  - It was easy to change the heading using the TID
  - It was easy to change the cleared altitude using the TID
- Conflict detection:
  - It was obvious to me how I could solve potential conflicts
- DST general:
  - I felt sufficiently trained and felt comfortable using the system
  - I was able to derive and execute my preferred strategy
  - I had a complete mental picture of the traffic
  - I could handle the traffic safely
  - I could handle the traffic efficiently

A.9.2. After Decision Support Tools

The groups and questions used:

- Intro:
  - Age and experience
- Automation in ATM:

  - Automation will change the way controllers operate
  - Automation can aid me in my control task
  - It is important that the human takes the final decisions and not the computer
  - New decision support tools are required in order to facilitate TBS in combination with fixed approach trajectories
  - In the future (in 10 years), I believe that aircraft can be delivered to the FAF with a 5-second accuracy

- Realism of simulation:
  - Radar screen looks familiar
  - Touch input device looks and feels familiar
  - Aircraft performance is realistic
  - The wind effects on the aircraft flight path is realistic
  - Traffic density is realistic
  - Traffic type mix is realistic
  - Traffic delivery at the IAFs is realistic

- Ease of control task:
  - It was clear and easy to select an aircraft
  - It was easy to change the aircraft label position
  - It was clear and easy to select a waypoint
  - it was easy to change the speed using the TID
  - It was easy to change the speed using the TSD
  - it was easy to change the trajectory of the aircraft using the right mouse button
  - It was easy to change the cleared altitude using the TID

- Element rating (please state whether the following display elements were useful):
  - Distance-To-Go in aircraft label
  - Wind visualization
  - Margin Indicator on trajectory
  - Delay space representation
  - Time-slider (Ghost projections)
  - Horizontal axis on the TSD (Distance)
  - Vertical axis on the TSD (Time)
  - Uncertainty visualization on the TSD
  - Uncertainty visualization on the radar screen

- Conflict detection:
  - Conflict detection on TSD was helpful
  - Conflict detection on trajectory was helpful
  - Conflict detection in aircraft label was helpful
  - It was obvious to me how I could solve potential conflicts

- DST general:
  - I felt sufficiently trained and felt comfortable using the newly designed tools
  - I was able to derive and execute my preferred strategy
  - I was controlling air traffic more strategically using the new tools
  - The additional tooling caused too much screen clutter
  - TSD on touch screen makes sense
  - The uncertainty visualization on the TSD was useful
  - I had a complete mental picture of the traffic
  - I used both the TSD and radar screen to create my mental picture
  - I could handle the traffic safely
  - I could handle the traffic efficiently

B
Scenario Creation

Scenarios loaded into SectorX are of .xml format. The .xml files contain information about the airspace, aircraft and weather. An example scenario can be seen in Code Block B.1.

```xml
<?xml version="1.0" encoding="UTF-8"?>
<scenario>
   <airspace centerlat="52.30805556" centerlon="4.764166667">
      <sectors>
         <sector include="lvnl/SCHIPHOL TMA 1" type="sector" bottom="1500" top="10500"/>
      </sectors>
      <georegions>
         <georegion include="nl/Dutch_Border_Part_2" type="geoborder"/>
      </georegions>
      <airports>
         <airport include="EHAM">
            <runway include="36R"/>
         </airport>
      </airports>
      <waypoints>
         <waypoint include="nl/SPL"/>
      </waypoints>
      <routes>
         <route include="R5B" show="true"/>
         <route include="REDFA 1A" show="false"/>
      </routes>
   </airspace>
   <traffic>
   <aircraft id="KLM21B" icao="B738" sqwk="3314" start_time="0" lat="52.2324" lon="4.2425"
       heading="25" ias="210" altitude="5225" target_altitude="3000" exit_altitude_ft="2000"
       flightState="assumed" ownNavigation="true" route="R5B" copx="AM621" departure="EGLL"
       destination="EHAM" rtas="420" rFL="380" rwy="18R" gate="G1"></aircraft>
   </traffic>
   <weather>
      <windfields>
         <windfield id="actual" type="GRIB" foldername="CLEANSKY_select_I_L_2018103000"
             centerlat="52.30805556" centerlon="4.764166667"/>
      </windfields>
   </weather>
</scenario>
```

Code Block B.1: Scenario file example

Between the scenarios used by participants, only the wind field, routes and traffic elements differ. The routes change because of the two runways that are used, hence only the approach trajectories to the runway in use are shown. The traffic sample for each scenario is based on real traffic samples, hence the wind fields used are from the actual day and time of the traffic. An actual and predicted wind field are used to generate the uncertainty present due to the fact that predicted wind is never equal to the actual wind.

The generation of the traffic is a bit more complicated as currently no fixed approach trajectories are used. Therefore, the aircraft already within the TMA will have to be put onto the approach trajectories at the correct point. This is done such that aircraft do not conflict with each other within at least the first 5 minutes of the simulation as the (hypothetical) previous controller would have taken care of these conflicts. Aircraft outside the TMA are put on the most logical STAR (Based on their initial position) and adjusted along the STAR such that they arrive at the IAF at the same time as they did in reality.

Using python code the process of generating the scenarios and in particular the traffic characteristics has been made very quick and easy. Each scenario is summarized in a .csv file. This contains the following:

Table B.1: Scenario specifications part 1

ID	type	startTime	alt	altTgt	ias	hdg	initWpt	offset	route
KLM21B	B738	0	5225	3000	210	9	AM605	11	R5B

Table B.2: Scenario specifications part 2

lat	lon	sqwk	IAFTime	rwy	wind
52.225654	4.289584	1000	17:00:03	18R	GRIB
					CLEANSKY_select_I_L_2019071117
					CLEANSKY_select_I_L_2019071116
					52.30805556
					4.764166667

As can be seen in Table B.1 and Table B.2, all information is present to create the scenario. The last two columns providing info regarding the active runway and the wind present. The first 14 contain traffic information with a new aircraft on each row (only one aircraft is the shown tables). These include the following:

- **ID:** Aircraft callsign.
- **type:** Aircraft type.
- **startTime:** Time at which the aircraft is initialized and shows up on the radar screen.
- **alt:** Altitude of Aircraft upon initialization.
- **altTgt:** Altitude target of aircraft upon initialization.
- **ias:** Indicated airspeed of aircraft when initialized.
- **hdg:** Heading of aircraft when initialized and no route if found.
- **initWpt:** Initial waypoint to start at.
- **offset:** Offset in NM from the initial waypoint.
- **route:** The route the aircraft is expected to follow.
- **lat:** Latitude of the real aircraft at the start time as is given in Table A.1.
- **lon:** Longitude of the real aircraft at the start time as is given in Table A.1.
- **sqwk:** Aircraft transponder squawk code from real aircraft.
- **IAFTime:** Manually obtained time over the IAF. Not used in code.

In order to explain the initWpt and offset parameters in more detail, Figure B.1 shows the result of the scenario specified in Table B.1 and Table B.2. KLM21B is shown 11 NM from AM605. The heading of the aircraft is aligned with the direction of the route. In this case, the values of hdg, lon and lat are not used in the placement of the aircraft as they are obtained from the route, initWpt and offset parameters.

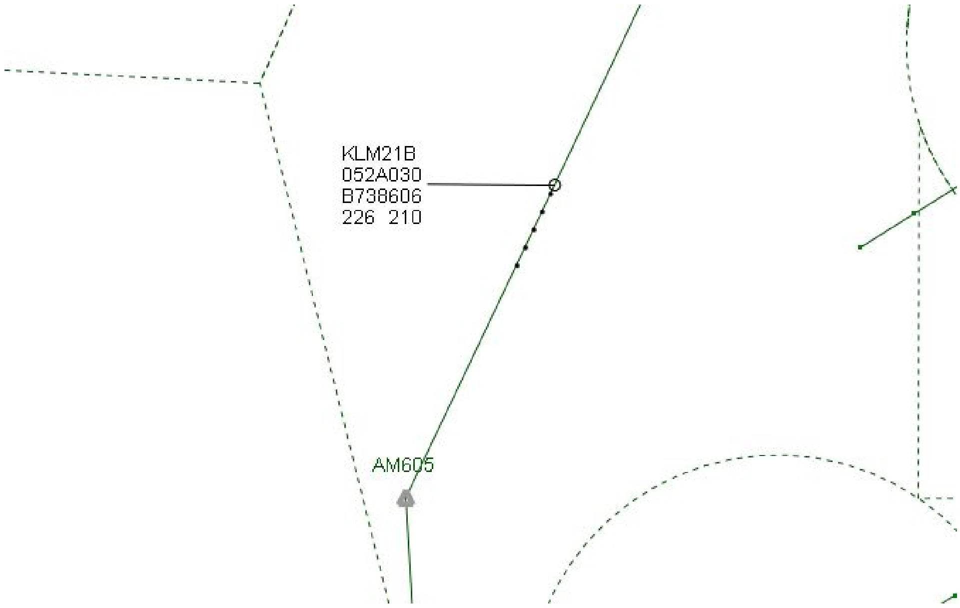


Figure B.1: Positioning of KLM21B

Finally, a few conditional and random elements are implemented within the scenario creation code. These are:

- Above FL100, all aircraft fly with an indicated airspeed of 250 knots.
- Above FL100, all aircraft are controlled by area control, the approach controller will have to use an “UCO” command on these aircraft before issuing other commands.
- Above FL100, all aircraft will have a target altitude of FL100.
- The final Waypoint, the COPX is set based on the active runway.
- A random gate is assigned to each aircraft, to be used in the interaction area.
- A random rTAS is assigned to each aircraft, to be used in the interaction area.
- A random rFL is assigned to each aircraft, to be used in the interaction area.

C
Questionnaire Results

Additional Questionnaire results are presented in the next sections, starting with the baseline after which the DST results are presented. In general, it was found that the group staring with the baseline configuration was less positive about the use of the DST. After starting with the DST configuration, the baseline configuration felt like a step back to the participants.

C.1. Baseline Results

Figure C.1 shows that the participants felt comfortable with the simulation software. From Figure C.2 it becomes clear that the TID did require more effort than the controllers are normally used to. This was mainly caused by not allowing multiple commands to be executed at once.

Figure C.1: Baseline, general questions

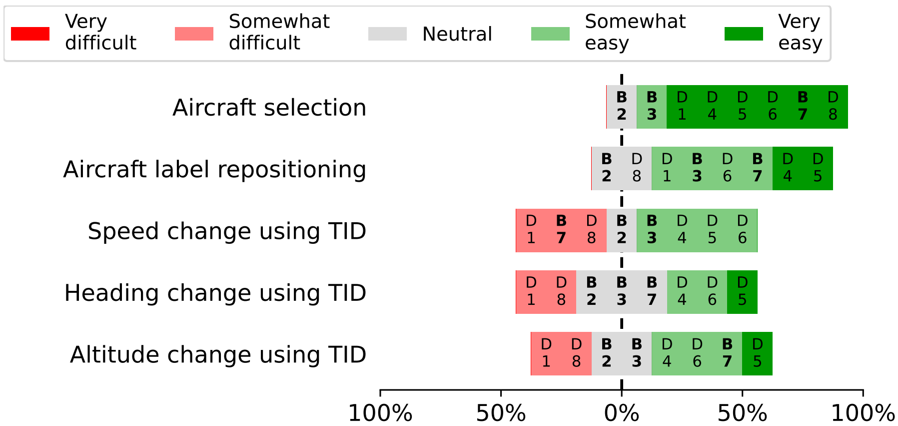


Figure C.2: Baseline, ease of control task

The realism of the simulation was adequate, according to the participants, as is shown in Figure C.3. Once again, only the TID showed a split vote due to slight differences to the real TID used normally by the participants.

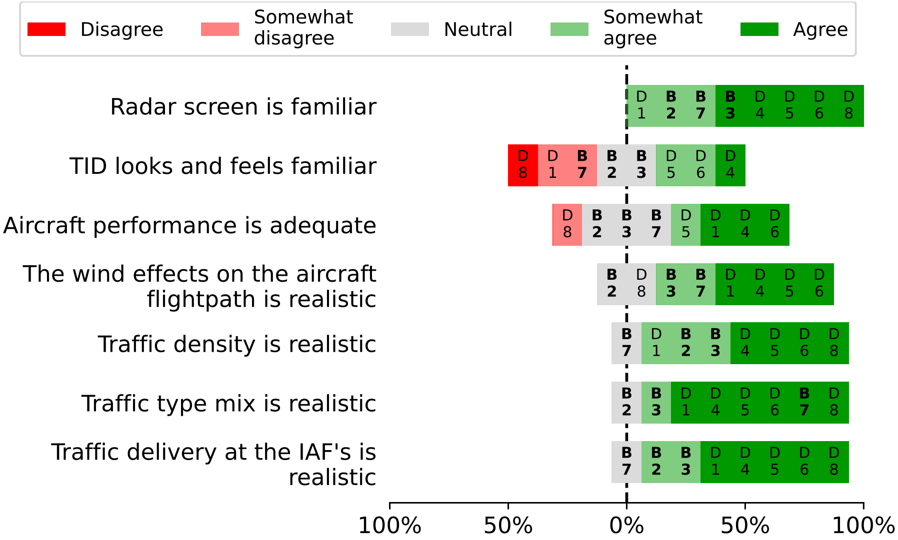


Figure C.3: Baseline, realism of simulation

C.2. DST Results

After the DST, more questions were asked regarding the newly added tools. The results regarding the general questions, shown in Figure C.4, indicate that there was not too much screen clutter, while uncertainty visualization was not found to be useful.

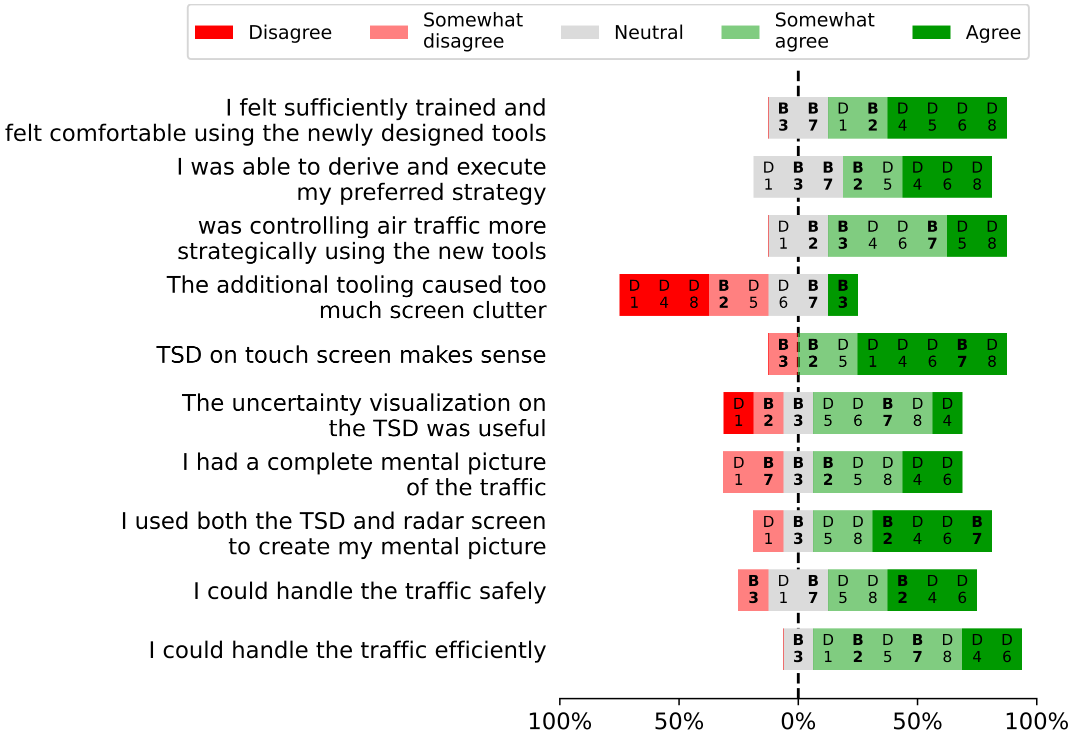


Figure C.4: DST, general questions

Figure C.5 indicated that the new elements were found easy to work with according to the participants. Only the speed change of on the TID did cause some issues for some, however, in general the new tools allowed the participants to execute their control tasks easily. This also showed from Figure C.6 as participants deemed the conflict detection on the radar screen and TSD to be very helpful.

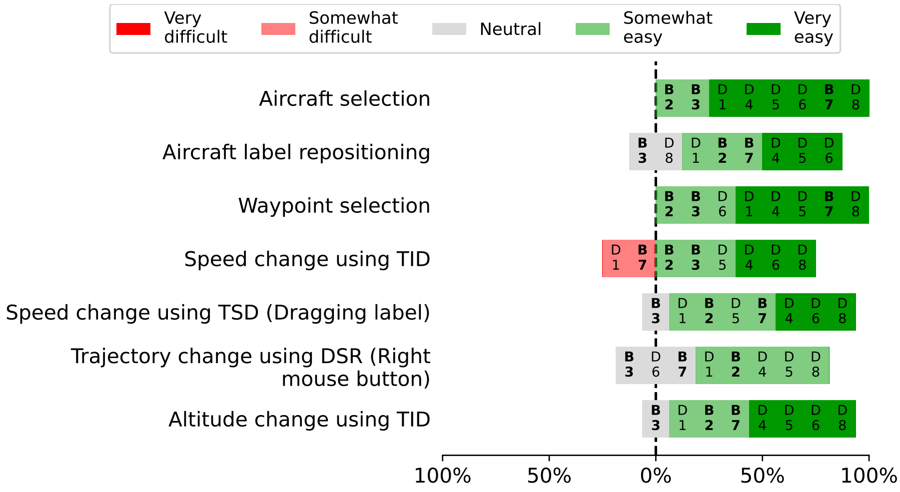


Figure C.5: DST, ease of control task

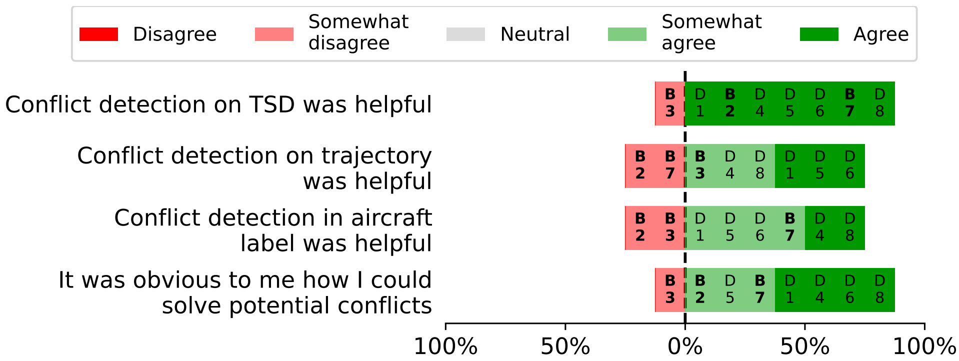


Figure C.6: DST, conflict detection

Finally, participants were asked about automation in ATM. As shown in Figure C.7, the participants stated that new DSTs are required in order to change the current operations to be more trajectory and time based. However, the responsibility and decision-making process should be done by the human. The last question showed that participants do not believe that aircraft delivery at the FAF in the next ten years will be within a 5-second accuracy.

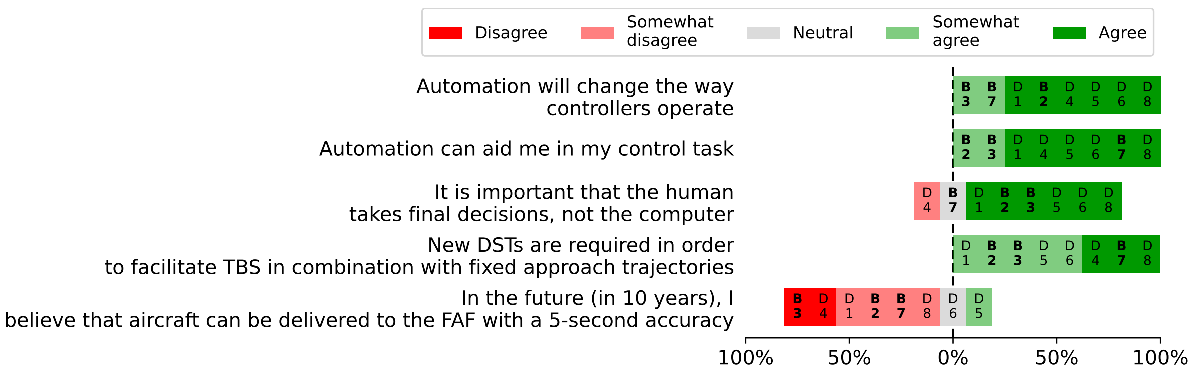


Figure C.7: DST, automation in ATM

Part III

Preliminary Thesis[1]

[1]This part has been graded as part of the preliminary thesis report under AE4020.

1
Introduction

1.1. Background

Aircraft descending towards their destination airport will fly through different sectors. Each sector is controlled by a different air traffic controller. The task of the air traffic controllers is to guide the traffic towards their sector exit point, which could be a waypoint, direction or runway. However, sometimes flight paths cross, causing a conflict or in extreme cases a loss of separation. Hence, air traffic controllers also bear the responsibility of maintaining enough separation between all aircraft. The separation is defined as the distance between two aircraft in terms of position and altitude, primarily to avoid a midair collision. Secondary, wake turbulence caused by the leading aircraft should be avoided in order to ensure safe flight, especially when a light aircraft trails a heavy aircraft. In approach control, all arriving traffic in the sector are guided towards the same runway (during single runway operations). Hence, aircraft have to be sequenced by approach controllers, meaning they follow each other and the effects of wake turbulence must not be neglected. However, there are some improvements to be made regarding the separation between aircraft on final approach. These improvements will be explained in the next section.

1.2. Problem Statement

In order to improve capacity while at the same time reduce the negative effects on residents, two new ways of handling air traffic are proposed. These include time-based separation and fixed approach trajectories. As will be explained further in the next two subsections.

1.2.1. Time-Based Separation

Aviation as a whole is expected to grow, therefore adjustments to the current Air Traffic Management (ATM) system will need to be made [6]. Currently, runway capacity decreases significantly when large headwinds are present. This is caused by the fact that aircraft are separated by distance instead of time. A switch from Distance-Based Separation (DBS) to Time-Based Separation (TBS) allows the runway capacity to be maintained even when strong headwinds are present [21]. The loss in runway capacity when using DBS is caused by the fact that aircraft flying into a strong headwind will fly slower with respect to the ground. Hence, less distance is covered per unit of time. By keeping the distance between aircraft constant, the landing rate decreases as the headwind increases. During strong headwind conditions (>25 knots) this can result in a capacity reduction of 15% [21]. Therefore, by switching to TBS, aircraft will be separated by time, which is not affected by the environmental conditions. An increased runway capacity will allow aircraft to land sooner and thus spend less time in the air, hence saving fuel and thus making for a more efficient operation. However, the implementation of TBS will complicate the Air Traffic Control (ATC) task and requires decision support tools for the controllers as TBS is not easily visualized on a 2D radar screen. This research will thus try to design, implement and test a decision support tool in order to support time-based separation in approach control.

1.2.2. Fixed Approach Trajectories

Complementary to implementing time-based separation, fixed approach trajectories will be placed within the Terminal Maneuvering Area (TMA) to guide aircraft from their Initial Approach Fix (IAF) to the Final Approach Fix (FAF) [11]. It should be noted that fixed approach trajectories are already in use at Amsterdam Airport Schiphol, however these routes are only used at night when the traffic density is low. Due to lack of flexibility and uncertainties in flight predictions, these routes are not used during peak hours. However, implementing fixed approach trajectories will provide pilots and controllers with a clear view of the flight path in terms of energy management. The amount of track miles to the runway is known, hence making it easier to execute a continuous descent profile. During a continuous descent, the engines will not have to be used resulting in less noise produced by the aircraft. Furthermore, fixed approach trajectories will reduce the effects of noise on local inhabitants as aircraft can follow a carefully chosen route, avoiding areas that are inhabited as much as possible. However, fixed approach trajectories will result in less control options available to air traffic controllers, as this means that only speed commands are available to the controller. Ideally the controller instructs the aircraft to change its speed as soon as possible, in order to have the largest solution space. However, this requires additional tooling since it is very difficult for a controller to predict the trajectories of multiple aircraft more than 10 minutes ahead of time. Additionally, when the traffic density increases even more, situations in which separation can not be assured by means of speed commands may occur. In these situations, aircraft vectoring may still be required. Using accurate prediction and decision support tools for the air traffic controller, the need for aircraft vectoring should be minimized.

1.2.3. Trajectory Prediction Uncertainties

In order to make the previous two subsections a reality, accurate trajectory prediction is required. With any prediction, uncertainties are present. For aircraft trajectory predictions, these uncertainties arise from the following factors:

- **Environmental uncertainties:** The effect of wind has a large impact on the trajectory prediction as it has a direct influence on the ground speed. Hence, aircraft arrive earlier or later than predicted along the intended flight path. With the use of high resolution wind data, the effect can be minimized. However, it will be near impossible to have access to the exact wind an aircraft will encounter in the future.
- **Aircraft performance uncertainties:** Upon arrival, aircraft descent towards the runway. However, there are uncertainties present in the exact descent rate. This is influenced by the aircraft type, age, mass and configuration. An aircraft has a higher ground speed at higher altitude, hence uncertainties in the descent profile causes uncertainties in the prediction of the trajectory.
- **Pilot behavior uncertainties:** Finally, the way the pilot operates the aircraft add to the uncertainty of the trajectory prediction. This includes differences between airlines who might have a different procedure of operating their aircraft, or differences between the pilots who execute commands from the air traffic controller with different delay timings between receiving and executing a command. This can also include cultural differences based on the airline and/or pilots origin.

All listed uncertainties will add to the error of the trajectory prediction. Therefore, the to be designed display tooling will have to take these uncertainties into account and provide the air traffic controllers with the information. Allowing them to make the correct control decisions.

1.3. Research Objective

Following the background information and problem statement, the research objective for this thesis is as follows:

Research Objective

Supporting approach controllers in traffic merging while time-based separation and fixed approach trajectories are used by means of providing a complete set of solutions through an informative decision support tool.

This objective can be divided into three secondary objectives. The first aims to support TBS in approach control. The second is about implementing fixed approach trajectories within approach control, even when the traffic density increases during inbound peaks. The third secondary objective is to provide the approach controller with a full set of solutions through the means of an informative decision support tool.

1.4. Research Question(s)

With the problem statement and research objective determined, the research question and sub-questions can be set. These are defined as:

Research Question

How can traffic merging in approach control be supported, while time-based separation and fixed approach trajectories are used?

Sub-questions

1. What information does an approach controller require to support time-based separation, and how is the information presented?
2. How will uncertainties be visualized to an approach controller?
3. What effect will the switch to time-based separation have on the workload of the approach controllers?
4. How flexible is the solution space when merging traffic from different IAF's to a single runway?

1.5. Report Outline

This report includes descriptions of the current and future state of approach control in Appendix 2 and Appendix 3, respectively. After which a cognitive work analysis is performed in Appendix 4 and concepts obtained from previous work are presented in Appendix 5. This all leads to the content of the preliminary work in Appendix 6. Finally, the future work is presented along with the conclusion of this report in Appendix 7 and Appendix 8, respectively.

2 Current State of Approach Control

In order to make improvements to approach control, it is important to have a good understanding of the current state of approach control and its position in the Air Traffic Management (ATM) system. Therefore, this chapter will explain in Section 2.1 where approach control is located within the ATM system. Next, Section 2.2 explains the current operation practices in use at Amsterdam Airport Schiphol.

2.1. Position of Approach Control within the ATM System

In Figure 2.1 the position of approach control can be seen within the airspace structure. The altitude ranges shown with a tilde are not always the same, depending on location of the airspace. Furthermore, note that in this situation the airport is located at zero feet, which in real life will be different. Hence, this figure is to be used in order to get a broad understanding of how the airspace in The Netherlands is structured. It should be clear that approach control is located above tower control and below area control. LVNL provides area, approach and tower control to aircraft flying in Dutch airspace below Flight Level (FL)245. Above FL245, aircraft are controlled by upper area control, which in the case of The Netherlands is provided by Maastricht Upper Area Control (MUAC).

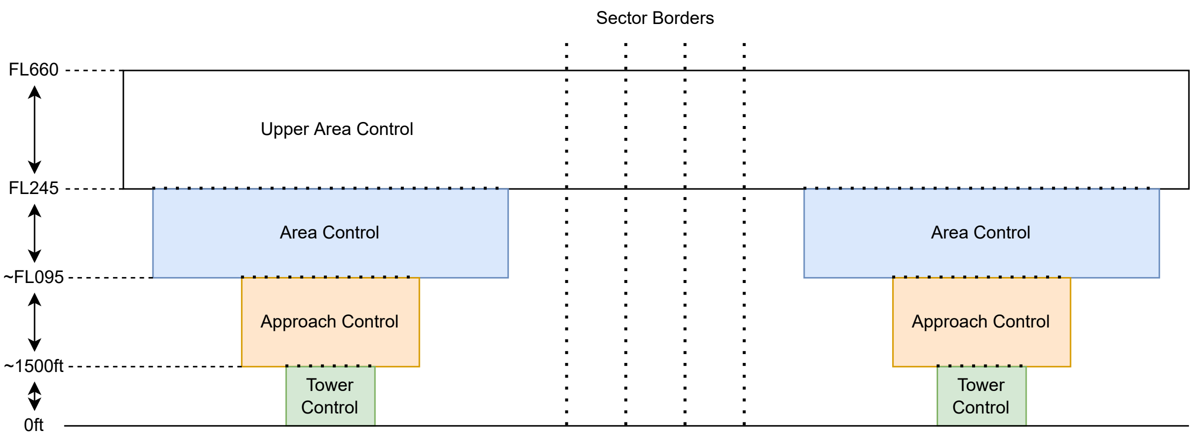


Figure 2.1: Airspace Structure

Figure 2.2 shows the current airspace division and arrival routes into Amsterdam Airport Schiphol. The information on waypoints and airspace division is obtained from the Aeronautical Information Publication (AIP) maintained and distributed by [1]. The AIP is updated every four weeks, hence the arrival procedures shown in this report could be different from the newest publication. In Figure 2.2, it can be seen how the Standard Terminal Arrival Routes (STAR's) in red enter the TMA. For a more detailed overview of the STAR's, Figure A.1 shows the official standard arrival chart [1]. Aircraft flying along the STARs are controlled by area control. The area controller guides the aircraft to the IAF, the IAF's are labeled in the figure and are named ARTIP, RIVER and SUGOL. From the IAF's, aircraft enter the TMA of Amsterdam Airport Schiphol, the black area in Figure 2.2. Around the IAF, the approach controller will take over from the area controller.

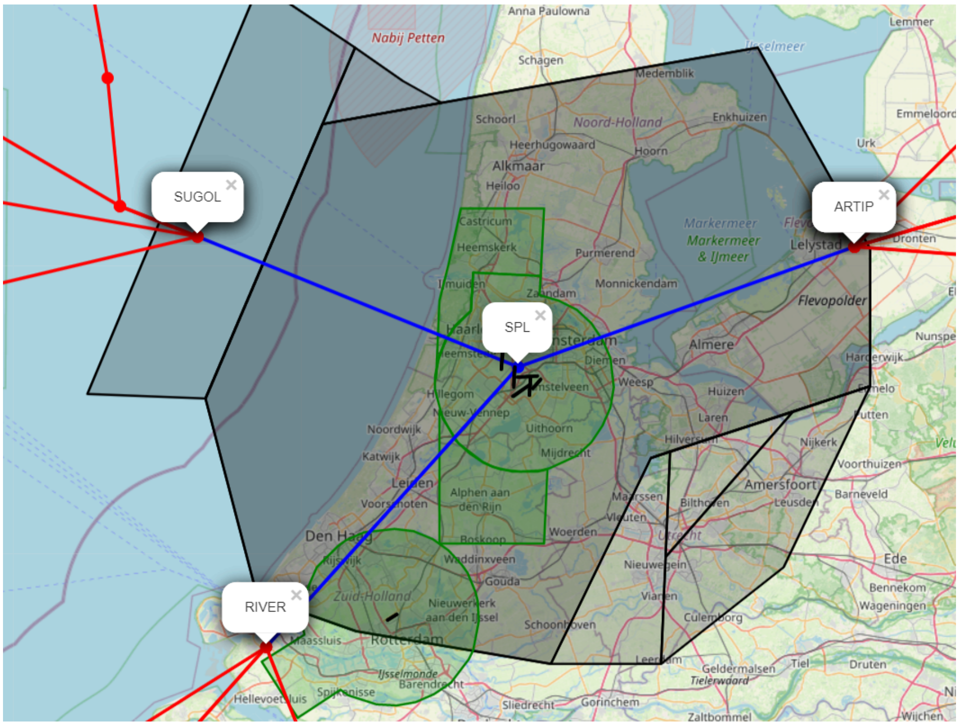


Figure 2.2: Current Airspace Division and Arrival Routes to Amsterdam Airport Schiphol [13]

2.2. Current Operations Practices

In order to guide the incoming aircraft from the IAF's to the FAF, the approach controllers give instructions to aircraft by voice. Initially, aircraft fly directly towards the SPL (Schiphol) radio beacon. These routes are shown in blue in Figure 2.2. When there is space, aircraft are taken off these routes and are guided towards the runway. This is done by using the following three voice commands:

- **Heading command:** This type of command allows the controller to give the controlled aircraft a direction. This can be in the form of a heading, from 0 to 360 degrees. However, the controller can also give the aircraft instructions to fly towards a known point (e.g. a radio beacon or a waypoint with known GPS (Global Positioning System) coordinates). An example would be "KLM123 turn left heading 060".
- **Speed command:** This type of command allows the controller to let the aircraft fly at a preferred speed. At high altitude usually a Mach number is issued by the air traffic controller. For approach control however, Indicated Air Speed (IAS) in knots is used. When a speed command is issued, the controller will have to keep in mind the performance limitations of the aircraft and the regulations that are current. An example of performance limitations are the maximum speed of the airframe and the stall speed. An example of regulations that are in place is that aircraft must not fly faster than 250 IAS below FL100. An example would be "KLM123 reduce speed 220 knots".
- **Altitude command:** Finally, an altitude command gives the aircraft permission to change its altitude. During a descent, aircraft are cleared to descent to a so-called stop altitude. This stop altitude is set in place in order to prevent the aircraft from descending to into the path of other traffic. The same practice is done for climbing traffic. Another form of an altitude command is to give a "level at" command, which tells the pilots how they should plan their vertical profile in order to be at the required altitude at the waypoint given with this command. An example would be "KLM123 descent and maintain FL100, level at ARTIP".

During normal operations, the approach controller will give the aircraft heading (also known as giving an aircraft vectors), speed and altitude instructions in order to separate aircraft onto the ILS in sequence. However, during the night, fixed routes are flown to the ILS in order to reduce the noise effects on residents. These fixed routes are called night transitions and are published by LVNL [1]. These routes can be seen in Figure 2.3, clearly showing the night transitions to runway 18R, also known as the

Polderbaan. More information on the exact night transitions can be found in Figure A.2 and Figure A.3. Also shown in Figure 2.3 in white are flight tracks from operations during the day. Clearly the night transitions are not followed and aircraft are sequenced by adding or removing track miles to their flight path. At night however, aircraft are using the night transitions, as can be clearly seen in Figure 2.4. This fixed route allows pilots and controllers to know how many track miles to the runway they have, enabling a smoother descent path and thus less need for using the engines at low altitude. Hence, reducing noise, emissions and fuel consumption. However, fixing the lateral path of aircraft does limit the options an approach controller has to separate the aircraft, hence better decision support tools are required if these kind of operations are implemented with high traffic density situations during the day. These type of approaches can also be applied to different runways. Currently, only three runways at Amsterdam Airport Schiphol have night transition approaches, namely 18R, 18C and 06.

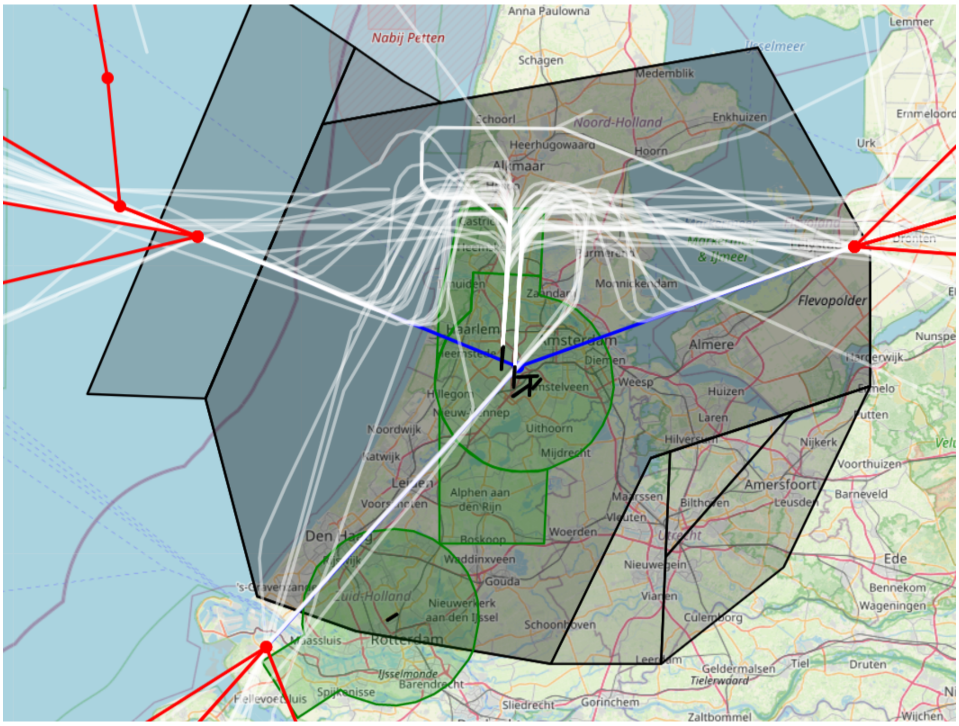


Figure 2.3: Normal Operations to the Polderbaan (18R) Using Vectoring (01-07-2019 04:00 - 01-07-2019 06:00) [13]

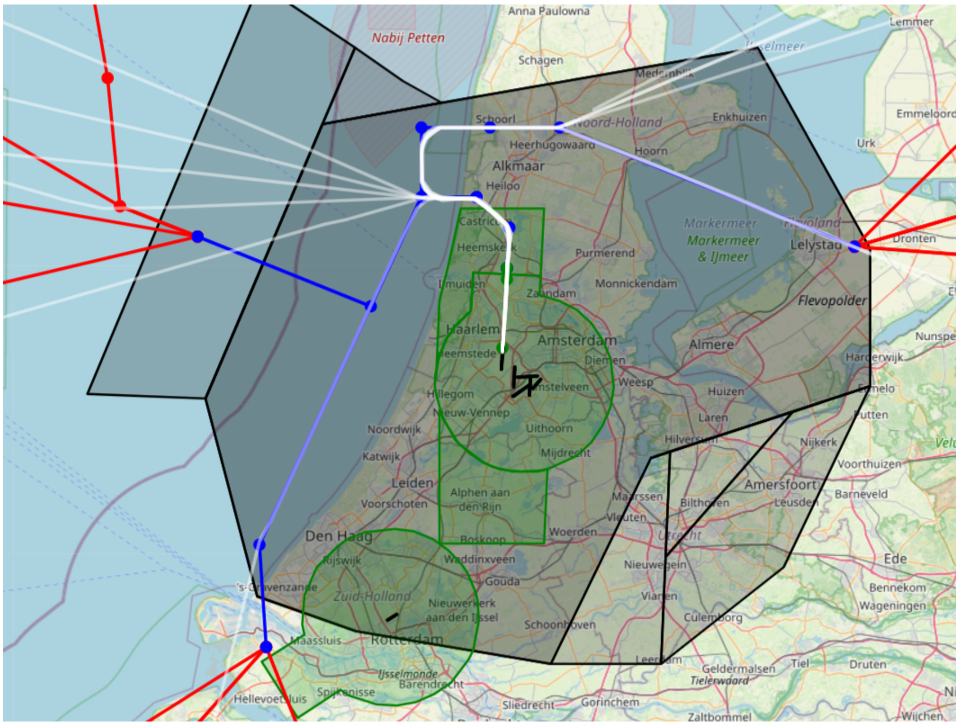


Figure 2.4: Night Operations to the Polderbaan (18R) Using Night Transitions (01-07-2019 02:00 - 01-07-2019 04:00) [13]

Depending on the amount of landing traffic, one or two runways are used for landing. At Amsterdam Airport Schiphol, the FAF is located on the extended centerline of the associated runway at an altitude of 2000 feet and 6.2 nautical miles from the runway threshold as found in the AIP by [1]. The combination of distance from the runway and altitude allows the aircraft to intercept the Instrument Landing System (ILS) right after the FAF is reached if the altitude of 2000 feet is reached when arriving at the FAF. When aircraft approach the FAF, aircraft have entered the Controlled Traffic Region (CTR). They will be cleared by the approach controller to intercept and follow the ILS, after which the aircraft are handed over to the tower controller.

2.3. Departing Aircraft

It should be noted that while this research focuses on arriving traffic, the approach controller is also responsible for guiding departing traffic through the controlled sector. Hence, this complicates operations for the approach controller, as less solution space is available when vectoring aircraft. The departing aircraft fly according to predefined Standard Instrument Departure (SID) routes. This research assumes that these SIDs do not conflict with the published night transition approaches, hence departing aircraft are not considered at this point of the research.

3

Future State of Approach Control

Global airborne operations are expected to increase. In order to ensure safe and efficient operation, the European Union and Eurocontrol have established the Single European Sky ATM Research (SESAR) program. In the US a similar program is present under the name NextGen. These programs aim to facilitate airborne operations in the near future. This includes aircraft flying at higher altitudes, drone integration with current ATM, and optimizing current airspace usage [7]. Among all proposed improvements of the ATM system are the implementation of TBS and fixed approach trajectories [7]. TBS and fixed approach trajectories are further explained in Section 3.1 and Section 3.2, respectively.

3.1. Time-Based Separation

TBS has proven to increase runway capacity at Heathrow and is envisioned to be beneficial at Amsterdam Airport Schiphol [5, 21]. Because large headwinds result in a lower ground speed of incoming aircraft, DBS would result in more time between incoming aircraft. This leads to fewer aircraft landing per hour, as is visualized in Figure 3.1. TBS allows aircraft to follow each other to the runway based on a time difference, hence allowing the runway to be used to its full capacity in all weather conditions. TBS is visualized in Figure 3.2 in order to get a better understanding. Taking different aircraft types into account, the required separation time can be obtained using the RECAT wake turbulence categorization and separation minima [18]. When TBS is implemented correctly, it is possible to use the runway at a higher capacity in strong headwind scenarios. Therefore, less holding time or delays will be needed. As aircraft spent less time in the air, less fuel is used, noise and emissions are reduced. This also improves the life cycle of aircraft as less time in the air reduces the stresses and fatigue on the airframe and engines. Allowing airlines to operate their fleet more efficiently. Due to the benefits regarding efficiency and the environment, TBS also makes the whole operation less costly for the airlines to operate their aircraft.

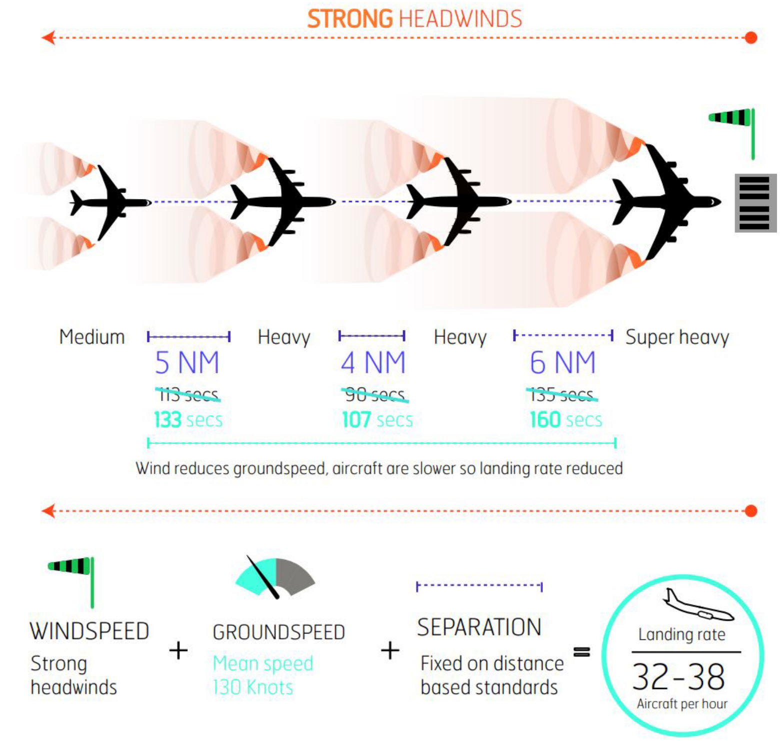


Figure 3.1: Distance-Based Separation (DBS) Visualized [16] (Colors Inverted)

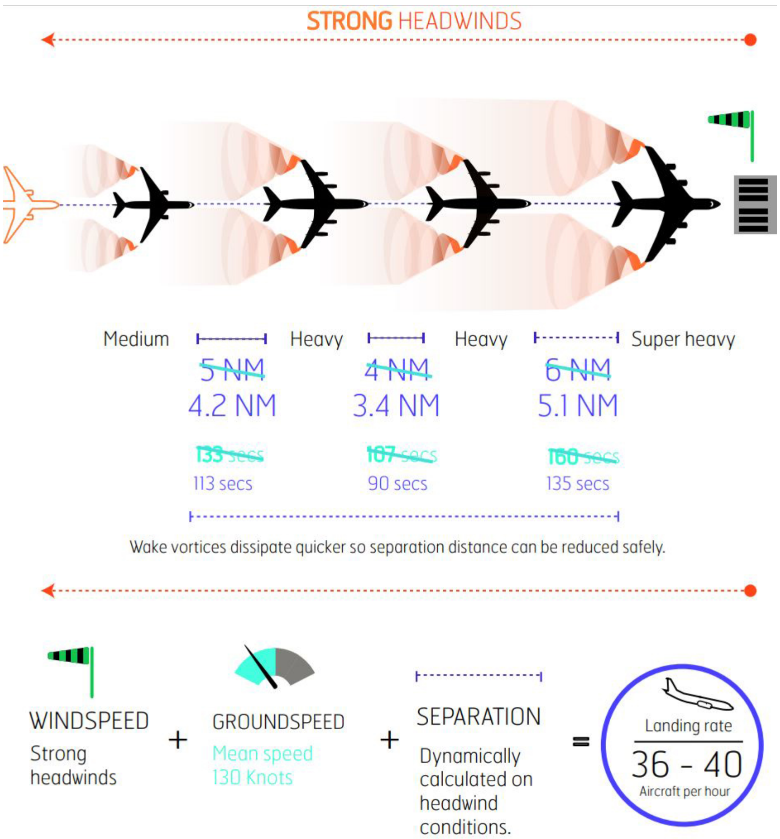


Figure 3.2: Time-Based Separation (TBS) Visualized [16] (Colors Inverted)

3.2. Fixed Approach Trajectories

Combining TSD with fixed approach trajectories will allow the runway to be used to its full capacity while at the same time increasing efficiency, reducing societal effects and reducing controller workload. This can be explained as follows:

- **Environmental effects:** If the aircraft follows a predefined route such as is shown in Figure A.3, the pilots know the amount of track miles to the runway. This enables them (and the onboard automation) to plan the descent such that a continuous descent approach can be executed. This is more efficient than descending in steps and thus saves fuel and reduces the amount of noise produced.
- **Societal effects:** Due to the position of the fixed approach trajectories, the aircraft can be flown in between cities and densely populated areas. This will be appreciated by the people living around the airport.
- **Controller workload:** By knowing which route to fly, the air traffic controller no longer has to tell each aircraft when to turn, reducing the amount of instructions per aircraft. This will most likely reduce their workload, allowing them to handle unforeseen situations such as a go-around, diversion or emergency aircraft better.

Currently, traffic densities are too high during daytime to fly fixed approach trajectories as more margin between the aircraft is required. Fixed approach trajectories are Therefore only flown in at night when traffic densities are lower. However, if a tool can be designed such that it allows the controller to separate the aircraft based on time and keep the same capacity, flight paths as shown in Figure 2.4 can also be flown at daytime in combination with high traffic densities.

However, it should be noted that during peak hours, or when spacing gets tighter than expected, minimal use of vectoring might still be required. This may be in the form of giving an aircraft a shortcut or add an intermediate waypoint to add track miles to its flight path. But it is assumed that this is only required in a minority of cases.

4
Cognitive Work Analysis

In this chapter a cognitive work analysis is performed, following the Ecological Interface Design (EID) framework. This framework makes use of five steps: A work domain analysis, control task analysis, strategies analysis, social organization analysis and a worker competencies analysis [23, p.113-114]. These five steps are further explained in Section 4.2-4.6. First however, more explanation is provided on the EID framework in Section 4.1.

4.1. Ecological Interface Design

Nowadays, it's hard to imagine a world without automation. Automation has had a major impact on the aviation industry, even complex tasks like flying the plane can be automated. However, automation is still not at the level at which it can fully replace the human in unforeseen situations. Therefore, the human operator must be taken into account when designing a system. Not by replacing the human operator, but rather assisting the operator in the work domain [3]. A well-known taxonomy on human behavior is the Skill, Rule and Knowledge (SRK) taxonomy by Rasmussen [17].

The SRK taxonomy defines three levels, based on the required human cognitive effort per level. These levels are Skill, Rule and Knowledge Based Behavior (SBB, RBB, KBB). With SBB being the level for which the least cognitive effort is required, and KBB the level for which the most cognitive effort is required. These levels can be further explained by looking at how they are activated. SBB occurs when a signal is given, and the reaction on this signal is based on intuition or training. These kind of tasks are most often perceived as easy as little cognitive effort is required. RBB is activated by a sign. Meaning the actor reacts to this sign through previous experiences, recognizing the situation and performing tasks which suit the situation. Finally, KBB is activated based on a symbol. These symbols are not known to the actor, hence an unfamiliar situation occurs for which it is not clear what kind of action is required in order to obtain the goal determined by the actor. Hence, KBB requires the most cognitive effort and is the slowest of the three levels of human behavior. The SRK taxonomy is further visualized in a flowchart in Figure 4.1.

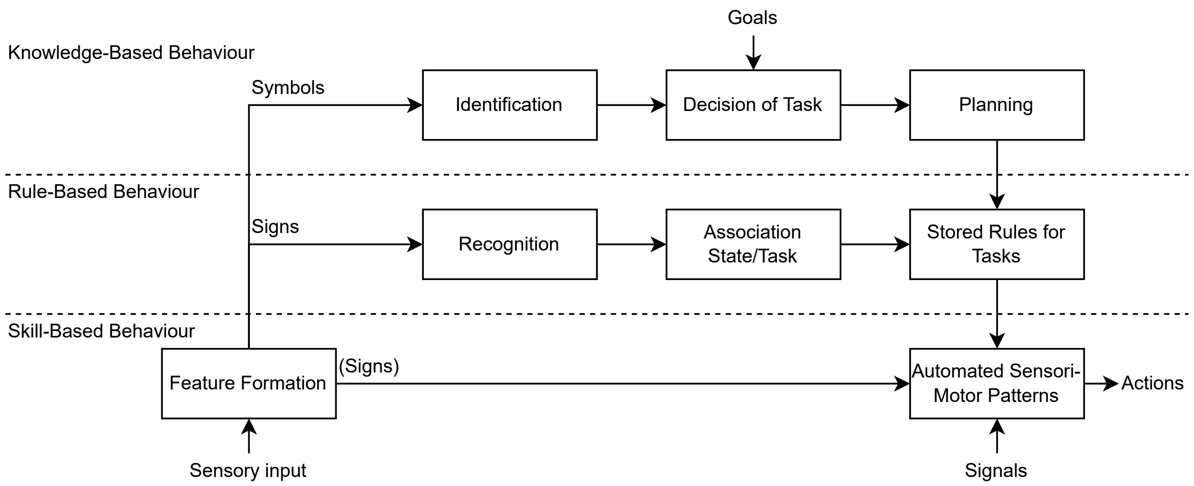


Figure 4.1: Skill- Rule- and Knowledge-Based Behavior Flow Chart

Returning to the EID framework, a constraint-based approach is envisioned. This relates to visualizing the possible solutions to the actor, while taking into account the physical boundaries of the solution space and supporting skill-, rule- and knowledge-based behavior. In approach control, the controllers use a 2D radar screen to create a mental model of the system. By means of training this has become a skill to the controllers. However, in order to solve conflicts and/or determine which aircraft will be first delivered to the runway, the controllers make use of rule or even KBB. When switching to TBS and fixed approach trajectories, the controllers will have to take the time separation component into account. However, time separation is not as easily perceived from a 2D radar screen as the distance separation component is. Therefore, requiring more KBB and consuming more cognitive resources. By implementing the correct decision support tools which provide the controller with the right information at the right time, these cognitive tasks can be transformed to a perceptual task. Hence, reducing the need for slow KBB. Showing (physical) constraints on the display provides the controller with the freedom of making the decisions, while the automation only informs the controller on the possible range of solutions. At the same time, one must be aware that too much information could clutter the screen, which would reduce the use of the display. Therefore, a way should be found to supply the controller with the information required at the correct time. This could be done automatically, or at the request of the controller by activating a feature by means of a button press (for instance).

4.2. Work Domain Analysis

In order to design a tool to aid the approach controller, the work domain that is worked in should be well known. The current state of approach control has already been discussed in Appendix 2. However, to determine the constraints of the work domain, an Abstraction Hierarchy (AH) is made. This abstraction hierarchy follows the why-what-how structure, as this relates the levels of the abstraction hierarchy as is shown in Table 4.1.

Table 4.1: Abstraction Hierarchy Structure. Adapted from [23, p.166]

Functional Purpose	Why?
Abstract Function	What? Why?
Generalized Function	How? What? Why?
Physical Function	How? What?
Physical Form	How?

The abstraction hierarchy including means-end links between the different abstraction levels is shown in Figure 4.2. This AH is adapted from [14], with the addition of terrain influence and additional means-end links. Connecting routing to terrain and the sector physical functions. Terrain has an important role in the (re-)routing of aircraft when considering airports located in a mountainous area. As for the sector, it is linked to routing because the sector includes waypoints, airways, arrival/departure routes and more. As all these elements are needed in order to route aircraft through the sector.

In order to make the switch to TBS and fixed approach trajectories, certain elements will become more important. The decision support tools will aid the controller by calculating the predicted state values, including the effects of the weather, flight plan, aircraft and sector information. This allows the controller to better coordinate the locomotion of the traffic, increasing the safety, efficiency and productivity of the system. Additionally, in the near future, communication will be extended with digital communication. Allowing a new route to be uploaded to the aircraft.

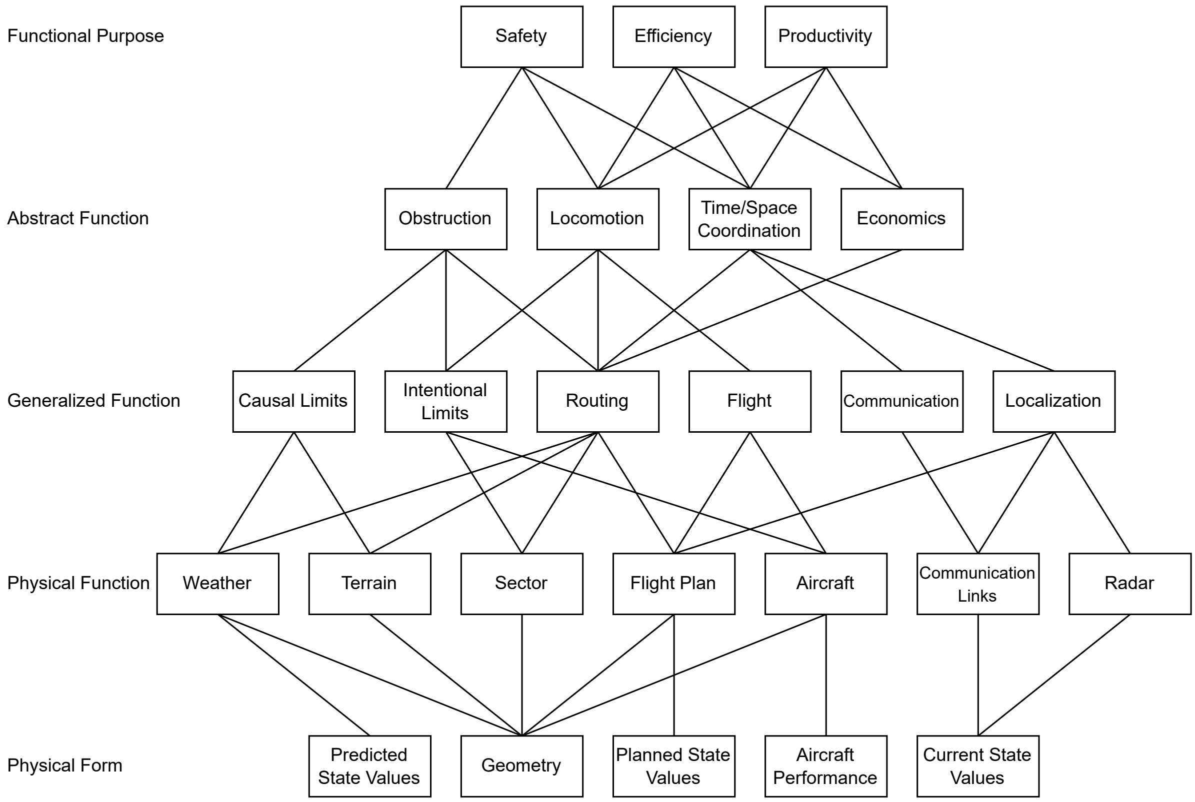


Figure 4.2: Abstraction Hierarchy

4.3. Control Task Analysis

This section will discuss the control tasks performed by approach controllers. The control tasks include the following:

- **Initial contact with aircraft entering the sector:** Departing aircraft are handed over to approach control shortly after take-off. Arriving aircraft approaching the IAF are handed over to approach control. Pilots check in with approach control by using their call sign and current position. Currently, this is done by voice communication. This can be related to the communication block in the abstraction hierarchy in Figure 4.2.
- **Routing aircraft towards their destination:** Every aircraft within the sector will have a flight plan stating their intent. Departing aircraft will be routed towards their destination airport along one of the SID routes. Arriving aircraft are routed towards the ILS of the active runway. In order to execute this task, planned and current state values, sector geometry and aircraft performance need to be taken into account. This covers a large part of the abstraction hierarchy in Figure 4.2.
- **Rerouting aircraft in order to guarantee separation:** In order to avoid a Loss of Separation (LoS), it may occur that rerouting of aircraft is required to guarantee enough separation. This can be done with a heading, altitude or speed command. By rerouting an aircraft to avoid a loss of separation, the controller predicts the future state values by taking the current state, planned state, aircraft performance and geometry into account. These elements all cover the bottom row of the abstraction hierarchy in Figure 4.2.
- **Handing-off aircraft to adjacent sector:** Similar to aircraft entering the sector, when aircraft leave the sector they are instructed to contact the next sector by voice communication. Arriving aircraft are put on the ILS and are handed over to tower control. Departing aircraft, once clear of conflicts and cleared to climb to FL130 are handed over to Area control. Again, this can be related to the communication block in the abstraction hierarchy in Figure 4.2.

Figure 4.3 shows the decision ladder used for rerouting an aircraft task. The SRK areas are indicated as well. Currently, air traffic controllers only have a single radar screen which shows the state of the system. Using the current position altitude and expected route, controllers are trained to identify potential conflicts. By means of training and experience, controllers solve the identified conflicts. Using vectors gives the controller great flexibility to solve the conflict. By switching to fixed approach trajectories, the flexibility of the solution space becomes much more limited. Controllers will have to predict the position of aircraft in the future. Taking into account the descent path, aircraft performance, encountered wind, etc. This would require a lot of cognitive effort and can be classified as KBB.

Using DSTs, the controllers are provided with information which enables them to make shortcuts in the decision-making process, as is shown in the decision ladder in Figure 4.3. The use of the decision support tool aims to transfer parts of the cognitive workload from the knowledge-based domain to the rule-based domain. Additionally, other elements, previously part of the rule-based domain, can be skipped due to the additional information provided by the decision support tool. This lowers the perceived workload of the controller.

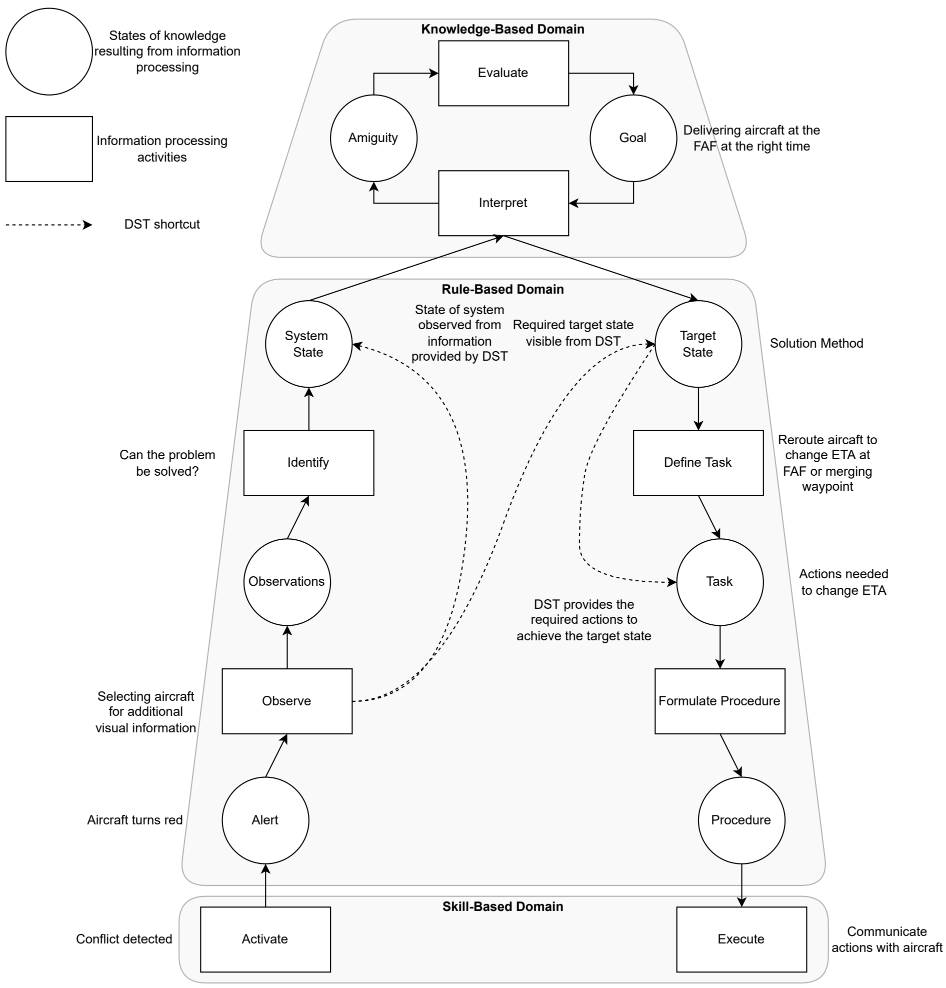


Figure 4.3: Decision Ladder for Rerouting of an Aircraft. Adapted from [23, p.187]

The shortcuts shown in Figure 4.3 are the following:

- **State of system observed from DSTs:** The addition of the decision support tools allows the controller to directly see when aircraft are arriving with the use of trajectory prediction.
- **Required Target State visible from DSTs:** With the use of visualized time separation between aircraft, and the knowledge of other aircraft arriving at a predefined point, the controller can directly see where the possible gaps in the sequence are.
- **Speed suggestions and/or rerouting options provided by the DSTs:** In order to achieve the target state, there are two possible actions that the controller can perform. The first and preferred action is a speed instruction. The second option is to add track miles to the aircraft's

flight path. The DST will provide the controller with the information needed to achieve the required delay/shortcut in order to optimize the delivery of aircraft to the FAF.

4.4. Strategies Analysis

In this section the strategy analysis is performed on the rerouting task. Figure 4.4 shows the typical workflow for an air traffic controller. The addition of the decision support tool is envisioned to aid the controller with the observation of the solution space, as well as providing the controller with the corresponding command that can be communicated to the aircraft.

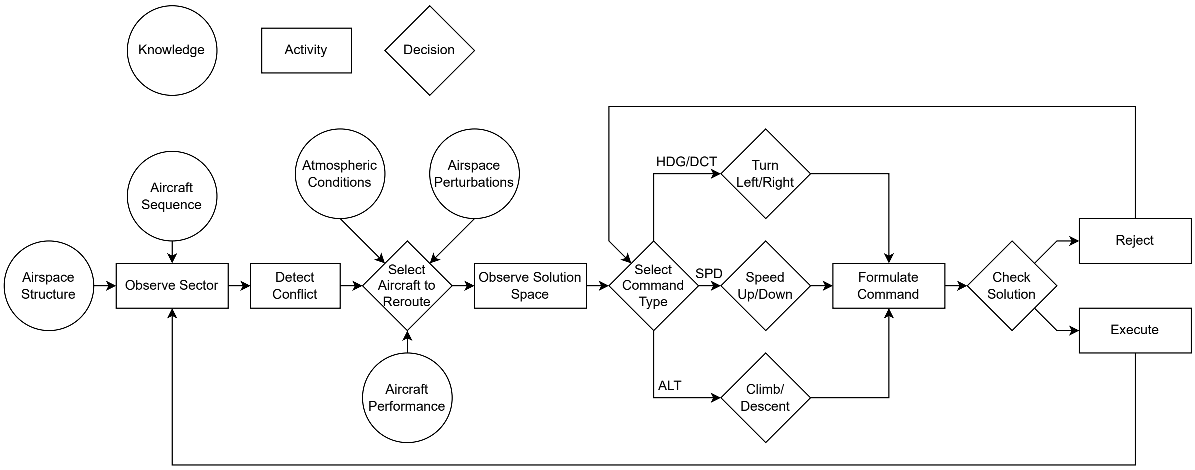


Figure 4.4: Current Work Flow for Aircraft Rerouting

4.5. Social Organization Analysis

After determining the used strategies, the work needs to be divided between the different actors. Therefore, the different sub-tasks related to rerouting an aircraft with the decision support tools are divided between the human and the computer or automation, as can be seen in Figure 4.5. Furthermore, in the next subsection, the level of automation is discussed for the to be designed decision support tool.

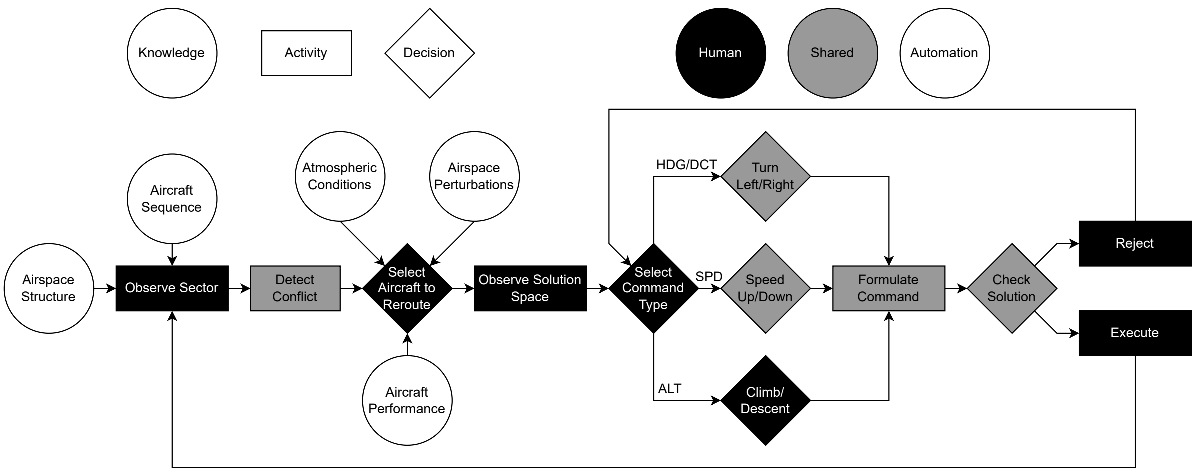


Figure 4.5: Division of Work Between Human and Automation for the Rerouting of an Aircraft with the decision support tools

4.5.1. Level of Automation

Using the levels of automation model proposed by [15], the level of automation can be determined for each step in the Human Machine Interface (HMI). A combination of the levels of automation of decision and action selection shown in Figure 4.6. The four independent functions presented in Figure 4.7 will be used to determine the level of automation used for the to be designed decision support tool.

High 10: The computer decides everything, acts autonomously, ignoring the human.
9: Informs the human only if it, the computer, decides to.
8: Informs the human only if asked.
7: Executes automatically, then necessarily informs the human.
6: Allows the human a restricted time to veto before automatic execution.
5: Executes that suggestion if the human approves.
4: Suggests one alternative.
3: Narrows the selection down to a few.
2: The computer offers a complete set of decision/action alternatives
Low 1: The computer offers no assistance: human must take all decisions and actions.

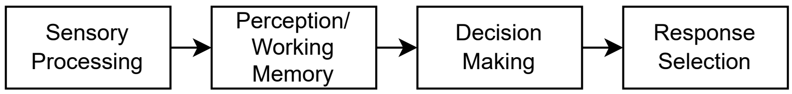


Figure 4.6: Levels of Automation of Decision and Action Selection [15]

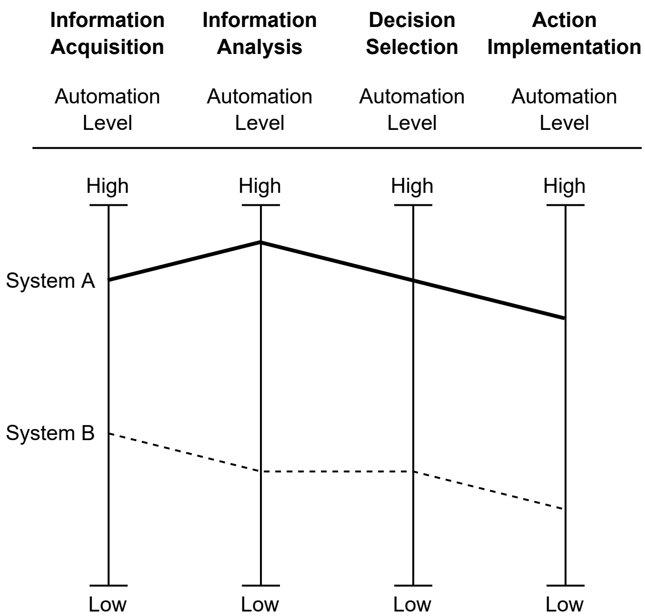


Figure 4.7: Levels of Automation for Independent Functions [15]

The levels of automation for the four independent functions of the decision support tool are:

- **Information Acquisition:** Would be a high level of automation as the data obtained from the system (aircraft/weather/etc.) are processed automatically. Therefore, this could be classified as an automation level of 9 out of 10.
- **Information Analysis:** The information is then analyzed and processed which in turn is displayed on the decision support tool display. Therefore., this could also be classified as an automation level of 9 out of 10.
- **Decision Selection:** This is where the level of automation drops significantly in respect with the previous two independent functions. As the decision support tool only provides a complete set of decision/action alternatives, this step would be classified as an automation level of 2 out of 10.
- **Action Implementation:** Finally, the execution of the action will have to be done by voice. However, in the future this might change to a text form, but currently simple voice communication is

used. Hence, this would be classified as an automation level of 1 out of 10, as no assistance is provided by the computer.

These levels of automation can then be visualized as:

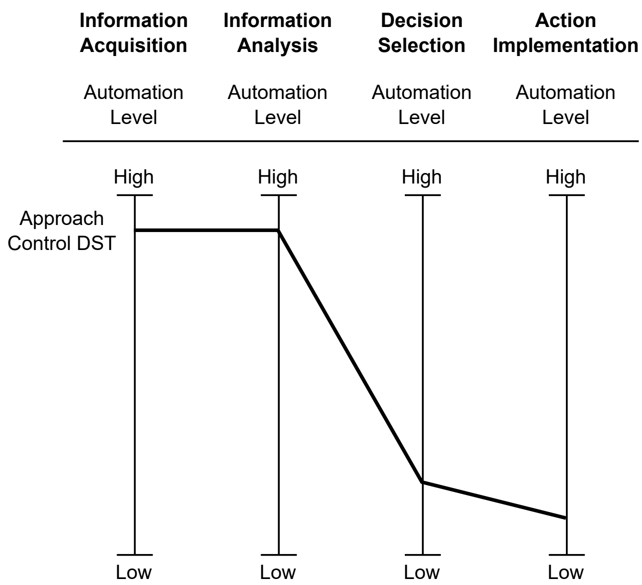


Figure 4.8: Levels of Automation for the Approach Control Decision Support Tool (DST)

4.6. Worker Competencies Analysis

As part of the final phase of the cognitive work analysis, a worker competencies analysis has been performed, as is presented in Table 4.2. A worker competencies analysis evaluates the control tasks and the corresponding human behavior that is supported by the decision support tool.

Table 4.2: Worker Competencies Analysis

Information Processing Step	**Resultant knowledge State**	**Skill-Based Behavior**	**Rule-Based Behavior**	**Knowledge-Based Behavior**
Scan for indicated conflicts	Whether the time between two aircraft arriving at a merging point becomes less than required	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 most critical conflict	Which conflict has the largest priority in solving	Perceive which ACs in conflict are using the DST	Use heuristics to estimate which ACs will first have LoS	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 DST	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 new route can cause conflicts in the future and whether it is in line with previous conflict resolutions

5
Concept Design

This chapter will present concepts from previous work that are used for this research. From these concepts, elements are taken in order to design a new decision support tool in Appendix 6.

5.1. Previous Work

This section will present the previous work that is relevant to this research. This includes the Time-Space Diagram in Section 5.1.1, Travel Space Representation (TSR) in Section 5.1.2, Ideal Turn-In Point (ITIP) in Section 5.1.3, 4D trajectory management including wind in Section 5.1.4, arrival management interface in Section 5.1.5 and finally the Intelligent Approach (IA) interface in Section 5.1.6.

5.1.1. Time-Space Diagram

At first, Figure 5.1 shows the display designed by Rolf Klomp [8]. The added display is called a Time-Space Diagram (TSD). On the right two IAF's are shown with aircraft labels in the corresponding IAF column. The graph on the top left shows distance to the IAF on the x-axis, and time to the IAF on the y-axis. By dragging the aircraft label, the arrival time of the aircraft at it's IAF can be manipulated. Dragging the label results in a new commanded airspeed. By assuring no overlap of the blue bars, aircraft will not arrive at the runway at the same time. Furthermore, the light gray area shows the range in which the aircraft can be maneuvered, based on minimum and maximum airspeed. The white line being the currently selected airspeed. Also shown on the top left graph are red boxes, these boxes show a potential conflict with another aircraft, hence these red area's should be avoided when a speed command is issued. Finally, on the bottom left, the vertical situation is shown. Once again, distance to the IAF is projected on the x-axis, however in this case the altitude is projected on the y-axis. This complete display allows controllers to see when an aircraft arrives at it's IAF, if there would be a potential loss of separation and how aircraft are positioned with respect to the vertical plane. However, no wind was taken into account in this simulation.

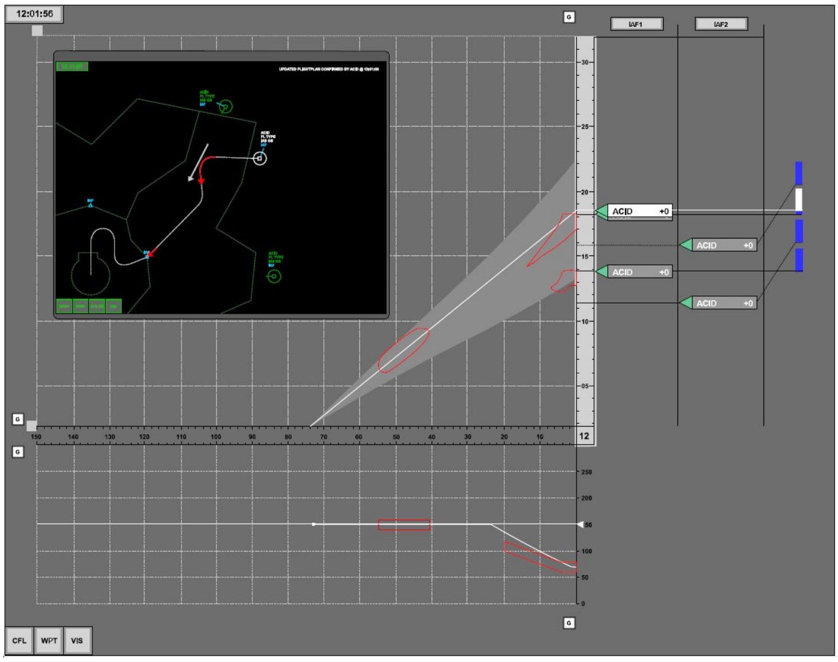


Figure 5.1: Time-Space Diagram Display Concept [8]

5.1.2. Travel Space Representation

In order to alter the flight plan intuitively and show controllers areas of conflict, a Travel Space Representation (TSR) was added [9]. The TSR is shown in Figure 5.2. The TSR shows the controller the area in which the aircraft can (or can not) be directed, without inducing a delay. A deviation of the original flight plan adds track miles to the flight plan, therefore an increase in airspeed is required in order to adhere to the sector exit time without any delays. Hence, the TSR is bounded by the maximum speed of the aircraft, as can be seen on the left most figure in Figure 5.2. Additionally, the TSR can also show controllers area's of conflict. These conflict areas are shown to the controller by a red color within the TSR. By rerouting the aircraft to the green area on the TSR, the conflict can be resolved. This is also demonstrated on the right most figure on Figure 5.2.

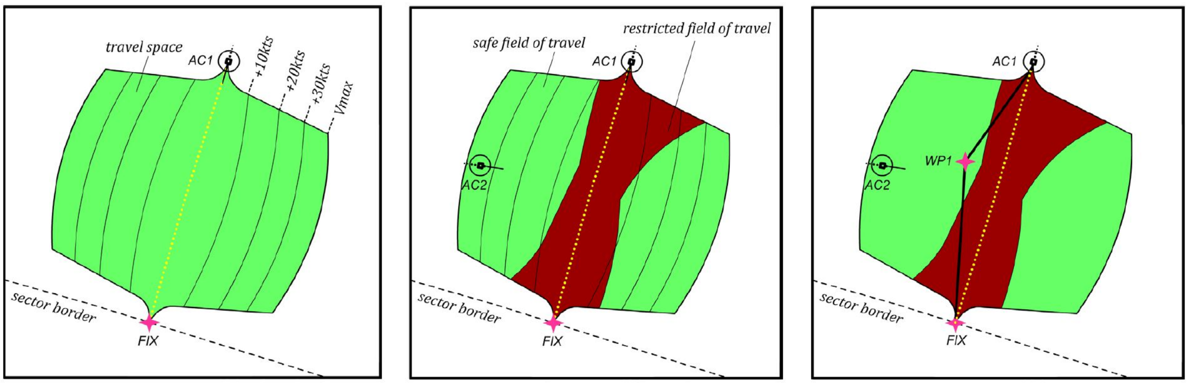


Figure 5.2: Travel Space Representation with Conflict Areas [9]

In [10], this concept was further researched in order to display a TSR on the horizontal, vertical and TSD displays. As is shown in Figure 5.3. Once again, within these green area's, red conflict area's can appear, showing the controller where (in position and altitude) and when in time a potential loss of separation may occur.

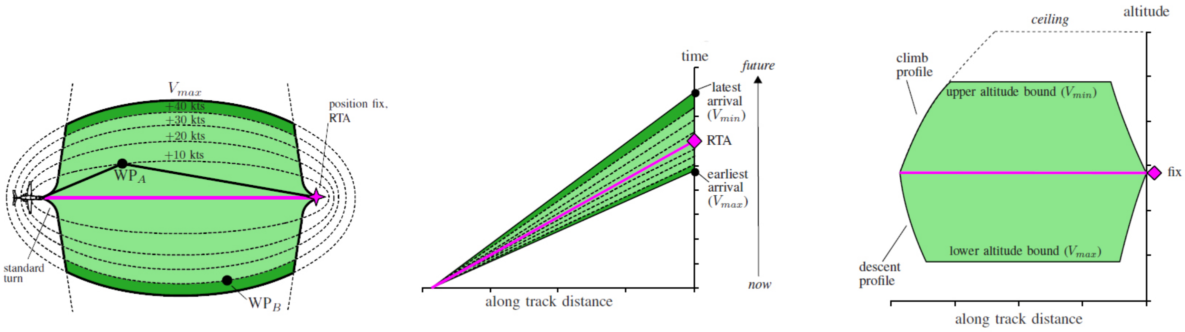


Figure 5.3: Travel Space Representation on Horizontal, Time and Vertical Displays [10]

5.1.3. Ideal Turn-In Point

Figure 5.4 gives an idea of the Ideal Turn-In Point (ITIP) display designed by Mats Dirkzwager [4]. This display projects a solution space on the radar display once an aircraft is selected. It assumes aircraft arrive on a downwind leg and have no fixed turn to base point. This display gives a range of possible turn-in points without a loss of separation. It also takes into account current wind conditions. However, due to the variable amount of track miles, losses occur that could have been avoided if pilots and controllers were more aware of the flight path that the aircraft would fly to the FAF. By flying such an approach, it would be difficult to execute a continuous descent. This could for instance cause the aircraft to descent too early, resulting in more fuel used and noise produced at low altitude as the engines will have to spool up in order to maintain speed at low altitude. Furthermore, it could happen that the aircraft is suddenly sequenced onto the ILS while the aircraft is still too high, therefore having to use its spoilers or configure earlier than required by extending its flaps and landing gear. Besides, after the crash of Turkish Airlines flight 1951 at Amsterdam Airport Schiphol, intercepting the glideslope from above is avoided as much as possible as was advised in the conclusion of [19].

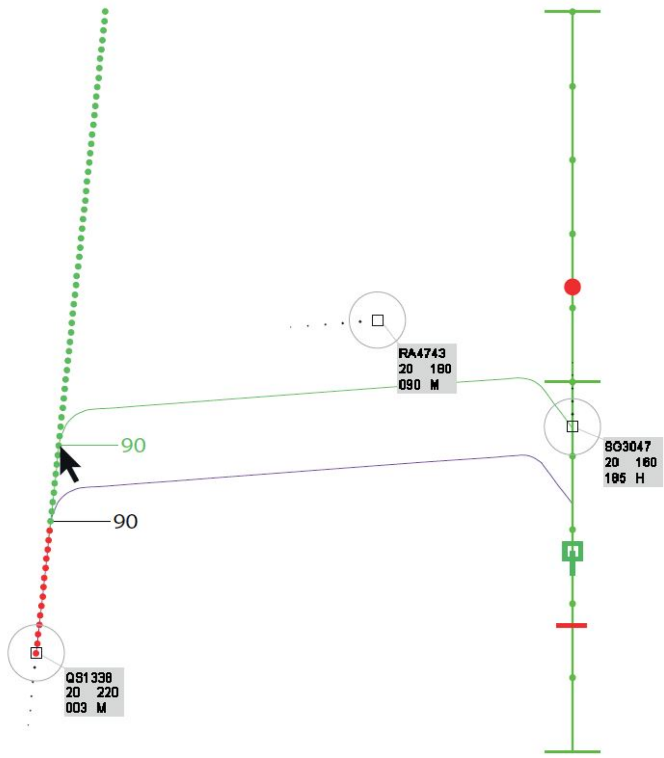


Figure 5.4: Ideal Turn-In Point (ITIP) Display Concept [4]

5.1.4. 4D trajectory management in wind and uncertainty

Figure 5.5 shows the concept display designed by Matthijs Ottenhoff [14]. This display and thesis is focused on area control. It provides the controller with a way to manipulate the 4D trajectory of aircraft from the radar display and complementary displays. In order to solve conflicts with other aircraft, a solution area is projected within the flight envelope of the aircraft. Selecting a green area on the radar screen will result in a newly added waypoint and speed command to the flight plan. The new speed is computed such that the sector exit time is still achieved, despite the additional track miles. The same method applies to the Vertical Situation Display (VSD). Instead of a change of direction and speed, a change of flight level is issued by selecting a point in this display. The aircraft will still need to exit the sector at a predefined flight level, hence this flight level change should also be undone as the aircraft exits the sector. Finally, the Time Space Display shows the along track distance vs the time. This display operates in the same way as the other two. In addition to adding new waypoints to the 4D flight plan, the three displays allows the operator to change the sector exit conditions. This is shown by the thick black lines at the bottom of the radar screen and right in the other two displays. This is a valid way to solve potential conflicts, however the next controller will have to be informed about the change issued to the 4D flight plan. This display concept also takes into account the wind. This is done by making use of GRIB weather files obtained from KNMI. These files contain wind information at specific position and altitude, which is very important when predicting trajectories of aircraft at high altitudes. The wind is used in the flight path predictions and additionally projected on the display to increase the situation awareness of the controller.

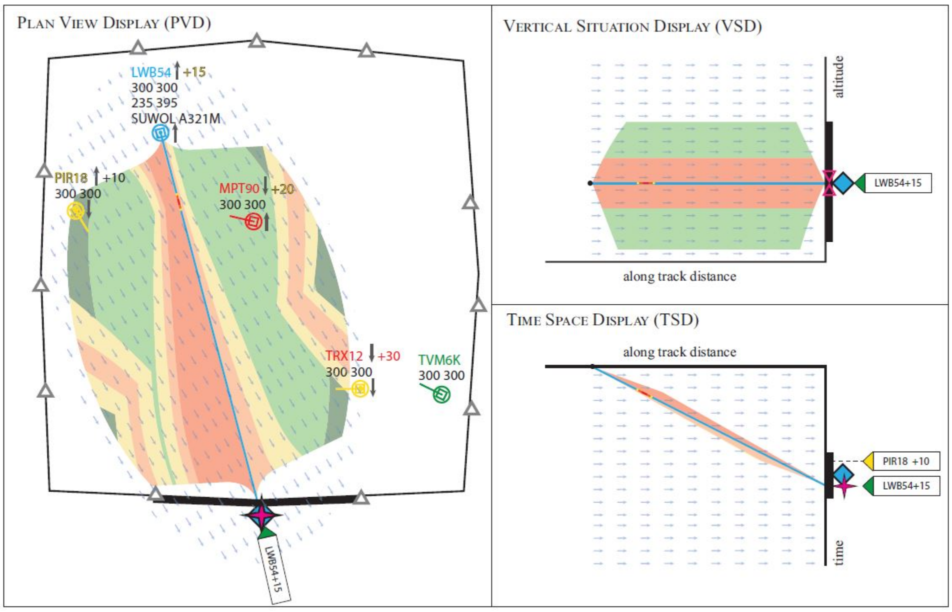


Figure 5.5: Display Concept [14]

5.1.5. Arrival Management interface

In order to visualize runway capacity, an enhanced timeline with probability distributions of the ETA of aircraft was researched [20]. This timeline shows the runway capacity on the y-axis, and the time on the x-axis. By making use of distributions, a range is displayed on the time axis in which the aircraft is expected to arrive. By looking at the height of the capacity, the controller can clearly see when the runway capacity (of 1) is exceeded. Additionally, a capacity of 0 shows the controller where runway capacity is still available which could guide the controller in solving the exceeded runway capacity by delaying or providing shortcuts to arriving aircraft.

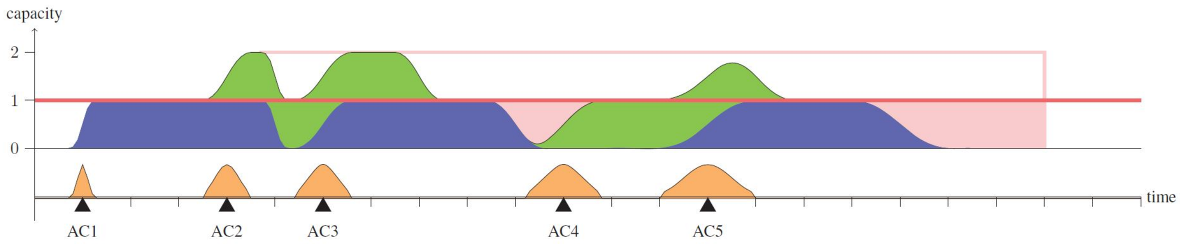


Figure 5.6: Presentation of Expected Excess Demand, Visualizing Uncertainty [20]

5.1.6. Intelligent Approach

Figure 5.7 shows the Intelligent Approach (IA) display tool currently used at Heathrow, and in the near future also at Amsterdam Airport Schiphol and Toronto. Although it is not clearly documented, this tool looks to add separation markers on the extended centerline which are used by approach controllers to aim arriving aircraft at. By doing so aligning the aircraft on the ILS in a safe and efficient way.

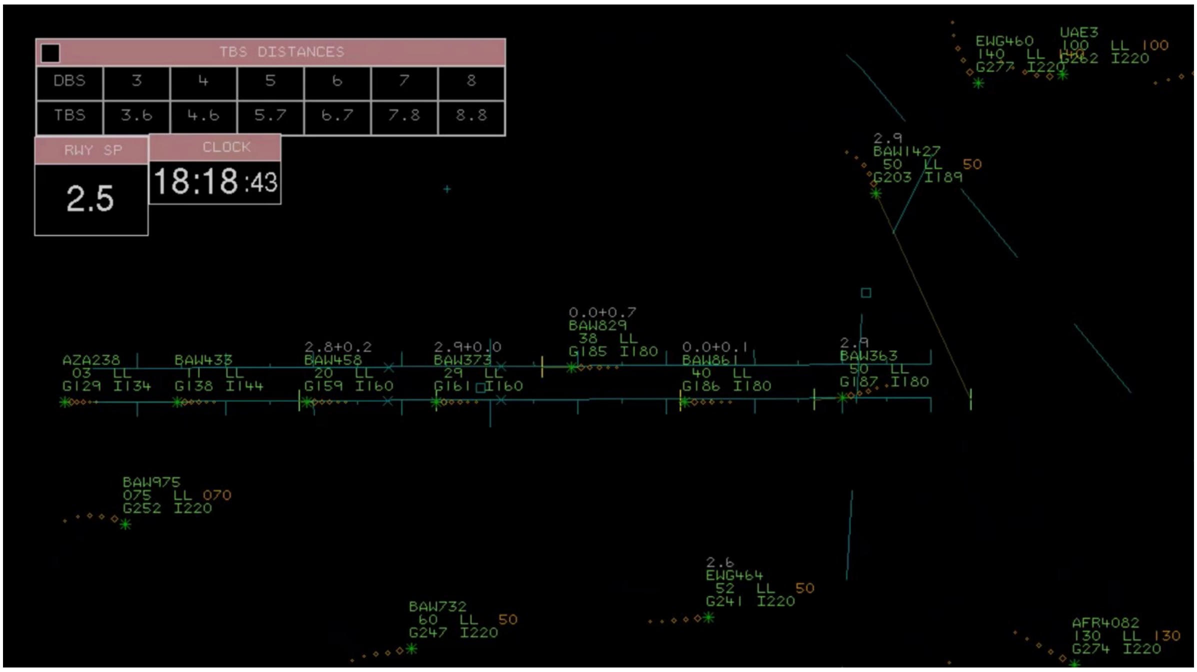


Figure 5.7: NATS Intelligent Approach Display Concept [2]

5.2. Previous Work Conclusion

The display concepts discussed in the previous section form a basis for the design of the approach control decision support tool. The ITIP display concept by Dirkzwager et al. could be a solution to situations in which the traffic density is too high, and speed commands only are not sufficient to assure separation. From Klomp et al. the Time-Space Diagram (TSD) and time slider look very promising. In order to have a realistic simulation, the wind and trajectory uncertainty elements researched by Ottenhoff et al. will be a valuable addition. The uncertainty distribution designed by Tielrooij et al. can be used to visualize the uncertainty that is present due to e.g. the presence of high resolution wind within the simulation. Combining all these elements will result in a more versatile decision support tool.

6 Preliminary Work

This chapter will present the work that has been done during the preliminary thesis phase. This includes the redesign of the SectorX display as will be elaborated upon in Section 6.1. Next, the implementation of the Time-Space Diagram (TSD) and Delay Space Representation (DSR) as part of the decision support tool will be explained in Section 6.2 and Section 6.3, respectively. Finally, in order to make the simulation more realistic, a 4D wind field is implemented within SectorX. The implementation, visualization and verification of the wind field can be found in Section 6.4.

6.1. Creating a Familiar Environment

In order to make the Experiment as realistic as possible, the approach control display is replicated in SectorX. This speeds up the experiment briefing, as approach controllers are already familiar with the elements on the display and the input devices used. Furthermore, creating a familiar environment for the approach controllers allows for a more accurate testing environment of new display elements. In Section 6.1.1 the main radar screen elements will be discussed. As for the input to the simulator, a Touch Interface Device (TID) is used. The alterations made to the TID will be discussed in Section 6.1.2.

6.1.1. Approach Control Display

The display currently used by approach controllers can be seen in Figure 6.1. This is a screenshot of the AAA (Amsterdam Advanced ATC or triple-A) system. The layout and information shown on this display are mimicked in SectorX. With the biggest addition being the so-called interaction area on the bottom right, as presented in more detail in Figure 6.2. Providing information on the state of the display and information regarding the selected aircraft. The information on the display state includes weather state, radar state/range and current time. Once an aircraft is selected, detailed information on the selected aircraft is shown such as Pilot Selected Level (PSL), current heading (HDG), current Indicated Airspeed (IAS) and information on squawk code, departure airport, arrival runway/airport, expected gate, aircraft type, and more. Finally, the command line is shown on this part of the display. Commands issued by the controller are shown and executed from here. In reality, the command line is merely used as a way to memorize the commands given to aircraft and keep track of what aircraft are doing. In the simulator however, with the absence of voice control, the command line is used to directly issue commands to the aircraft. The interaction area used in SectorX is shown in Figure 6.3.

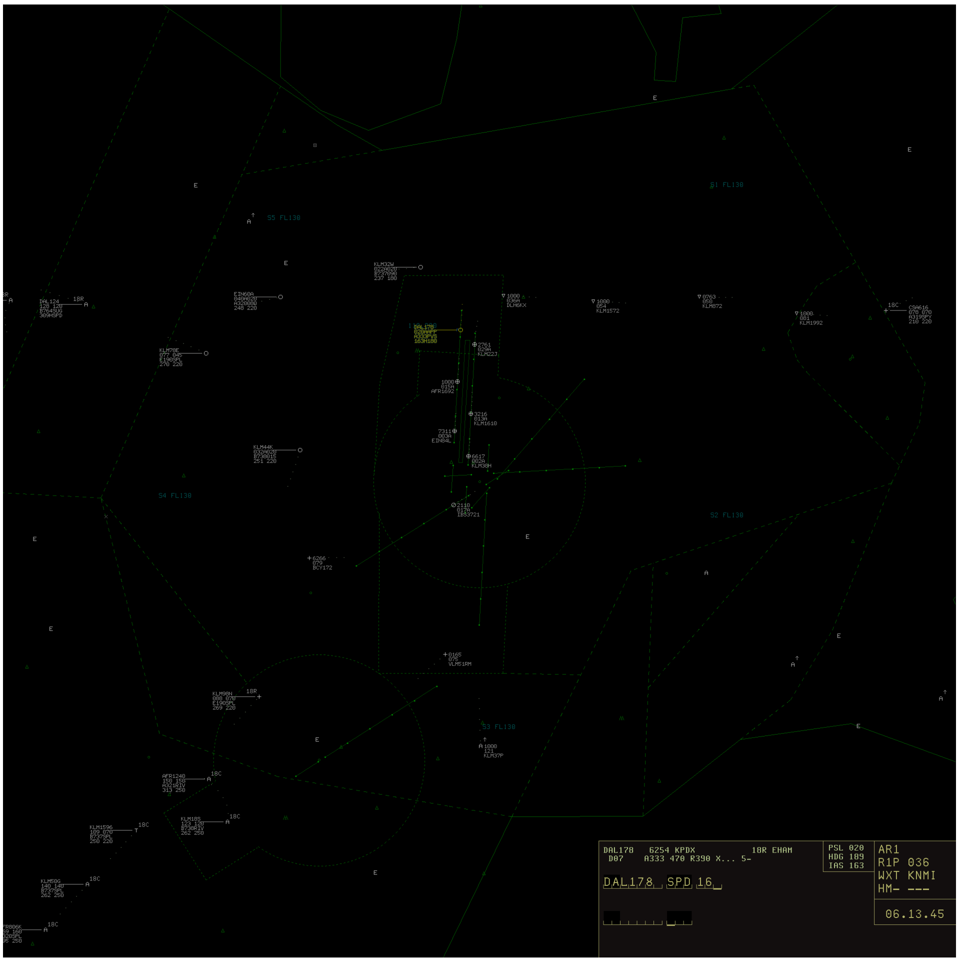


Figure 6.1: Amsterdam Advanced ATM (AAA) Approach Control Display

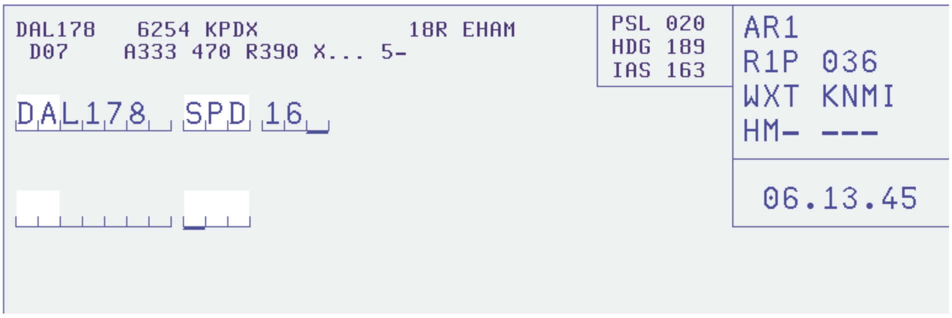


Figure 6.2: Bottom-Right Interaction Area in the AAA Approach Control Display (Colors Inverted)

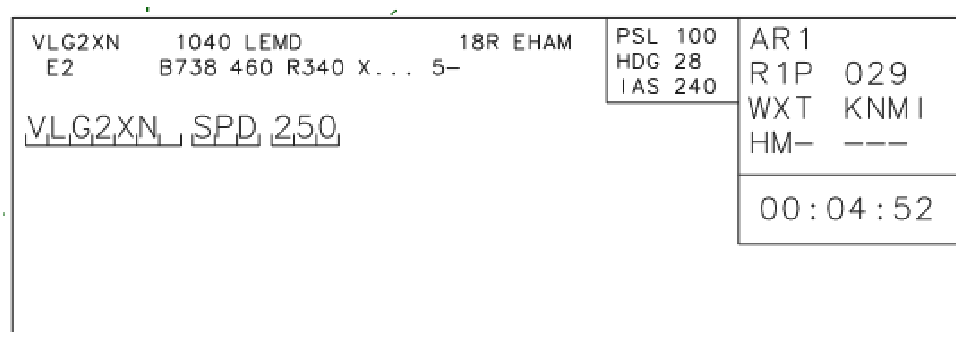
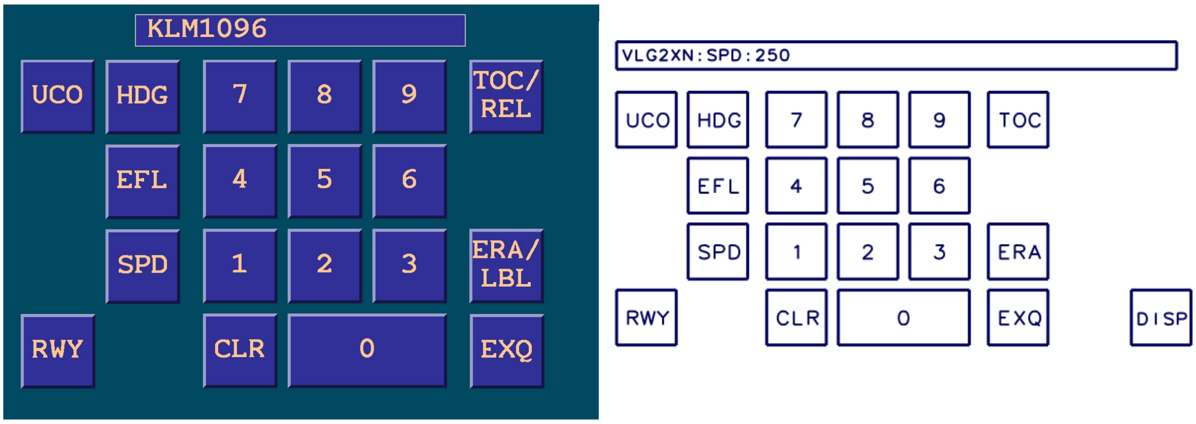


Figure 6.3: Bottom-Right Interaction Area in SectorX

6.1.2. Touch Interface Device

During current operations, instructions are given by use of voice communication. However, since voice communication is not supported in the current simulators, a Touch Interface Device (TID) is used to issue commands. Once an aircraft is selected, the TID can issue a change in direction, speed and altitude. These operations are also used in real ATC, however these serve as a memory help to the controller to see what kind of clearances a certain aircraft has. The commands given by the TID are also shown on the radar screen on the command line which is located within the interaction area.

The TID used at the LVNL Simulator can be seen in Figure 6.4a, while the TID in SectorX can be seen in Figure 6.4b. It should be noted that certain buttons do not have a function (yet). These inactive buttons include the UCO, RWY and TOC buttons. Additionally, a DISP button is added to the SectorX TID, pressing this button opens a new page on the TID, allowing the operator to change different display elements, such as hide/show waypoints, routes, runways and wind visualization particles. On the top of the display, additionally the command line is shown. The information in the command line is the same as on the radar screen, as can be seen in Figure 6.3. Both displays indicate the callsign of the selected aircraft, VLG2XN with a SPD command of 250 knots.



(a) TID in LVNL Simulator

(b) TID in SectorX

Figure 6.4: Touch Interface Device (TID)

6.2. Time-Space Diagram

In order to implement TBS, additional information is needed for the approach controller as time separation is not as easily obtained as distance separation from a 2D radar screen. Therefore, an additional decision support tool will be needed in order to implement TBS in the current ATM system. This is why a Time-Space Diagram (TSD) is added, as was proposed by [22]. The blank TSD is shown in Figure 6.5. Without a selected waypoint, no information is shown on the TSD, waypoint selection is further explained in Section 6.2.1. Once a waypoint is selected, the TSD will provide the operator with information. This is shown in Figure 6.6.

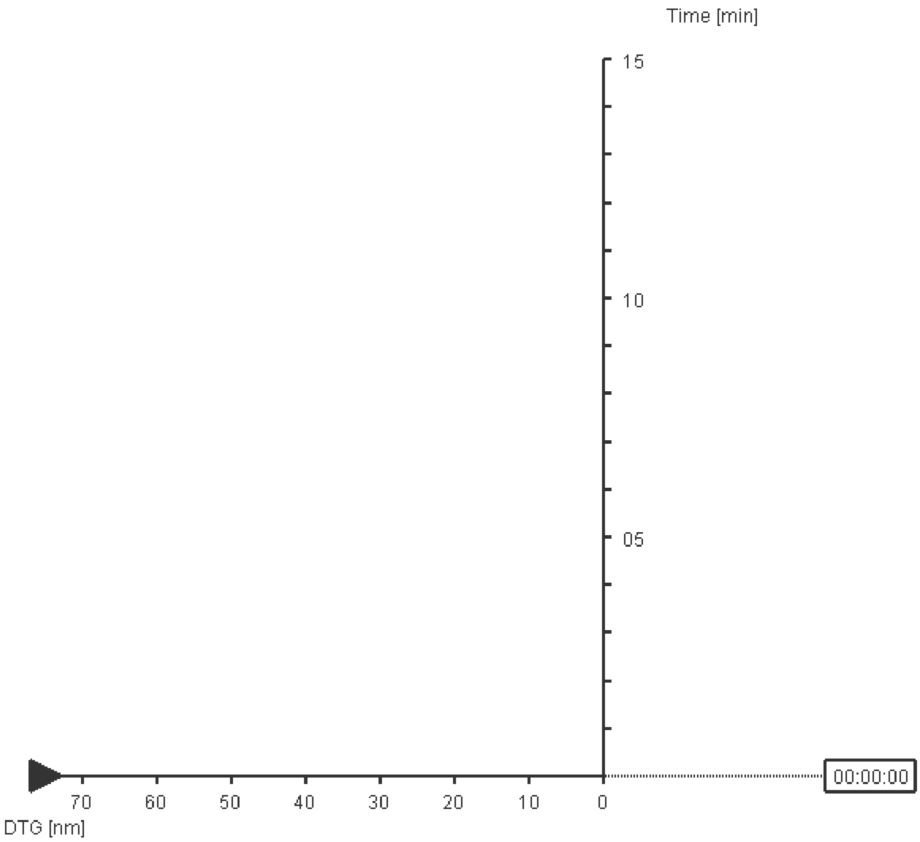


Figure 6.5: Time-Space Display, No Waypoint Selected

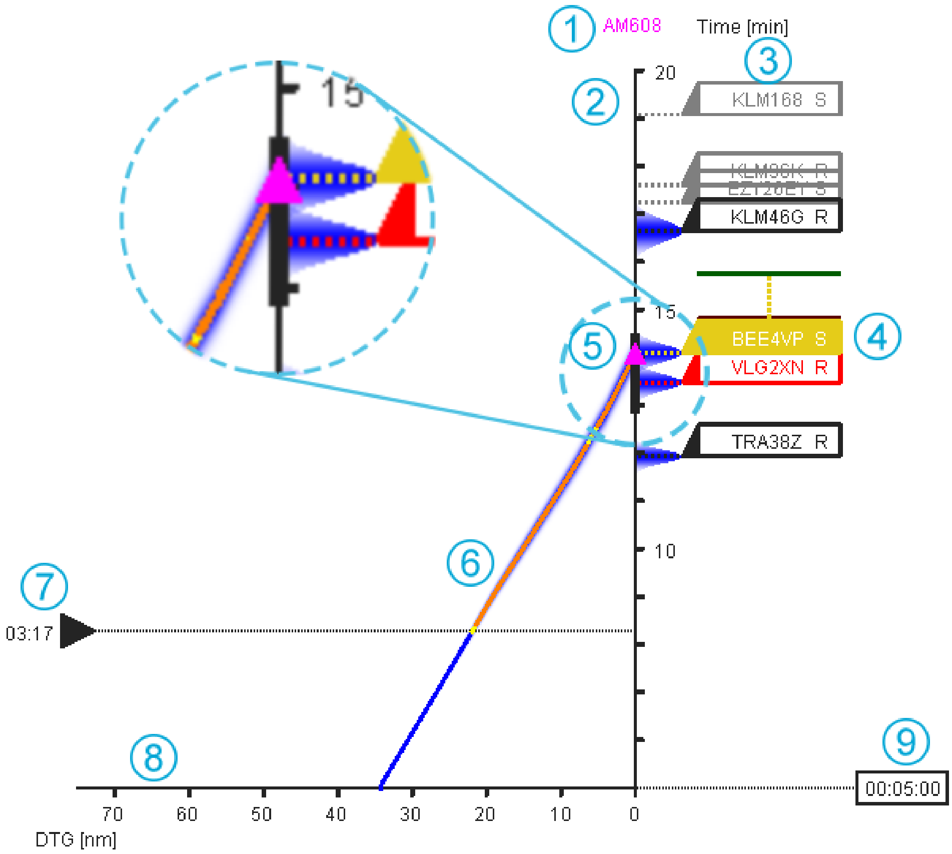


Figure 6.6: Time-Space Display, Waypoint Selected and Labeled

The labels in Figure 6.6 represent the following:

1. **Selected waypoint:** At the top of the TSD, the ID of the selected waypoint (AM608) is shown. This is displayed with the same color as the waypoint highlighted on the radar screen.
2. **Time axis:** The vertical axis of the TSD represents the time axis in minutes. As the time passes, this axis moves down.
3. **Flight label:** Along the time axis, the aircraft passing the selected waypoint are shown. In the label, the call sign of the corresponding flight is shown, as well as a single character to identify the IAF from which this aircraft approaches. So an S for an aircraft arriving from SUGOL, R represents RIVER and A corresponds to ARTIP. The color of the label is used to indicate different states of the aircraft, as is explained in the next two points
4. **Conflict aircraft:** Aircraft labels shown in red indicate the aircraft having a potential loss of separation at the selected waypoint. These occur in pairs as can be seen in the figure.
5. **Selected aircraft:** When the aircraft is selected, the label color changes to yellow/orange. In addition, the time separation required for the selected aircraft and the aircraft in front are drawn with the dotted line along the time axis and the green (when the separation criteria are met, otherwise the bar turns red) bar.
6. Here multiple elements are shown:
   - **Fat axis line:** Arrival time range with a speed range of 200 to 250 knots. The top of the fat line represents the latest arrival time when a speed command of 200 knots is issued, vice versa for the bottom of the line.
   - **Purple triangle:** Representation of the selected waypoint. The position of this triangle on the time-axis represents the arrival time of the selected aircraft at the selected waypoint.
   - **Blue line:** The line drawn from the DTG-axis to the time-axis shows the relation between the distance and time to the selected waypoint. In this figure about 20 nautical miles will be covered in about 3.5 minutes.
7. **Time slider:** The triangle shown can be dragged up, resulting in ghost aircraft to be drawn on the radar screen at the location in time that the time slider is set at. As can be seen in Figure 6.8b and Figure 6.8a. The time will also be shown when the triangle is dragged up. Showing how far in the future the time slider is set.
8. **Distance-to-go axis:** The horizontal axis of the TSD shows the distance to go in nautical miles. As aircraft approach the selected waypoint, the distance to go reduces, hence the blue line of (6) shifts to the right.
9. **Current time:** Finally, in the bottom right the current (simulation) time is shown. This is done in a hh:mm:ss format.

6.2.1. Waypoint Selection

In order to get information shown on the TSD, a waypoint needs to be selected in order to be used as a reference. A waypoint can be selected in the same way as aircraft are selected, hence being a familiar interface to approach controllers which makes it easy to use and explain. Once a waypoint is selected on the radar screen, it changes to a purple filled triangle instead of the default open green triangle as is shown in Figure 6.7. In the same color of purple, the waypoint name is shown on the top of the TSD, indicating all information shown on the TSD is relating to the selected waypoint as is shown by label 1 in Figure 6.6. It should be noted, that the purple triangle also appears in the TSD at label number 6, to indicate the estimated arrival time at the selected waypoint on the time-axis. If another waypoint gets selected, the previous selected waypoint automatically gets deselected. In contrast, if the current selected waypoint is clicked again, it is deselected and the TSD turns blank again, as is shown in Figure 6.5.

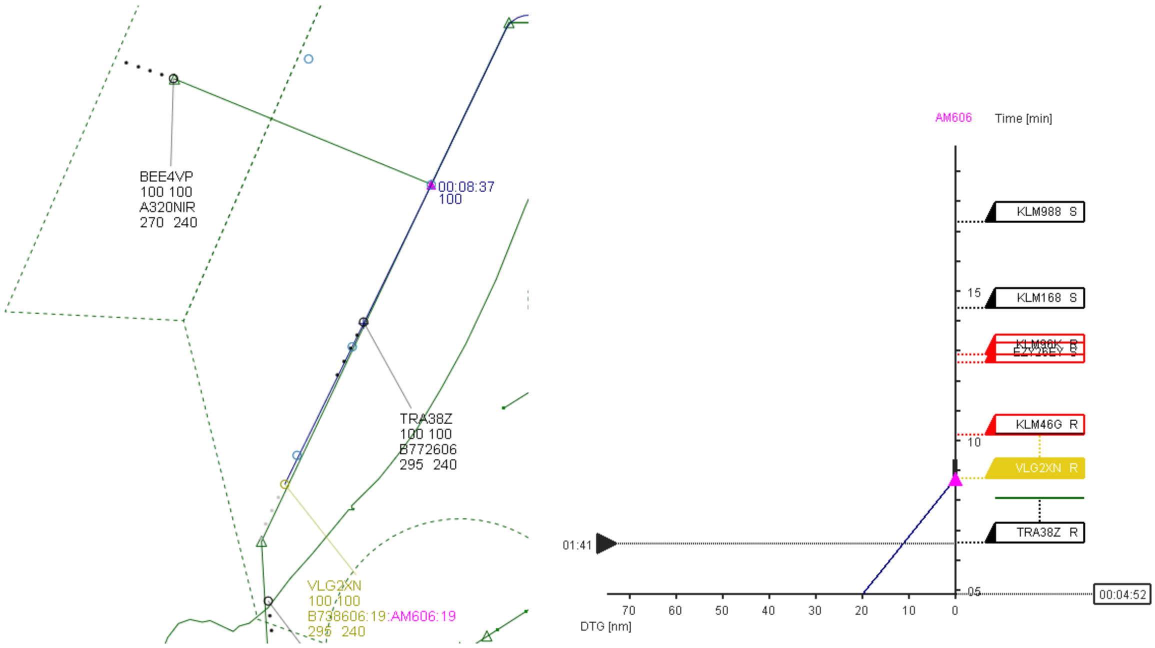
Figure 6.7: Waypoint Appearances

6.2.2. Speed Suggestion

In order to merge incoming traffic, speed commands can be used to manipulate the Estimated Time of Arrival (ETA) of an aircraft at the selected waypoint. On the time axis of the TSD, at label 6 in Figure 6.6, the arrival time range is given for a speed between 200 and 250 knots. Hence, the earlier a speed change is commanded, the larger the range of possible ETA's. By dragging the aircraft label over the range of possible ETA's, a speed instruction is advised. The speed instruction ranges from 200 to 250 knots in steps of 5 knots. In Figure 6.6 the label of VLG2XN is dragged to the earliest possible ETA. This corresponds to a speed instruction of 250 knots (maximum allowable speed below FL100), as can be seen in Figure 6.3 and Figure 6.4b. By executing this command, the aircraft is predicted to arrive at the selected time on the TSD.

6.2.3. Ghost Projection

In order to show the predicted state of the sector in the future, a ghost projection is used. The ghosts are projected by making use of a time slider on the TSD, label 7 of Figure 6.6. By dragging this label up, the ghost aircraft move through the sector on the radar screen at their predicted positions. Figure 6.8 shows the usage of the time slider, set to 1 minute and 41 seconds in the future. The effects on the TSD and radar screen are shown.



(a) Ghost Projection on the Radar Screen

(b) Time Slider on Time-Space Display

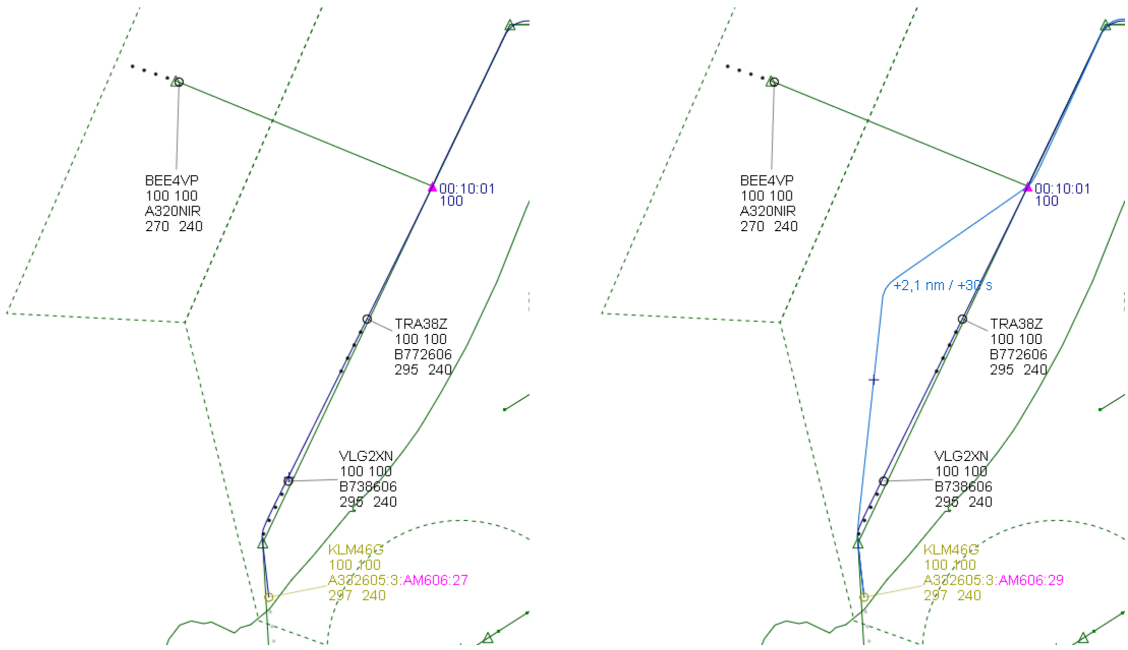
Figure 6.8: Ghost Projection and Time Slider

6.2.4. Required Separation Visualization

The required separation between aircraft at merging waypoints is visualized by a horizontal bar, connected to the aircraft label on the TSD by a dashed line. As is displayed at label 5 in Figure 6.6. The horizontal bar turns red if the required separation is not met, and if enough separation is predicted, the bar turns green. Currently, the required separation is not dynamically changed based on aircraft types, and is set to a fixed value of 90 seconds. Future improvements to this element of the TSD are presented in Section 7.1.2.

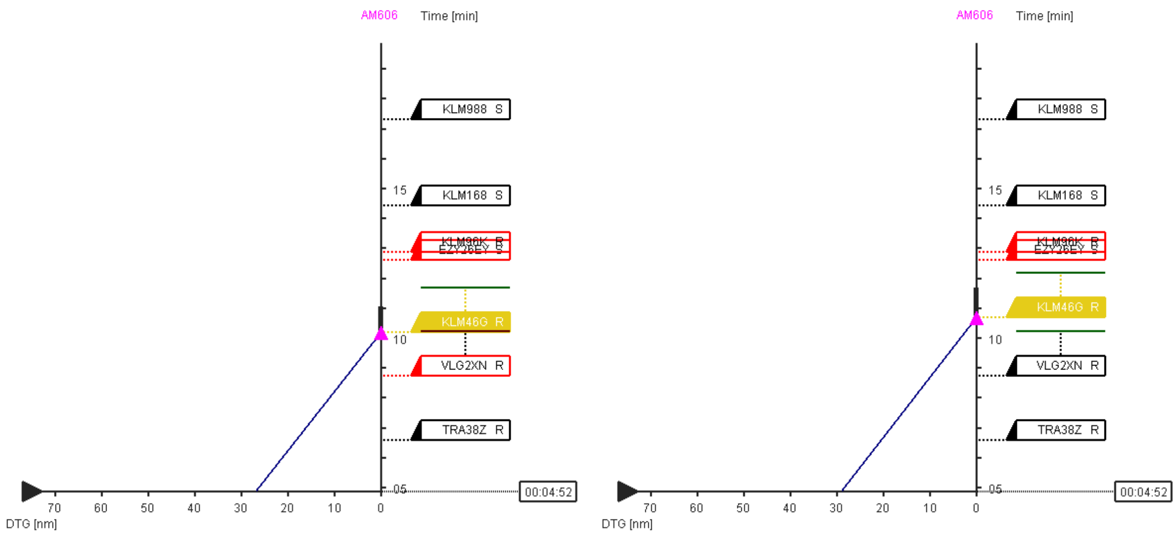
6.3. DSR Implementation

In some scenarios, speed instructions alone are not enough to guarantee sufficient separation between aircraft, hence the Delay Space Representation (DSR) has been added to aid the ATCo. The DSR is adapted from the TSR [12]. However, instead of increasing the speed to make up for the time loss due to the added track miles, the speed is kept constant as in the DSR a delay is the goal in order to maintain enough time separation. The DSR directly shows the implications of a diversion on the sequencing of the traffic. Allowing the controller the option to effectively vector the aircraft within the TMA provides more flexibility in certain situations. Such as a thunderstorm on the arrival transition route or a missed approach/go around of a preceding aircraft causing problems in the sequence. The DSR is an adaption from the Travel Space Representation, however instead of keeping the ETA at the next waypoint constant, the speed is kept constant and this results in an added delay to the select aircraft.



(a) DSR off **(b)** DSR on

Figure 6.9: Delay Space Representation (DSR) on Radar Screen



(a) DSR off **(b)** DSR on

Figure 6.10: Delay Space Representation effect on Time-Space Diagram

6.4. 4D Wind Field

In order to improve the realism of the simulation, a 4D wind field is added to SectorX. A 4D wind field changes over time, and has wind information at specific positions in 3D space. This is especially important as the area covering the approach sector is large enough that the wind direction and magnitude change significantly throughout the sector. Furthermore, since in approach control the traffic is either descending or climbing, the wind at different altitude layers can change as well drastically. Making wind a very important factor of approach control.

6.4.1. Implementation

The implementation of the 4D GRIB weather has been adapted from [14]. Meaning the same code is used for reading and extracting the wind data from the GRIB weather files. Creating a windField object which includes a function called “getWindVectorAtPosition” which returns the wind at a specific time and location in space. This is used for the propagation of aircraft trajectories and the visualization of the wind. The wind visualization is further discussed in the next subsection.

6.4.2. Visualization

The wind is visualized by particles traversing the map according to the wind at their location. This has been implemented with the use of shaders, allowing very fast computing of more than a thousand particles on the GPU, without slowing the simulation down. These shaders were obtained from [14]. The shown wind is dependent on the selected aircraft’s altitude, since the wind at multiple altitudes is available through the 4D GRIB weather files. An example on how these particles can look like is shown in Figure 6.11. In this figure the opacity parameter is set to 1, meaning the particles don’t fade away. Also, the pixel width of each particle is set to a higher than normal value, in order to make it more clear when trying to verify the implementation of the wind, as will be explained further in the next subsection.

6.4.3. Verification

In order to verify the position and scaling of the wind field, the wind direction is reversed at known latitude and longitude. The effects of this are shown in Figure 6.11. Clearly showing lines drawn by inverting the wind direction. Adding waypoints on the known latitude allows the position and scale of the wind field to be verified.

In order to verify the magnitude of the wind, the simulation is compared to the implementation of [14]. This showed identical wind speeds when the same files were used for the simulation. By making use of the “getWindVectorAtPosition” function of the windField object, it was found that these vectors in north-south and east-west direction were identical. Which is to be expected since the same implementation and files are used.

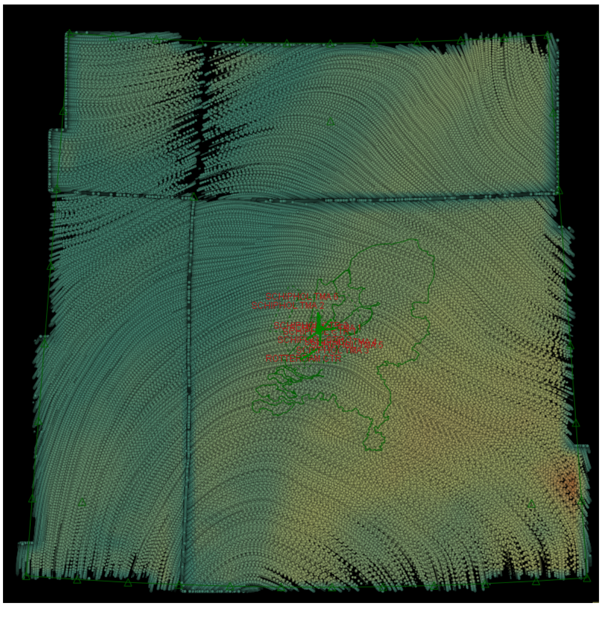


Figure 6.11: Wind Position Verification

7 Future Work

This chapter will present the future plans for this research project. The work includes certain elements that still need to be implemented into the simulation, as will be presented in Section 7.1. Once the simulation interface and elements are implemented, the experiment can be designed according to Section 7.2.

7.1. Simulation Additions

In order to improve the accuracy and realism of the simulator, additional elements need to be implemented. Three categories group the different features. These categories are: Uncertainty, Merging and Separation and Nice-To-Haves as will be explained in Section 7.1.1, Section 7.1.2 and Section 7.1.3, respectively.

7.1.1. Uncertainty

In order to add realism to the simulation, uncertainty will be implemented and visualized. In particular, the information on the TSD should not be exact, as in the real world there are always unknowns regarding trajectory predictions. Therefore, it would make sense to have some error on the trajectory prediction in the simulation. This also add to controller acceptance, as they will be able to test a new tool which supports uncertainties within the system. The uncertainty in the trajectory prediction could be modeled by using a standard deviation that is obtained from current trajectory predictors. In doing so, the error will decrease when the aircraft gets closer (in time) to the predicted arrival time. However, adding the uncertainty will also have implications on the TSD. Hence, elements will have to be added, or existing elements will need to be changed in order to accommodate the presence of uncertainty in the system.

7.1.2. Merging and Separation

In the end, the added decision support tool will have to make the merging and separating tasks easier for approach controllers. Therefore, it is important to help the controllers in an environment that they are familiar with. Hence, more information should be made available on the radar screen, instead relying on an additional display. Having two separate displays can cause information to be lost due to the controller having to split their attention between the two displays. Furthermore, on the radar screen, conflict detection should be extended to check all merging waypoints instead only the current selected waypoint. This ensures that information is not missed because the controller was focused on a different waypoint. An additional improvement to the radar screen could be the addition of aircraft ghosts on the different arrival routes when an aircraft is selected. This allows the controller to see where the current selected aircraft stacks with respect to aircraft arriving from different directions.

Regarding the TSD, the addition of showing conflict area's on the TSD (as can be seen in Figure 5.1) will give more meaning to the large time-space area, as currently only distance to go and predicted arrival time are connected with a line and shown on the TSD. Additionally, the separation interval shown is currently still set to a fixed value, which can be improved by looking at the aircraft types and determining the required time separation based on RECAT-TBS [18].

7.1.3. Minor Improvements

Finally, there are always little things that can be improved. These are however not of the highest priority, but more quality of life improvements and adding to the realism and familiarity to approach controllers. Such features include the following:

- An option to command an expedited descent function, which is a command sometimes given to aircraft when they are sequenced earlier and higher than expected, meaning the aircraft will have to increase its descent rate and slow down at the same time.
- The aircraft symbols on the radar screen can be made conform the current used radar screen by approach control, making the aircraft symbols indicate which controller has that certain aircraft under control.
- On the TID, an UCO button is present but not used currently. As aircraft are only controllable by the controller when aircraft are flying into the sector. This is sometimes not the case, as aircraft may be transferred from area control to approach control earlier than entering the TMA. Adding the UCO option enables the controller to actively take control of the aircraft. The same goes for the TOC button on the TID. Which stands for “Transfer of Control”. This button can then be used when aircraft are aligned on the ILS and are handed over to tower control.
- Something to be added which could be useful for experiment design, are no-fly zones. This could be weather related, requiring the controller to reroute aircraft around the weather cell. This could be problematic when the weather cell is right on the fixed approach trajectory transition. Showing the versatility of the added tool in this scenario could be interesting.
- Finally, some minor annoyance fix could be implemented. When operating the touch display, the mouse cursor jumps to the touch controlled display. Hence, losing the mouse on the radar screen and requiring the controller to “search” the mouse each time the TID is used.

7.2. Experiment Design

Last, when all simulation and display elements have been added, an experiment needs to be set up. This includes the creation of scenarios with varying traffic density and merging difficulty. Ideally a real life scenario is played, in order to let controllers compare their workload with the addition of the decision support tool enabled/disabled. Additionally, the participating air traffic controllers will have to be trained to use the simulation software. Hence, a training phase will need to be designed and executed. Finally, in order to make the experiment a success, the simulation should log all relevant parameters. These parameters still have to be determined, but one should think about the amount of commands issued, mouse activity, times an aircraft is selected, periodical workload surveys on a scale from 0% (easy) to 100% (overload), etc. By collecting these parameters, comparisons can be made between the different scenarios and setups used during the experiment.

8
Conclusion

The aim of this report has two parts. The first aim is to explain the problem and provide background on the issues that airports and approach controllers encounter during their current operations. This includes loss of runway capacity for airports during strong wind conditions, and the high workload approach controllers experience due to the vectoring method used. Hence, this research tries to solve these issues by making time based separation under fixed approach trajectories possible. The second aim is to present part of a possible solution. This possible solution is inspired from the previous work which was explained in this report. However, it remains a concept which has to be further developed and tested before any real conclusions can be made regarding the research question.

With the addition of a decision support tool, part of the approach controller's work can be automated. However, the approach controller will still be responsible for the decision-making, hence the name decision *support* tool. Approach controllers however will need to accept these new tools made available to them in order to make the new tools most useful. Therefore, communication with the controllers is key in order to satisfy their needs and concerns.

Currently, the uncertainty in the system is not shown to an approach controller through the decision support tool. However, in order to improve the flexibility, reliability and confidence in the tool, uncertainty will have to be visualized to the approach controller. This uncertainty will decrease as the predicted arrival time comes closer. Visualizing uncertainty will increase controller acceptance, since the controllers are familiar with the stochastic nature of trajectory predictions. By showing the controllers that automated predictions can be accurate and of use to the controller in a carefully chosen decision support tool, controllers will see the benefits that come with using the tool.

When all (new) parts of the decision support tool are implemented, the tool will be tested by approach controllers by means of an experiment. This experiment will provide answers to the research question regarding controller performance and runway capacity management.

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Part IV

Preliminary Thesis Appendices

A

LVNL Charts

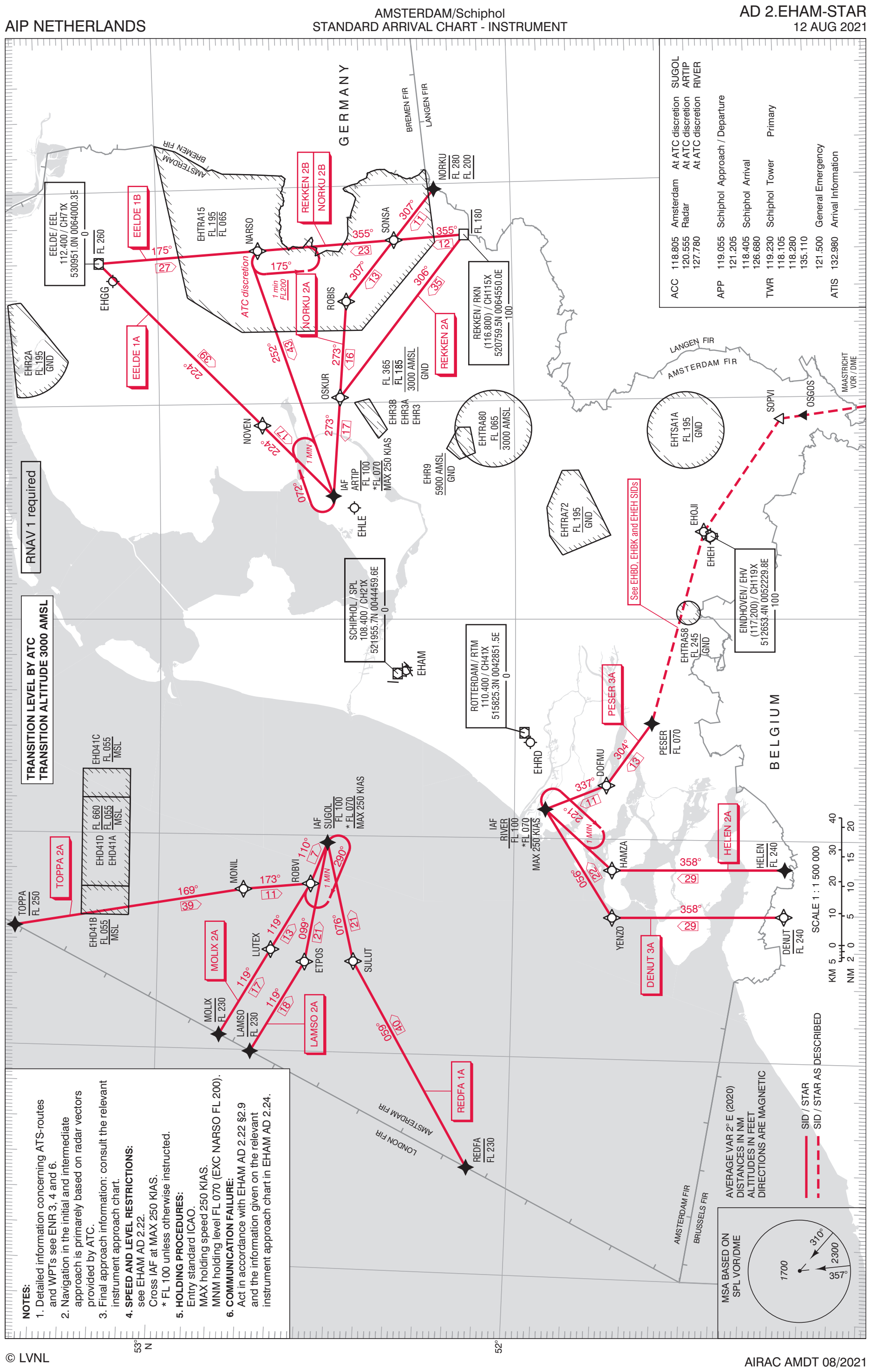


Figure A.1: Amsterdam Aiport Schiphol, Standard Arrival Chart [1]

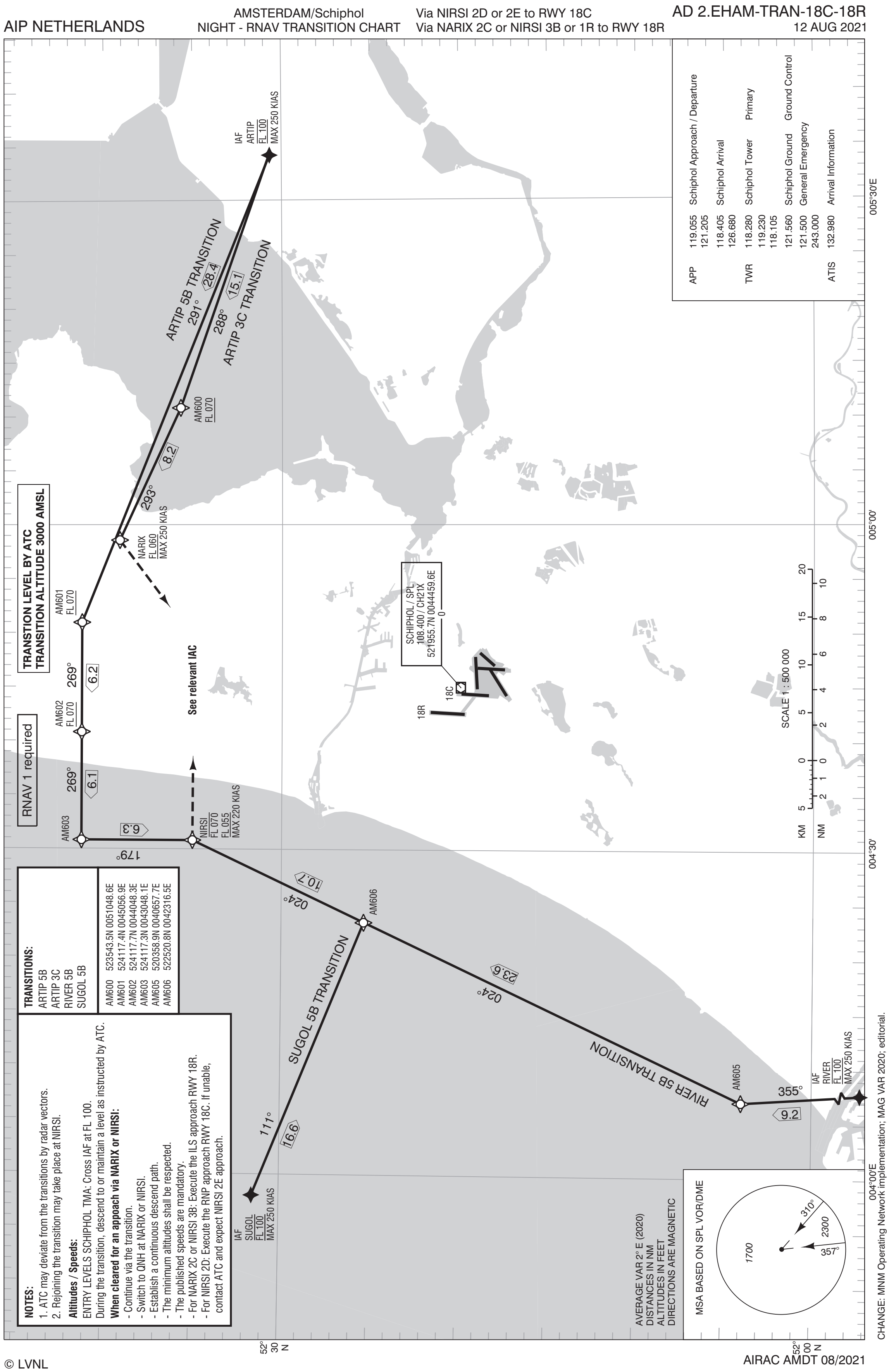


Figure A.2: Night Transition to Runway 18C and 18R [1]

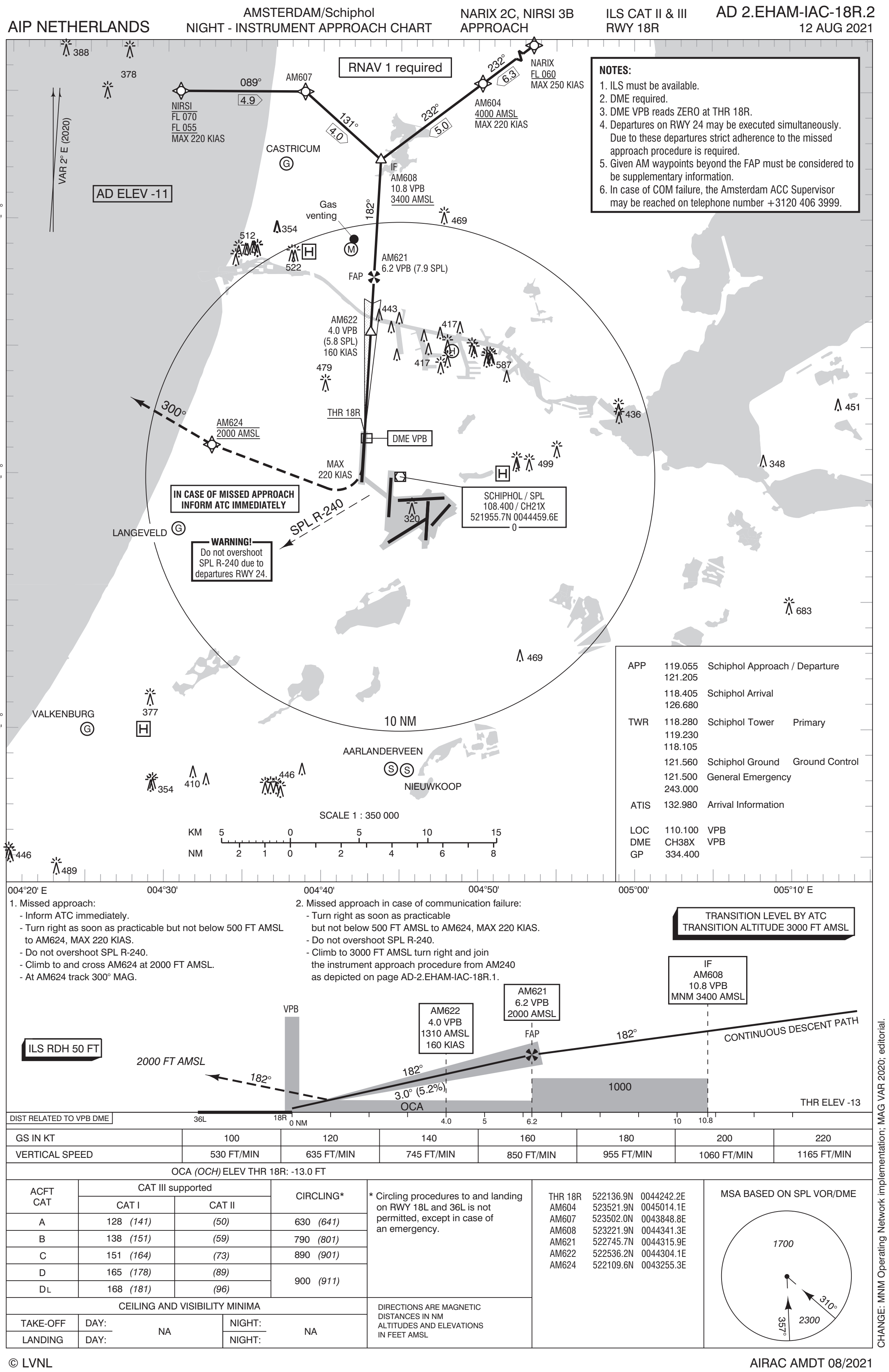


Figure A.3: Night Transition to Runway 18R [1]

Part V

Experiment Briefing

Air Traffic Merging in Approach Control in Combination with Time-Based Separation and Fixed Approach Trajectories

Increasing the Efficiency of Approach Control

by

S. van Selling

1 Introduction

Dear participant, thank you for participating. This document provides important information to prepare you for the experiment. First, some context is given to the problem in Section 1.1. The experiment goal is explained in Section 1.2. Next, the concept of operation is explained in Chapter 2. Finally, the Decision Support Tools are explained in Chapter 3.

1.1. Background Information

In order to reduce emission and noise pollution produced by aircraft, alterations are required to the way aircraft are directed through the airspace. One of these alterations is the use of fixed approach trajectories. Aircraft are instructed to follow a predefined route which guides them around inhabited area's. Additionally, the use of a known route means the pilot is able to plan a continuous descent more easily. This results in less noise produced and a more efficient operation. These routes are already being used at night at Amsterdam Airport Schiphol. However, due to capacity demand being higher during the day, these routes are not used since they limit the controllers in their ability to separate traffic, requiring larger separation margins at the cost of a capacity loss. Another change to current operations is the switch from Distance-Based Separation (DBS) to Time-Based Separation (TBS) on final. This allows landing capacity to remain high in events when a large headwind is present on the main runway. Additional tooling will be required to support these two changes in operations, hence this research aims to design, implement and test such tooling.

1.2. Experiment Goal

The goal of the experiment is to test a newly designed set of Decision Support Tools (DST). This will be done by executing traffic scenarios with two different display types. One of which facilitates the current operations in the Terminal Maneuvering Area (TMA), while the other aims to help the controller in executing TBS in combination with fixed approach trajectories. Your goal during the experiment is to guide the aircraft safely to the runway, while trying to be as efficient as possible.

2 Concept of Operations

During the experiment your task is to guide arriving aircraft to the runway. The active runway is either 18R or 27. The simulation runs at 2x speed. Since there will be two different ways of operating, both the baseline and decision support tools will be discussed. First, the basic use of the simulator is explained:

- **Display commands:**
  - A left mouse click on the aircraft label or symbol selects the corresponding aircraft.
  - Commands to aircraft are given using the Touch Input Device (TID), shown in Figure 2.1.
  - On the top of the TID, the command line is present. Here the current command is shown. Additionally, the command line is shown in the interaction area.
  - Deselecting aircraft is done using the ERA button on the TID.
  - In order to clear the command line, the CLR button is used. The aircraft remains selected.
  - The range of the radar screen can be changed to 36 or 48 NM using the 36 or 48 button.
  - A wind overlay can be activated using the WIND button, currently not active in Figure 2.1, as can be seen by the grayed out color of the button. This option is only available for the scenarios with all decision support tools enabled.
- **Aircraft commands**:
  - The UCO button is used to take aircraft under control arriving from ACC.
  - Heading, altitude and speed commands can be given by using the HDG, EFL and SPD buttons, respectively. The numpad is then used to enter the desired command.
  - Using the decision support tools, TRA(jectory) commands can also be issued.
  - The EXQ button executes a HDG, SPD, ALT or TRA command.
  - All aircraft are programmed to follow the transition to the runway. Additional to the lateral trajectory, speed restrictions are automatically adhered to as shown in Figure 2.2. Any instruction from the controller will overwrite this initial trajectory and/or speed. Note: only speeds lower than the restriction can be commanded by the controller, any higher speed will be overruled by the speed restriction that is in place.
  - All aircraft will need to be instructed to descent by the controller.
  - The APP button clears the aircraft for the ILS approach. This will command the aircraft to intercept the ILS. Upon reaching the FAF, the aircraft is removed from the simulation.
  - The TOC button transfers the selected aircraft to tower control.

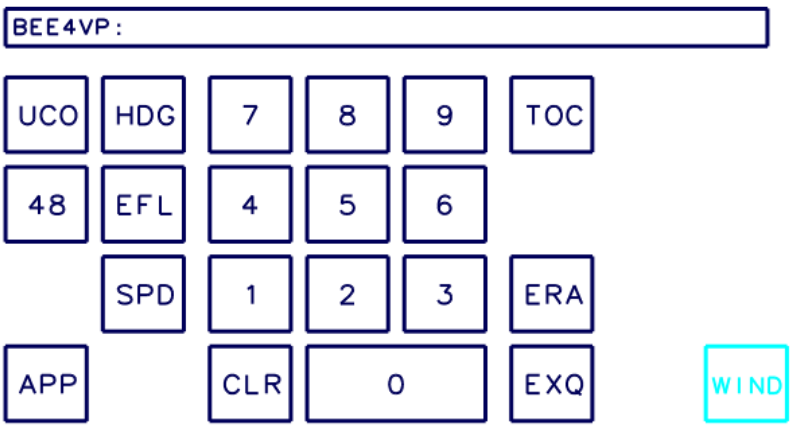
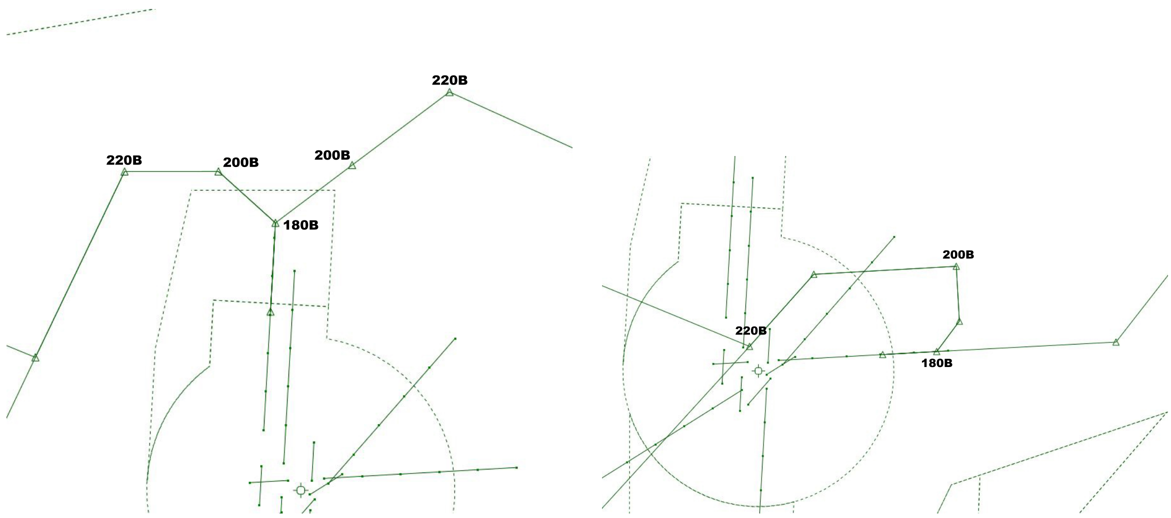


Figure 2.1: Touch Input Device (TID) (Colors adjusted)



(a) Speed Constraints for 18R (b) Speed Constraints for 27

Figure 2.2: Speed Constraints on Approach Transitions

2.1. Baseline

When using the baseline display setup, the traffic will have to be handled by means of vectoring. No additional information is provided. This should be similar to what you are used to in your daily work. Aircraft are separated by distance with the different aircraft types taken into account. Hence, this requires less introduction than the decision support tool display type.

2.2. Decision Support Tools

The decision support tools require some more introduction compared to the baseline. New features are added and some are disabled to enforce you using the newly designed tools. The new tools are explained in more detail in Chapter 3. For this display type, the HDG button on the TID has been made inoperative in order to stimulate the usage of the Delay-Space Representation (see Section 3.2).

2.3. Trajectory Prediction

In order to feed the decision support tools from information, trajectory prediction is used. This includes a number of assumptions and limitations that you should be aware of:

- It is assumed that aircraft descent to 2000 feet immediately.
- There are two wind fields present. One actual and one predicted wind field. The actual wind field is used when moving the aircraft. The predicted wind field is used for all information on the decision support tool.
- The prediction takes the speed constraints into account.
- The prediction is updated every radar update.

When the trajectories are displayed, the color of the trajectory indicates the change of a future loss of separation (separation between aircraft being less than 2.5 NM). Four colors can be seen on each segment of the trajectory:

- **Cyan:** No conflict detected (0%-5% probability)
- **Yellow:** Low possibility of a loss of separation (5%-50% probability)
- **Orange:** Medium possibility of a loss of separation (50%-90% probability)
- **Red:** High possibility of a loss of separation (90%-100% probability)

The probability of a loss of separation is based on the “Time To Conflict” (TTC), and the “Closest Point of Approach” (CPA). Therefore, the conflict probability is updated every radar update, resulting in a possible change in color on the display as the time to conflict becomes smaller.

3
Decision Support Tools

This section explains the additional tooling in more detail. Starting with the Time-Space Diagram (TSD) in Section 3.1, after which the Delay-Space Representation (DSR) and label alterations are introduced in Section 3.2 and Section 3.3, respectively. Finally, the wind visualization is presented in Section 3.4.

3.1. Time-Space Diagram

The most obvious addition to the simulation is the usage of the Time-Space Diagram (TSD). This diagram is projected on the second TID and is operated by using touch inputs. The TSD provides information about aircraft flying towards a selected waypoint. If no waypoint is selected, the TSD remains empty. A waypoint is selected by clicking on a waypoint on the radar screen, after which the selected waypoint turns pink. The TSD is shown in Figure 3.1.

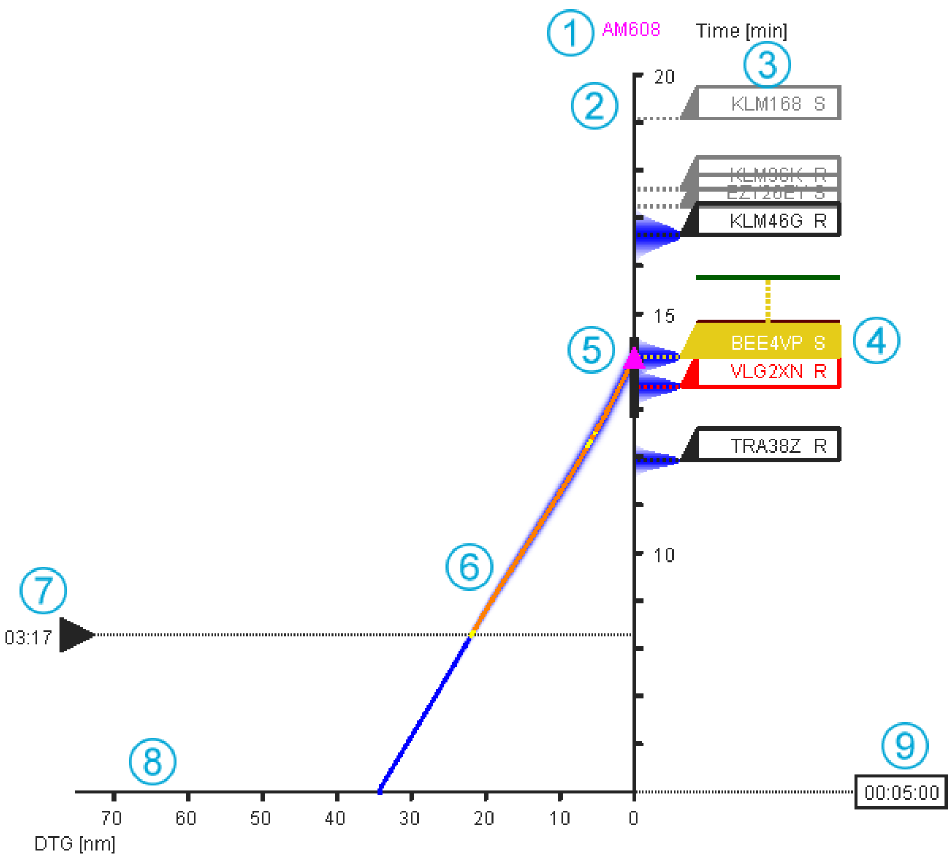


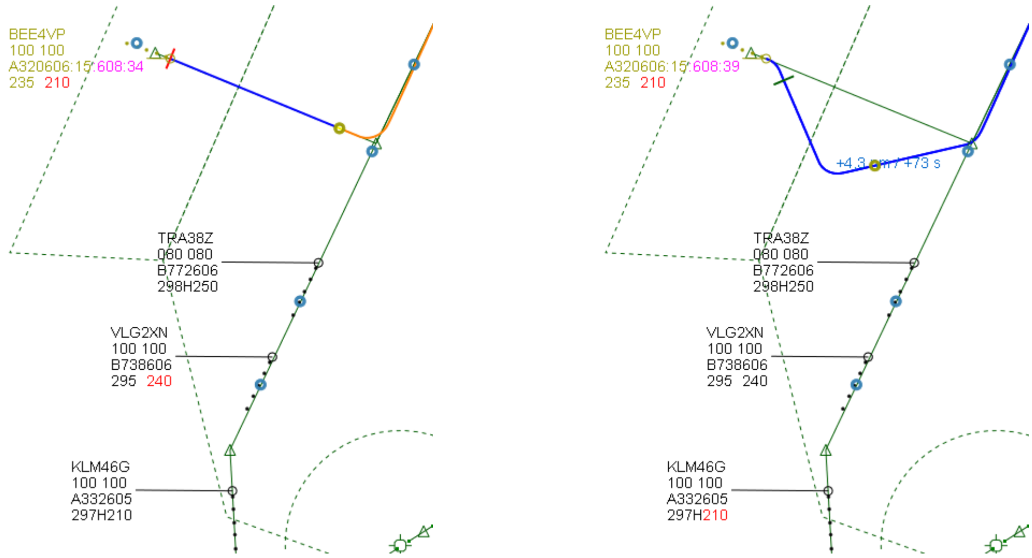
Figure 3.1: Time-Space Diagram (TSD) (Colors adjusted)

The labels in Figure 3.1 represent the following:

1. **Selected waypoint:** At the top of the TSD, the ID of the selected waypoint (AM608) is shown. This is displayed with the same color as the waypoint highlighted on the radar screen.
2. **Time axis:** The vertical axis of the TSD represents the time axis in minutes. As the time passes, this axis moves down. The range of this axis is set to 15 minutes.
3. **Flight label:** Along the time axis, the aircraft passing the selected waypoint are shown. In the label, the call sign of the corresponding flight is shown, as well as a single character to identify the IAF from which this aircraft approaches. So an S for an aircraft arriving from SUGOL, R represents RIVER and A corresponds to ARTIP. The color of the label is used to indicate different states of the aircraft:
    - **Grey:** Indicates aircraft not under our control.
    - **Black:** Indicates aircraft currently under our control.
    - **Yellow/Orange:** Indicates the current selected aircraft.
    - **Yellow:** Low possibility of a loss of separation (5%-50% probability)
    - **Orange:** Medium possibility of a loss of separation (50%-90% probability)
    - **Red:** High possibility of a loss of (time) separation (90%-100% probability)
4. **Selected aircraft:** When the aircraft is selected, the label color changes to yellow/orange. In addition, the time separation required for the selected aircraft and the aircraft in front are drawn with the dotted line along the time axis and the green bar (when the separation criteria are met, otherwise the bar turns red).
5. Multiple elements are shown here:
    - **Fat axis line:** Arrival time range with a speed range of 200 to 250 knots. The top of the fat line represents the latest arrival time when a speed command of 200 knots is issued, vice versa for the bottom of the line.
    - **Purple triangle:** Representation of the selected waypoint. The position of this triangle on the time-axis represents the arrival time of the selected aircraft at the selected waypoint.
    - **Blue normal distribution on the time-axis:** The blue normal distribution shows the probability that the aircraft will arrive at a specific point in time. The spread of the normal distribution becomes smaller when the look ahead time becomes smaller. This is visible when comparing the KLM46G distribution with the TRA38Z distribution.
6. **Time-Space Trajectory:** The trajectory shows the distance vs the time the selected aircraft has to travel with respect to the selected waypoint. The color of the trajectory indicates a potential loss of separation along the trajectory. As can be seen in the figure, about 3.5 minutes in the future a potential loss of separation is identified (as the trajectory line changes from blue (no risk) to yellow and orange). If the conflict is closer in time and distance, the trajectory may turn red, indicating immediate danger.
7. **Time slider:** The triangle shown can be dragged up, resulting in ghost aircraft to be drawn on the radar screen at the location in time that the time slider is set at. As can be seen in Figure 3.2a and Figure 3.3a, the selected aircraft is also shown with the same color as the selected label color. The relative time will also be shown when the triangle is dragged up. Showing how far in the future the time slider is set.
8. **Distance-to-go axis:** The horizontal axis of the TSD shows the distance to go in nautical miles. As aircraft approach the selected waypoint, the distance to go reduces, hence the blue line of (6) shifts to the right.
9. **Current time:** Finally, in the bottom right the current (simulation) time is shown. This is done in a hh:mm:ss format.

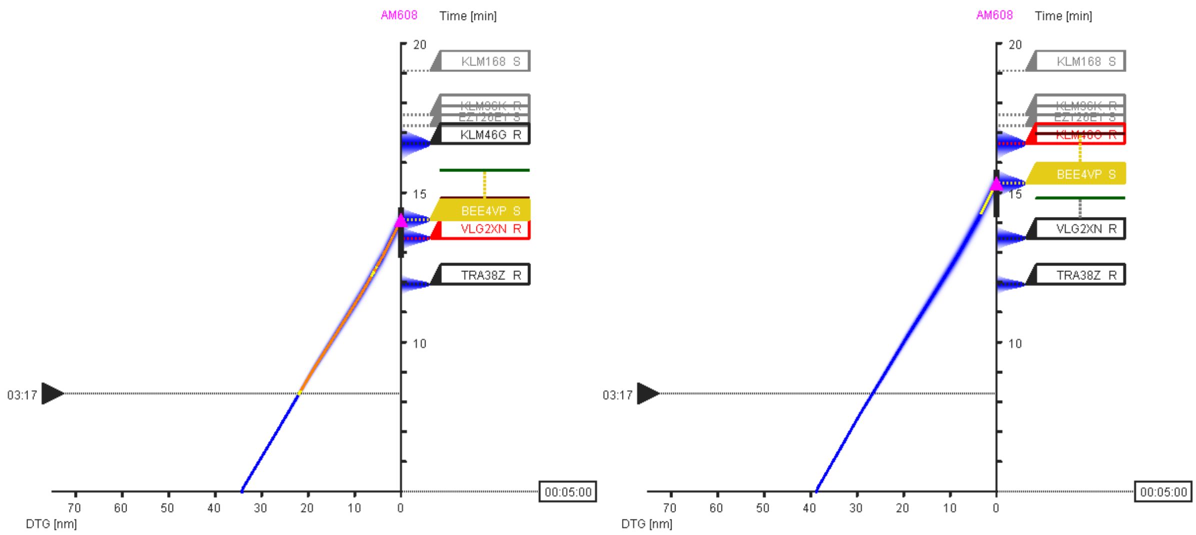
3.2. Delay-Space Representation

The Delay-Space Representation (DSR) is implemented to allow for deviating from the transition in order to solve conflicts that can not be solved with speed instructions alone and/or to avoid bad weather on the arrival transition. The DSR is activated by selecting an aircraft and pressing the right mouse button. This will either insert a new waypoint, or issue a direct to an already existing waypoint. The new waypoint is inserted at the position of the mouse pointer. By default, the aircraft will fly directly to this new waypoint after which the route is joined at the most convenient point. It is however possible to insert a waypoint further down the route. By using the scroll wheel to change the insertion point of the new waypoint. If the mouse pointer is located at a waypoint that is already in the flight plan of the selected aircraft, a direct trajectory is proposed. While holding the right mouse button, the left mouse button can be used to “hold” the trajectory. This trajectory can then be executed using the EXQ button on the TID. An example of inserting a new waypoint in the existing flight plan is shown in Figure 3.2, and the effects of this alteration can clearly be visualized on the TSD, as can be seen in Figure 3.3. Additionally, on the trajectory shown on radar screen, a separation margin indicator is shown which indicates how far the leading aircraft is in front. This becomes apparent when looking at Figure 3.2a, where there is no separation margin, hence the indicator is red and directly above the selected aircraft. In Figure 3.2b, sufficient margin is reinstated, and the margin indicator has shifted in front of the selected aircraft and its color has changed to green, indicating a safe separation margin.



(a) DSR off **(b)** DSR on

Figure 3.2: Delay Space Representation(DSR) on Radar Screen (Colors adjusted)



(a) DSR off **(b)** DSR on

Figure 3.3: Effect of Delay Space Representation on Time-Space Diagram (Colors adjusted)

3.3. Label Information

Changes to the aircraft label have been made to include more useful information to the controller. These changes include the following:

- **Color of commanded speed:** The color of the commanded speed changes to a warning color in case a potential loss of separation somewhere along the trajectory is predicted. The same colors are used as was explained in the Time-Space Diagram section at item 3. Only when no conflict is predicted the color of the label is the default white label color (for not selected aircraft).
- **Distance to go:** Upon selecting of an aircraft. The distance to go to the inbound waypoint is shown in the label. Additionally, when a waypoint is selected, the distance to the selected waypoint is displayed. All distances shown in the aircraft label take into account any turns and intermediate waypoints.

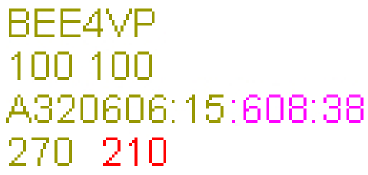


Figure 3.4: Label of a Selected Aircraft

3.4. Wind Visualization

The WIND button on the TID enables an overlay of the predicted wind. This overlay is shown on the radar screen with wind direction and magnitude corresponding to the altitude of the current selected aircraft. If no aircraft is selected, the wind at FL100 is shown. Additionally, if an aircraft and waypoint are selected, the encountered wind is also visualized on the TSD. The overlay on the radar screen is shown in Figure 3.5.

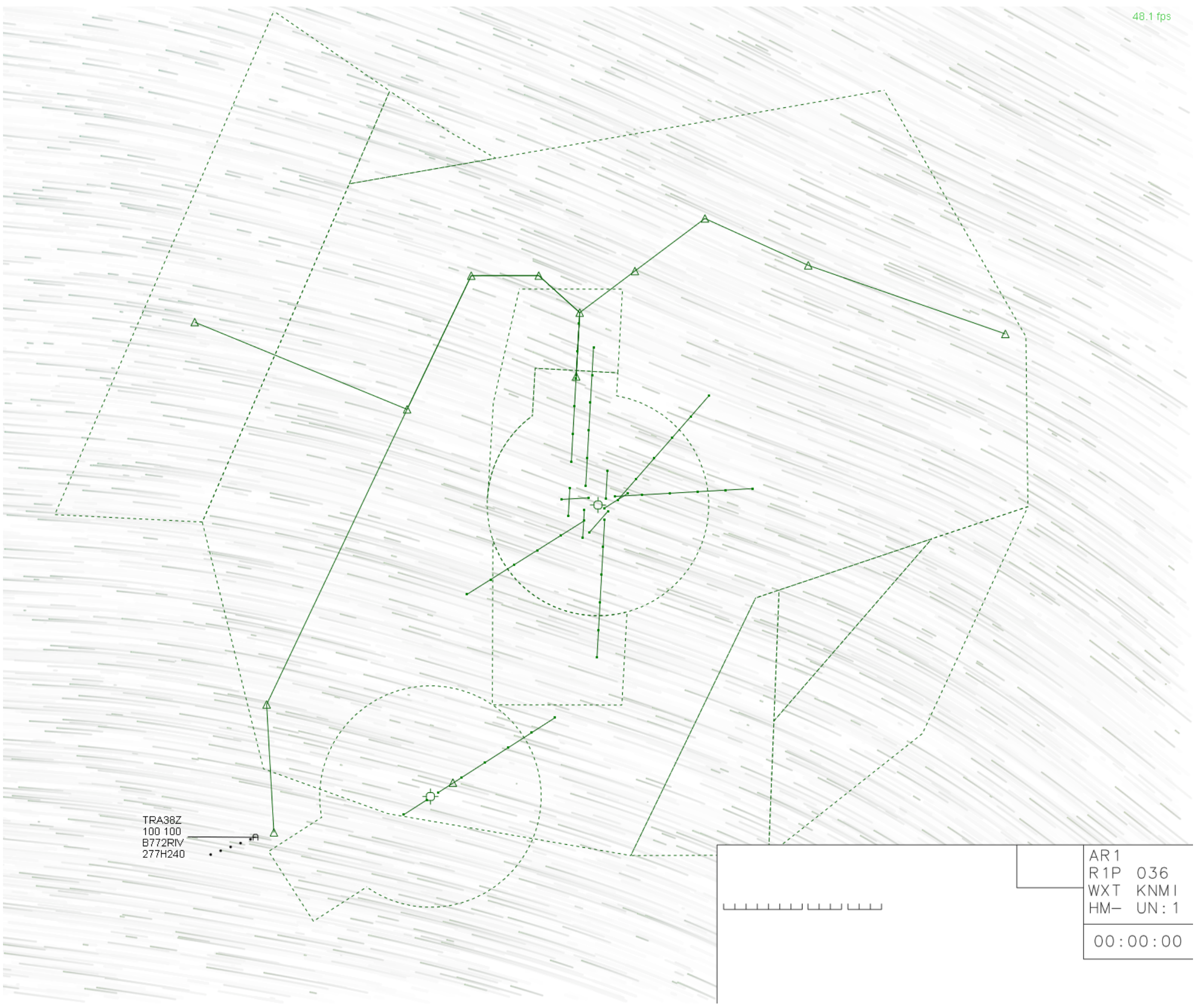


Figure 3.5: Wind Visualization (Colors adjusted)