Design and evaluation of a novel holding stack management tool

Master of Science Thesis

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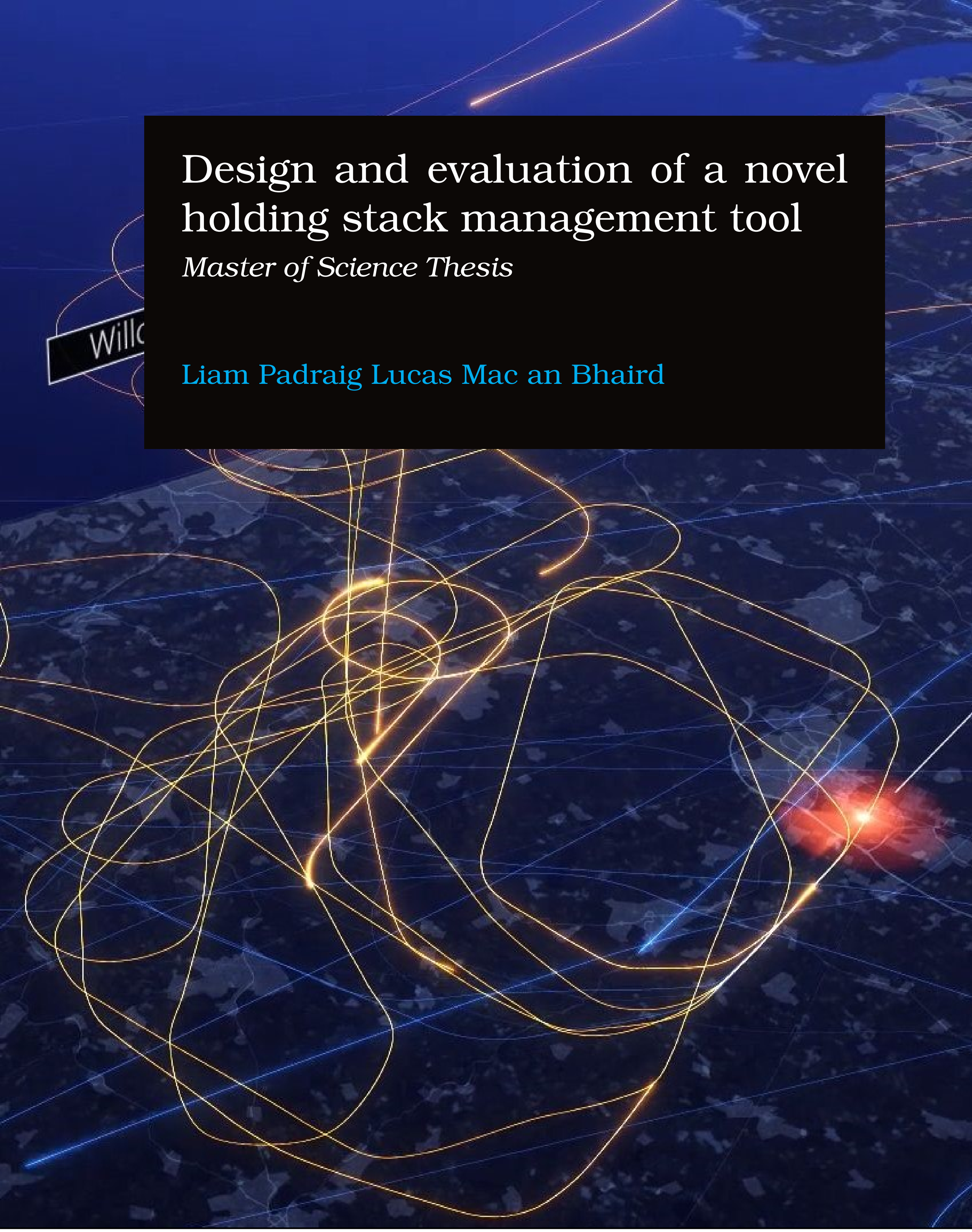

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Design and evaluation of a novel holding stack management tool

by

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Master of Science Thesis Paper

Design and evaluation of a novel holding stack management tool

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***Abstract*—Before an aircraft enters the Terminal Manoeuvring Area (TMA) a delay may need to be introduced due to capacity limits. An Air Traffic Controller (ATCo) has the opportunity to introduce a holding procedure. When multiple aircraft need to be delayed in this form a holding stack may be formed. This holding stack is formed above the Initial Approach Fix (IAF). Current industry standard is able to achieve an accuracy within two minutes of planned Estimated Approach Time (EAT), at which the aircraft is planned to fly over the IAF and proceed to the TMA. In this research a display tool to aid Area Controllers (ACC) in realising a more accurate delivery and improving their situational awareness is designed, called the Stack Planner (SP). The SP assists controllers with choosing an optimal holding leg time for aircraft in the holding stack to adjust their IAF flyover time. The display aims to assist ATCo by showing the possible space of their control actions as well as system constraints. In an initial proof-of-concept experiment, comparing the SP display with a baseline state of the art display, promising results are found; the SP display shows a more manageable workload with increased situational awareness that scales with scenario complexity. The new display also shows the potential to move from minute accuracy to second accuracy. Future studies would need to investigate the extent to which scenario complexity plays a role in accuracy of delivery for both baseline and SP displays.**

***Index Terms*—Air Traffic Control, Display, Tool, Holding procedure, Holding stack, Area Control, Human Machine Interaction**

I. Introduction

If an aircraft is nearing the TMA earlier than its EAT, the aircraft may then arrive earlier than can be accommodated by approach controllers. This may lead to a necessity for adding a delay to this aircraft. There are many strategies when it comes to introducing a delay such as tromboning and linear holding. This report will cover only one delay strategy called a "holding Stack" and investigate how a controller can manage this strategy in their work environment. Holding stacks have proven to be an effective strategy for delaying aircraft. This strategy may be appropriate when, for example, an airport temporarily closes its runway due to bad weather. ATC procedures and tooling will need to evolve to support this traffic.

A holding procedure is a path that an aircraft flies to maintain its position and altitude within certain bounds. The aircraft effectively flies in loops waiting for a follow up procedure. This procedure is either issued by ATC or a pilot can request one from ATC. A specific reference point is communicated to the pilot over which the holding procedure is executed. A stack emerges when multiple holding procedures are created on varying flight levels in the same area.

A need for holding stack support has been addressed in a report issued by the Dutch Knowledge Development Center (KDC) [1]. In this report a desire for a tool that provides decision support for speed, timing and rate of turn while holding is expressed. It is also stated that there is a goal to change holding operations such that it may "*lead to a better flow of traffic, less fuel flow and improved accurate delivery for approach Schiphol*" [1]. It is also stated that "Area controllers use only their expertise for efficient holding" [1]. From this report it is clear that there is a need for improving the current holding stack support tools or procedures available to holding stack controllers. Because flow of traffic, fuel flow and accuracy of delivery are interdependent, only accuracy of delivery will be used as a measurement. It is defined as here the time between exit time and EAT. A Key Performance Area in stack control is then: *accuracy of delivery*. Other additional KPAs that are not mentioned in the KDC report but that are also essential for ATC are *Situation Awareness (SA)*, *workload* and *system acceptance*. In the report, speed, timing and rate of turn are further listed as control parameters while maintaining a separation minimum. All of which will be discussed in display design.

A solution in ATC that is resilient to unforeseen situations is more important than an efficient solution that fails catastrophically in some specific situations [2]. In this paper a new display design will be discussed. This novel display is an attempt to improve *Accuracy of Delivery*, *Situation Awareness*, *Workload* and *System Acceptance*. The design of this display is inspired by Ecological Interface Design methodology. This display is used in an experiment using ATCos in a realistic scenario linked to the NARSIM simulator of NLR. Evidence in the form of experiment results and analysis will be created to either support or dissuade the use of the newly designed display.

In this article a background of the main problem is presented followed by a display design solution. Next an explanation of an experiment is described. Finally this article is concluded with analysis of the results and a discussion on their implications.

II. Problem background

To design a novel display. it is important to understand from where the need for such a display arises. This section is meant to document procedures, responsibilities and tools

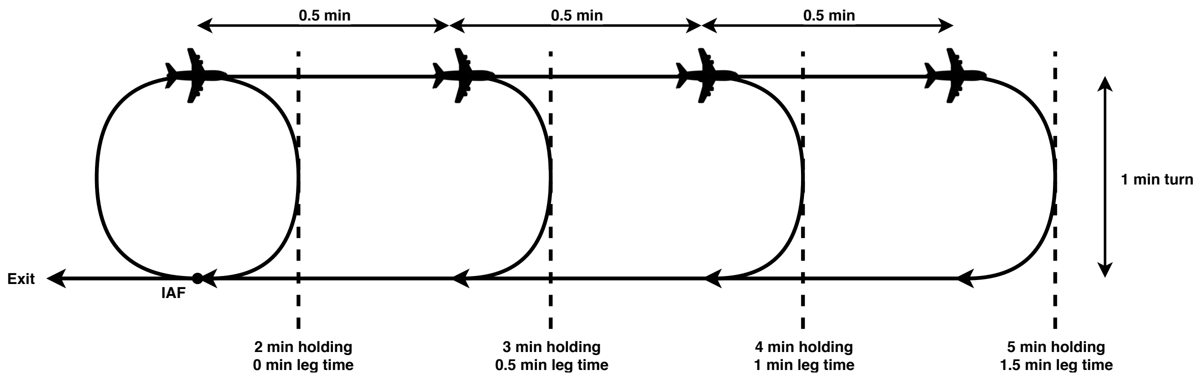

Figure 1. Variability of holding procedure timings. Image adapted from ICAO [5]

currently available with entering, remaining in and leaving a holding procedure and/or holding stack. Compiling this section was done with source material from ICAO [4] [5], IVAO [6] [7], skybrary [8] and an ATCo training course for ACC. Interviews with domain experts provided contextual knowledge to standard operational procedures [9].

A. holding procedure

A standard holding procedure is defined as follows: "*A predetermined maneuver which keeps aircraft within a specified airspace while awaiting further clearance from air traffic control*" [8]. Aircraft start their holding procedure at a holding fix which serves as a reference for both pilot and ATC. A holding fix is any VOR/DME or other mutually understood navigation point used to communicate holding intent. For example in the Netherlands, three of the four predetermined standard holding patterns are above an IAF ground-based navigation beacon known as a VHF Omnidirectional Radio Range / Distance Measuring Equipment (VOR/DME). Those beacons are RIVER, ARTIP and SUGOL. All segments of holding pattern geometry can be linked to this holding fix. If no operational considerations prevail, right hand turn holding patterns should be established by the pilot. Left hand turn holding patterns have symmetric properties. In the case of holding on VOR intersections or VOR/DME fixes, entries will be limited to radials [5].

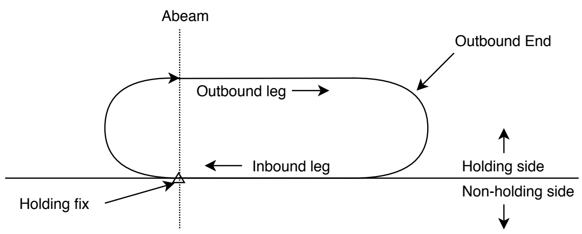

Figure 2. Holding procedure and terminology [5]

As can be seen in Figure 2, the geometry of a holding procedure has four segments:

- First half turn
- Outbound leg
- Second half turn
- Inbound leg

Each segment of a holding procedure is bound by the Initial Approach Fix (IAF). A standard holding procedure describes each leg to take 1 minute to fly if the aircraft is situated below 14,000 ft and 1.5 minutes to complete when above 14,000 ft [5]. Turns are done at either a bank angle of 25° or at a rate of 3° per second, whichever has a lower bank angle and will take approximately one minute. In practice the time it takes to fly these segments may vary as duration is a function of aircraft type, altitude and temperature [9]. However, nearly all commercial aircraft fly holding patterns with flight computers which tend to produce fairly accurate timings.

When a pilot uses a flight computer there are some options available specifically for flying a holding procedure. In Figure 3 a holding page is shown on a flight computer. Leg distance or leg time can be entered, influencing the duration of a holding procedure. If a leg time is entered, then a speed will be tied to the total holding procedure time. If a leg distance is used as an input, then the total time will vary based on the most fuel efficient speed to fly at that flight level, automatically decided by the flight computer. If a value is entered during a holding procedure, the holding procedure's properties will not change directly, but after the aircraft flies over the IAF.

In Figure 1 a holding geometry is shown, depending on the leg time. At the minimum leg time of 0 minutes, a 2 minute holding procedure will be flown which is essentially a circle.

From this it is clear that if a controller will anticipate needing to delay an aircraft for less than 2 minutes, a holding procedure will add too much delay. However, if a delay greater than 2 minutes is required then a holding procedure becomes a viable option. Equation 1 shows an approximation of holding duration given simple weather conditions:

$$t_{holding} = 2 * (t_{turn}) + 2 * (t_{leg}) \quad (1)$$

PAN-OPS document item 3.4.5 on outbound time [5] suggests that the outbound part of a holding procedure may vary between one and three minutes in half-minute intervals. This means that outbound leg + outbound turn may not exceed three

Table I
HOLDING SPEEDS [5]

Altitude	Normal conditions	Turbulent conditions
A < 14000 ft A < 4250 m	IAS = 230 KT or 425 km/h	IAS 280 KT or 315 km/h
14000 ft < A < 20000 ft 4250 m < A < 6100 m	IAS = 240 KT or 445 km/h	IAS = 280 KT or 520 km/h or 0.80 Mach, whichever is less
20000 ft < A < 34000 ft 6100 m < A < 10350 m	IAS 265 KT or 490 km/h	IAS = 280 KT or 520 km/h or 0.80 Mach, whichever is less
A > 34000 ft A > 10350 m	IAS = 0.83 Mach	IAS = 0.83 Mach

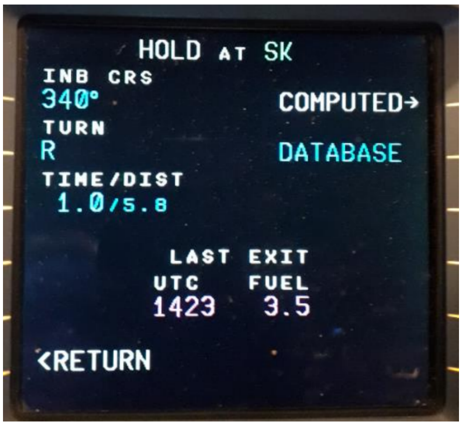

Figure 3. Holding procedure page on an A320 flight computer [10]

minutes. Because a turn should be one minute, the maximum leg time is two minutes, which brings the maximum holding procedure duration to six minutes. Figure 1 shows how half minute intervals affect the holding procedure duration.

B. *Speed restrictions*

Pilots are responsible for wind corrections to maintain the track and make allowances by controlling heading and speed. Aircraft entering the holding pattern shall be flying at or below the air speeds given in Table I. There are different holding speeds for category A and B aircraft as well as helicopters but this article will not cover these cases so they are left out.

C. *Holding pattern entries*

The holding pattern can be initiated by one of the holding entries shown in Figure 4 depending on which relative angle the aircraft approach the holding fix at. Figure 4 shows the multiple entries available to start a holding procedure depending on the direction of approach to the holding fix reference. Available entries include:

1) Parallel entry
2) Teardrop entry
3) Direct entry

There is a flexibility of 5° on either side of the direction boundaries for the pilot but all standard entries will fly over the holding fix. Variations of the basic entry procedures may be made to meet local conditions after appropriate consultation with concerned operators [5].

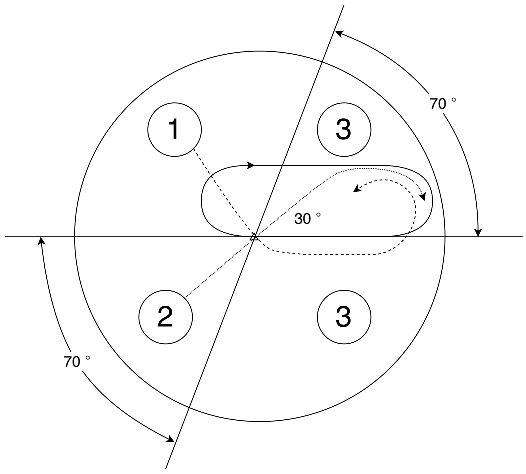

Figure 4. Entry options for a holding procedure [5]

Before a holding is authorized, the following must be communicated to the pilot by an ATCo [11]:

- the holding fix or IAF
- the heading of the holding direction
- if Area Navigation (RNAV) or DME is used, leg length (if none is specified a standard one minute leg is assumed)
- direction of turn (if none is specified right turn is assumed)
- Estimated time until further clearance

D. *Holding stack*

A holding stack is defined as follows: "*A number of aircraft holding at a common fix with vertical separation*" [12]. As holding stack control is not covered in ICAO documents in Aircraft Operations - Flight Procedures volume 1 or volume 2, instead the reference material almost solely consists of material from IVAO [6] [7]. Figure 5 is a visualization of a holding stack and its surrounding airspace. This figure shows the structure of a holding stack above an IAF. The subsequent airspace sections that an aircraft will pass through after exiting a holding stack such as the TMA and Control Zone (CTR) is also visualized.

E. *Filling a holding stack*

A holding stack is managed with the First In First Out (FIFO) principle [7]. An ATCo will put aircraft in the stack in order of arrival, the latter at a higher Flight Level (FL) maintaining a separation minimum of 10 FL, and remove them from the stack in the same order.

F. *Emptying a holding stack*

Aircraft may leave a stack and begin approach when cleared by an ATCo only at predetermined FLs, usually situated near the minimum holding stack FL. In the Netherlands these values are between FL 70 and 100, related to restrictions for entering the TMA. This means that if an ATCo plans to release an aircraft from the holding stack for approach, it must be guided to the bottom of the holding stack first.

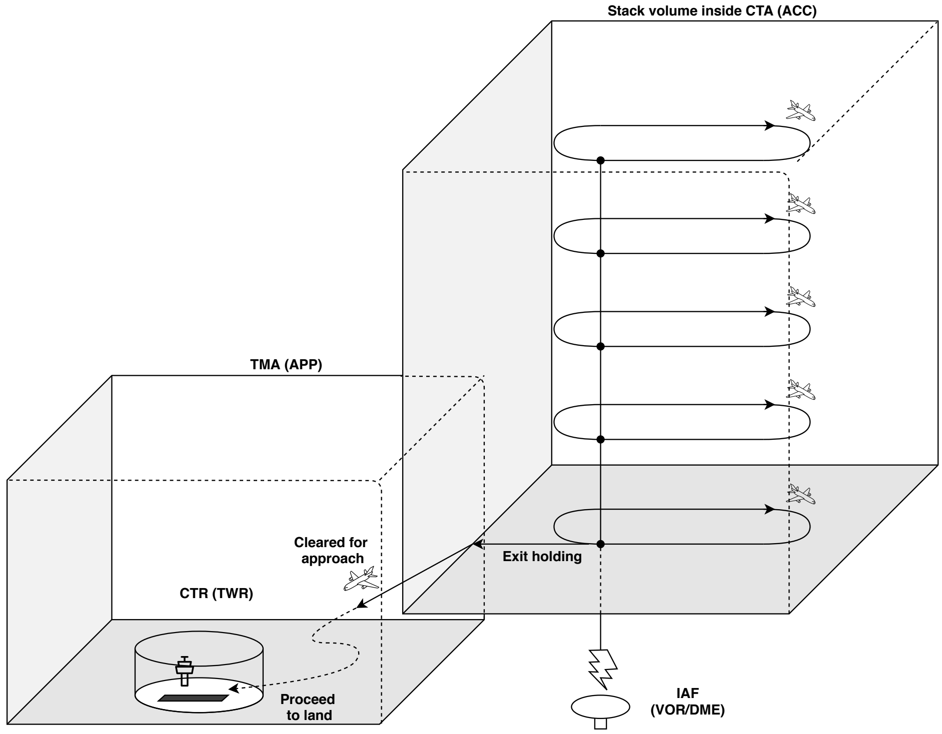

Figure 5. Airspace where holding is executed (not to scale)

Aircraft are preferably removed from the holding stack when on the inbound leg [7]. This will ensure a straight flight over the IAF which is more efficient and easier to predict. This aircraft will then start the approach sequence after entering the TMA and control is handed over to Approach Controller (APP). After the lowest level aircraft has been removed from the holding stack, the holding stack must be reorganised. The ATCo will descend each aircraft one by one to a lower flight level. The aircraft above the descending aircraft may not be cleared for descent until minimum vertical separation will be guaranteed by the air traffic controller. Once all of the aircraft in the stack descend one level, this frees up space higher up for new aircraft to join the holding stack.

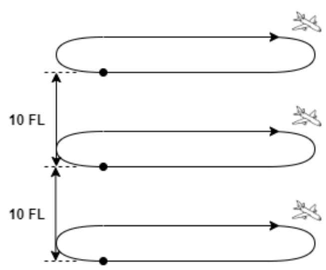

Figure 6. Minimum separation to be kept by ATCo (not to scale)

ATCos may anticipate the descent but may not forget about aircraft's performance or pilot's speed of response [7]. The holding procedures are separated by 10 FLs which is the minimum vertical separation used for holding procedures. Figure 6 shows the minimum separation to be adhered to by ATCos for holding stack operations.

In Figure 5 a holding stack and its stack volume are shown. In this volume are aircraft flying holding patterns at different FLs. At the bottom, aircraft exit the holding stack and enter the TMA to begin approach followed by a landing. Also shown are the different airspace types that it must pass through before it lands. It must be noted that the actual volume reserved for a holding procedure is more complex than depicted here.

G. Human responsibilities tied to a holding procedure

Next to all of the technicalities of holding procedures and holding stacks there is a human factors aspect. If holding stack control is seen as a system, humans are deeply rooted in this system. An expert holding stack controller from LVNL was able to provide valuable insight for this section [9].

1) Pilot in command (Captain): A pilot is responsible for their aircraft and passengers. They will fly a route given by an ATCo and may make requests if they deem it necessary. A pilot may for example make a request to divert to alternate when fuel is low. Captains will tend to fly efficiently to conserve fuel and may make requests or give reminders to ATCo so as to increase flight efficiency. Pilots are also responsible for the comfort of their passengers.

2) Area controller (ACC): An area controller is an executive controller. Before entering a holding stack, an aircraft is guided by an area controller. Area controllers are responsible for aircraft in their sector and for clearing aircraft for approach.

This means that if TMA is not able to accommodate any new aircraft a delay must be introduced by the ACC to aircraft which are destined for approach. This can be done a number of ways, one of which is clearing them for a holding procedure above an IAF, the main focus of this paper.

When operating under current LVNL practice, an ACC is assigned to a holding stack depending on traffic density and the amount of delay required per aircraft. If there is need for a holding stack, the size of the holding stack determines how it is handled. An ACC will handle a holding stack and its surroundings if it has few aircraft but will not be allowed to use an additional holding stack support display. If the stack is predicted to be large, there is the option to use a standby controller as a holding stack controller.

3) Holding stack controller: The holding stack controller is responsible for all aircraft which are cleared for holding and have access to an additional holding stack support display. Aircraft are cleared for holding by ACC. An ACC and a stack controller will have separate radio frequencies to communicate with aircraft under their control. All aircraft in a holding stack are descended in an orderly fashion and cleared for approach.

Stack controllers will abide by ICAO regulation when possible. When an unforeseen situation occurs, stack controllers are permitted to use creative solutions. An example of this may happen when the planning is updated and EATs change due to low visibility. Aircraft's EAT may change dramatically due to their certified Runway Visual Range (RVR), causing an existing holding stack to no longer be stacked correctly. In other words, an aircraft with a lower flight level may have a later EAT. In this scenario, a stack controller in the past has rearranged their incorrectly stacked holding stack by exiting the aircraft with a later EAT, only to let it climb and rejoin in its correct position in the holding stack.

Control actions are carried out verbally over radio frequency in the form of a command to the pilot in command. Available control actions include: FL descent clearance command, speed command, expedite descent command, rate of descent command, heading command, exit holding command, cleared for approach command and direct to command. Because controllers must be able to react to unforeseen information, it is imperative that controllers have a strong situational awareness of a holding stack.

The displays available to a stack controller may vary depending on ANSP as there is no industry standard. For example: Figure 7 shows a section of an LVNL holding stack display while Figure 8 shows a NATS holding stack display. These displays are support tools available to stack controllers. Currently, stack controllers are meant to use the plan view display to understand an aircraft's lateral separation and the holding stack display to understand vertical separation. Two separate displays are helping shape a controller's cognitive understanding of the holding stack's traffic.

4) Standby controller: Standby controllers are assigned for every X controllers. The amount "X" may differ depending on what a supervisor deems necessary. Their responsibilities are to support active controllers as well as provide redundancy. If there is a need for a stack controller, a standby controller will become a stack controller.

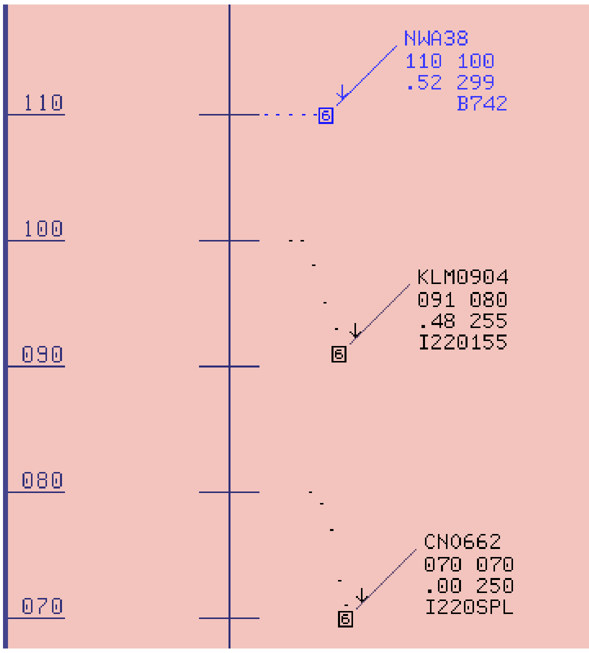

Figure 7. Snapshot of the "Vertical View". A holding stack display support tool for LVNL ATCos [13]. The colours in this figure have been altered for readability.

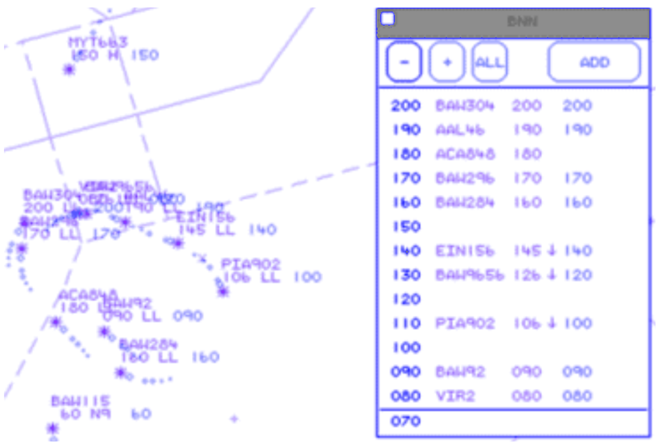

Figure 8. Snapshot of the "Vertical Stack List". A holding stack display support tool for NATS ATCos [14].

III. Display design

In this paper a novel display is introduced, named the "Stack Planner" or SP for short and is made up of 20 separate elements. Elements of the display are divided into three main sections. Namely the static elements, dynamic elements on the left hand side of the display and dynamic elements on right hand side of the display. For each element the shape will be described and reasoning for each will be elaborated upon.

The goal of this novel display design is to make improvements to the identified KPAs. This will be done within the

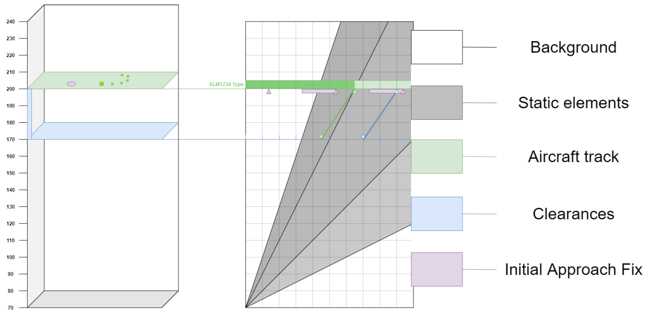

Figure 9. Final display design with colour language legend

bounds of what a stack controller is able to control. Initial design encourages control for accuracy. This is a feature which was lacking in previous display designs.

A. Colour language

Colour language is split into five main categories: Background, Static elements, Aircraft related elements, Clearance related elements and IAF related elements. A legend of these categories and their corresponding colours is shown in Figure V-C. Next to the legend is a display example. Colours were chosen to match industry standards.

B. Display overview

Two main control tasks have been identified and are analysed:

1) Lower aircraft to appropriate FL before clearing aircraft for approach in time for EAT
2) Align aircraft holding procedure with EAT using control actions

It was discovered that current display technologies support the first control task of lowering aircraft but not the second control task of aligning the aircraft with EAT. The lack of support for this second control task is likely the cause of difficulty for stack controllers to produce accurate deliveries. It must be noted that very accurate delivery is not important for safety of aircraft but rather important for efficiency. Now there are two main control tasks, one related to safety and one related to efficiency. The SP display gives support for both control tasks as will be discussed.

A short overview is given of all display elements. Figure 10 shows the final display with numbering of each display element and Table II gives a short description of each display element, corresponding to Figure 10.

C. Static display elements

Static elements of the display do not change over time. Information is presented as a backdrop and is meant to help an ATCo understand exact measurements of dynamic elements if they are required. In Figure 10, numbers 1,2,3,4 are all static elements. Element 1 has already been discussed in the colour subsection. Elements 2-4 will be explained in this subsection.

1) Element 2 - FL scale indicator: On the front left side of the stack volume, flight level indicators are shown with a scale from 70 to 240 (representative of Dutch airspace holding stack). These FL indications must be legible to the ATCO.

This will help ATCos determine exactly at what flight level an aircraft is flying. Other holding stack display strategies also use this technique in various means, such as holding stack support tools used by NATS described in Figure 8 and vertical display support tool as used by LVNL described in Figure 7. This is due to the importance of vertical separation in holding stack control. Stack controllers must control vertical separation much more precisely than lateral separation and it has been identified as the main control task corresponding with safety. The FL indicator will help controllers understand an aircraft's FL just as in the already implemented holding stack support tools. Flight level scale range corresponds with minimum and maximum holding flight levels within the controlled airspace. Because of the orthographic camera projection, constant shape language regardless of Flight level can be achieved as there is no shape warping from a traditional perspective camera projection.

2) Element 3 - Stack volume: The stack volume is a volume represented with three surfaces as a backdrop of the XY, YZ and XZ planes. Figure 10 shows how these planes are constructed and the volume that they encapsulate where the XY plane represent a plane parallel to the earth's surface and the XZ plane is oriented at right angles to the holding procedure's exit path. The holding airspace is meant to be encapsulated by this stack volume representation. The plane at the bottom of the stack volume represents the lateral plane which will overlap with the radar display. Other planes contain altitude information. The scale of the x,y and z axes are not one to one. An emphasis is lain on visualization of vertical separation, so the Y-axis will have scaling to help visualization. Lateral scaling will be one to one. The shape of the stack volume is viewed in an isometric projection camera frustum. The camera angle used to view the stack volume is chosen such that the depth of the aircraft plane will never overlap when tracks have a separation of 10 FLs.

Showing aircraft in the stack volume is meant to visualize constraints based on the holding airspace. Aircraft flying in this zone should appear in this volume. If an aircraft flies outside of this volume during a holding procedure then they are violating the holding airspace constraint. With this representation of the holding stack, ATCos will be able to improve their 3D situation awareness of the actual airspace they are responsible for. This section of the display is the main support for the first control task of guiding aircraft to the bottom of the holding stack while maintaining safe vertical separation. Dynamic display elements will move in reference to this stack volume.

3) Element 4 - FL/time grid with RoCD fan: Using a time axis in the X-axis and a vertical displacement in the Y-axis, a grid is displayed upon a plane named the FL/time grid. The grid units are 1 minute in the X-axis and 10 FLs in the Y-axis. Using these scales a gradient is drawn that represents a Rate

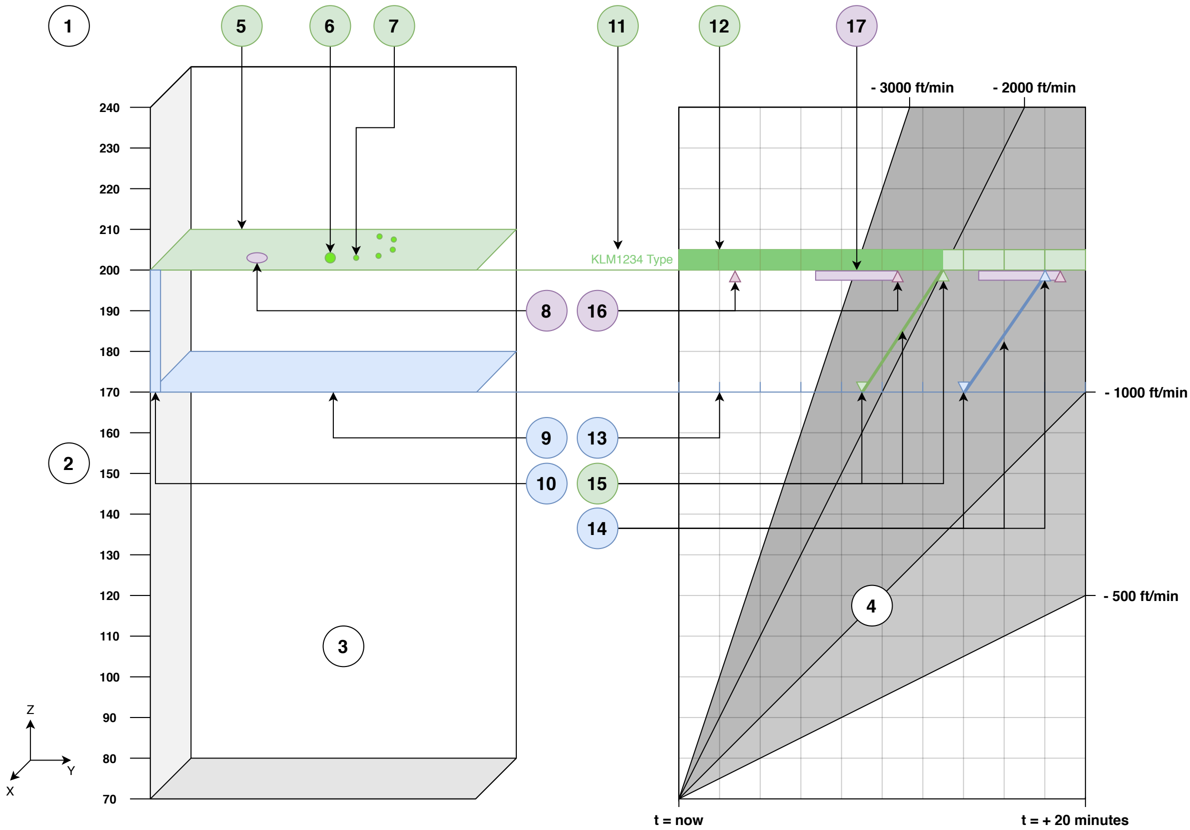

Figure 10. Final display design with display element number references

of Climb/Descent (RoCD). Four typical RoCDs are drawn to show the RoCD of 500 ft/min, 1,000 ft/min, 2,000 ft/min and 3,000 ft/min. Each of these RoCDs are drawn from the point of t=0 and FL 70. The minimum value on the time axis is 0 and the minimum value of the FL axis is 70. This means that each gradient will touch the bottom left graph. These gradients are called the "RoCD fan". Minutes on the x-axis are measured as "time from now until a given event". Figure 10 shows these RoCDs in bold on the right side of the figure.

Being a background display element, shades of gray are used for lines and areas. The RoCDs are shown darkening with each increasing step. RoCD below 500 and above 3,000 ft/min are given a larger contrast colour to differentiate from normal descent. Using this FL/time grid, a rate of climb provides information about how long an aircraft will take to reach FL 70 given different descent profiles. The chosen RoCD profiles are chosen as they represent a range of RoCDs that an average commercial airline might use to descend within an ACC sector.

Typical aircraft RoD values lie between 1500 and 3500 ft/min. When plotted on the FL/time grid a gradient is formed. ATCos can use these gradients to plan when their aircraft arrive at FL 70 based on when their given events occur. This element was added as an attempt to show the physical constraints of aircraft. It does not show exact physical constraints of aircraft but it does show a range of common profiles. This should be sufficient for an ATCo to understand what is a normal descent, if more communication in required and monitor the descent.

D. Dynamic display elements - Left side

Many dynamic display elements are included in this display. Included in the dynamic left side of the display are elements 5, 6, 7, 8, 9 and 10. Figure 10 shows these elements. All dynamic elements will change position on the display over time. Some will change shape. Each element will belong to only one instance of an aircraft. Each of the dynamic elements of the display will therefore be duplicated by the number of aircraft on the screen. There is one exception related to the clearances. If an aircraft reaches its clearance then the clearance-related elements will fade and disappear.

1) Element 5 - Aircraft plane: A cross-section of the aircraft track's vertical position. The aircraft plane will move with each track update, following the aircraft's track signal. Slight transparency in the plane will allow the controller to see the corners of the stack volume through the plane. A controller will be able to read an exact measurement of the aircraft FL when looking at the intersections between the aircraft plane and the FL scale indicator. This design is inspired by a common application of 3D navigation support often found in multistory shopping malls.

In a shopping mall there will often be a map to guide shoppers to their desired shopping destinations. On this map

Table II
OVERVIEW OF ALL DISPLAY ELEMENTS

#	Element name	Colour language	Element description
1	Background	Background	A background colour
2	FL indicator	static	Scale of flight levels in the vertical axis ranging from 70 to 240
3	Stack volume	static	Three planes which cover the backdrop of a holding volume
4	RoCD fan	static	Rectangle with grid. Large triangles situated within rectangle
5	Aircraft plane	Aircraft	A lateral plane within the stack volume intersecting aircraft position
6	Aircraft blip	Aircraft	Position of aircraft track within the stack volume
7	Velocity dots	Aircraft	Trail of dots left behind by aircraft track updates
8	IAF marker	IAF	Lateral IAF position within the stack volume
9	Cleared plane	Cleared	A lateral plane within the stack volume intersecting the aircraft's cleared flight level
10	Occupied flight levels	Cleared	A bar stuck to the FL indicator, the aircraft plane and the cleared plane
11	Aircraft information	Aircraft	Information on aircraft callsign and type
12	Aircraft timeline	Aircraft	Timeline situated on top of RoCD fan and connected to aircraft plane
13	Cleared timeline	Cleared	A timeline situated on top of RoCD fan and connected to the cleared plane
14	RoCD markers	Cleared	An event intersecting both timelines with a line connecting the two. Gradient is determined by RoCD
15	EAT	Aircraft	An event present on both timelines with a line connecting the two. The gradient is determined by the RoCD
16	IAF flyover	IAF	Repeating event markers with frequency equal to holding procedure duration
17	IAF flyover variability	IAF	A bar connected to the IAF event which stretches to the left. It will only stretch to two minutes after the previous IAF event and/or two minutes after the left side of the RoCD fan

can be found a lateral plane for each story. It is on the plane that the lateral information is found. If a shopper wishes to navigate to a shop on another story, there will be multiple steps to reach such a destination. First the shopper must navigate to the escalator/elevator. This is lateral navigation. Secondly the shopper must navigate to the correct floor. This is vertical navigation. Then the shopper must again navigate laterally again to their final destination.

Likewise in Air traffic control it is apparent that accuracy of delivery proves difficult to control for when given only a side view of an airspace is displayed. Adapting this shopping mall map is an attempt to heighten the ATCo's cognition with regards to their spatial understanding of the system. The extra lateral information on the screen may prove helpful for a controller's understanding.

This simplifies a 3D spatial navigation problem into simpler 1D and 2D spatial navigation problems. This design attempts to make use of this simplification to provide 3D spatial information at a lower cognitive cost. Understanding what FLs aircraft fly at is the most important feature of any holding stack display. If FL information is obscured, then the vertical separation constraint may be put at risk. This is absolutely unacceptable for safety. Because of the orthographic projection, each distance has consistent representation no matter the position in the display. Because of the chosen camera angle described earlier, aircraft planes will never overlap if separation constraints are met.

2) Elements 6 and 7 - Track blip with velocity dots: A similar indicator shape as that used on the radar screen will be used to represent an aircraft track's position. Velocity dots will trail from this position to indicate an aircraft's speed with the same rate as on the radar screen. The indicator will coincide with the aircraft plane. The velocity dots will be projected onto the aircraft plane. A controller will be able to interpret past present and, to an extent, future states.

Track updates are given at very low frequencies of the order 0.1 - 0.3 Hz. This hampers intuitive understanding of aircraft speed and direction. Velocity dots help the ATCo perceive speed and direction as well as improve cognition of the system. Furthermore, keeping similar shape and colour language helps consistency when ATCos switch between displays.

3) Element 8 - IAF marker: A circle projected onto the aircraft plane represents the IAF lateral position. This circle represents the relative position of the holding procedure compared to the stack volume. Aircraft are expected to fly over this point in the cross section once per holding. The position of this marker will depend on right hand turn or left hand turn holding stacks. The position of the waypoint is placed so that the aircraft is in line with exiting the left hand side of the stack volume.

4) Element 9 - Aircraft cleared plane: A plane with identical features to the aircraft plane is situated on the intersection of the cleared flight level of the aircraft. This acts as a virtual image showing a prediction of where the aircraft will be once it reaches its cleared flight level. There is only a difference in colour language and Y-axis position. The transparency of the plane will fade from 0.3 to 0 when the aircraft plane moves close to the cleared plane.

5) Element 10 - Occupied flight levels: A bar connecting aircraft plane and aircraft cleared plane. This bar is attached to the FL indicator. This cleared connection is a representation of the flight levels that are unavailable for other aircraft. Any flight level next to this bar is unavailable for other aircraft to be cleared for. Other aircraft may also not be cleared within 10 flight levels of this occupied space.

6) Element 11 - Aircraft information: Connection between aircraft plane on left hand side of display and time relevant information of that aircraft on right hand side of display. Additional information containing aircraft callsign, aircraft type and flight level are displayed hovering above this line.

All of the information on the left side of the display is connected to the right side of the RoCD fan. A connection will help ATCos to manage the distance between the two representations of information. A similar line connection without aircraft information connects the aircraft cleared plane with the cleared timeline.

E. Dynamic display elements - Right side

Dynamic elements that belong to the right side of the display include elements 11, 12 ,13, 14, 15, 16 and 17. Figure 10 shows these elements.

1) Element 12 - Aircraft timeline: The aircraft timeline is positioned at the same FL as the aircraft plane. The timeline is linked to the left side display. The "now" time of the display is shown on the left hand side of the grid and the timeline moves to the left at a rate of 1 unit per minute. Each event on the timeline will follow Equation 2. Important events on the timeline are EAT, IAF flyover and time until FL 70 is reached.

$$time\ until\ event\ = t_{event} - t_{now} \tag{2}$$

Relevant events to control of the aircraft will be displayed on this timeline in real-time. This representation of is useful for ATCos to plan their control actions. The RoCD fan helps the controller understand how the current RoCD will effect the aircraft's future states. It will also show how long it will take to reach FL 70 given different RoCDs based on the timeline intersect. If an aircraft is descending too slow or too fast, an ATCo can give commands accordingly. The time until a certain event is given by Equation 2. Figure 11 shows a graphical representation of how events may be displayed on the timeline with the exception of EAT.

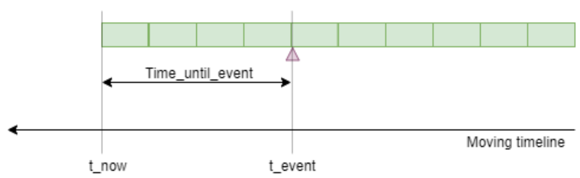

Figure 11. Timeline element of display with reference to Equation 2

2) Element 13 - Cleared timeline: A timeline showing a predicted future state of the aircraft once it reaches its cleared FL. To reduce the complexity of the display, this timeline has been kept simple and will only show two events. Namely: EAT and time until FL 70. The events portrayed on this timeline are simple projections based on current descent rates.

3) Element 14 - RoCD timing: A calculation is made using current RoCD revealing how long the descent may take to reach FL 70 from current FL if uninterrupted. This calculation can be done for any FL using Equation 3 where RoCD is positive in climb and negative in descent. The RoCD marker will appear as a triangle underneath the cleared timeline, marking the predicted duration that it will take to reach FL 70. A similar calculation is made for the time to reach the cleared flight level. A RoCD marker is displayed on the cleared timeline as an event representing time to reach FL 70 after the cleared flight level is reached. A line connects the RoCD event on the aircraft timeline and the cleared timeline. The gradient of this line will match the RoCD fan perfectly.

$$timeuntiltargetFL = (FL_{target} - FL_{current})/RoCD \tag{3}$$

The RoCD fan will help the ATCo understand approximate RoCD values without having to read exact values. When the aircraft approaches level flight, its RoCD will be near zero. As a result, the gradient of the RoCD will end as a straight line and the marker will tend to infinity. The ATCo will be able to quickly conclude that the aircraft has RoCD of near zero if there is no marker present. There is also a transition period between level flight and descending flight. There is also a short delay necessary for ATCo to pilot communication but this will be relatively small.

4) Element 15 - EAT: This is one of the most important events on the aircraft timeline, as this is the time at which the aircraft is to leave the holding stack. ATCos have no control actions that change EAT and will therefore take EAT into account when controlling for accuracy. Accuracy is the second main control task controlling for accuracy of delivery, an efficiency related control task. With this event displayed on the timeline, ATCos are able to perform control actions to shift other events in favour of EAT. EAT events are shown on the aircraft timeline and the cleared timeline. The EAT event shown on the aircraft timeline is represented as a depletion bar to stand out from other timeline events.

5) Element 16 - IAF flyover timing: An event displayed on the aircraft timeline. This event represents each time the aircraft is planned to fly over the IAF. Because of the nature of a holding procedure, the flyover time will repeat itself with a frequency equal to the holding procedure duration.

The duration of a holding procedure is predominantly reliant on leg time and is described in Equation 4 where t_{IAF} is the time until an IAF flyover, N represents the holding procedure sequence number, $t_{holding}$ is the total holding procedure duration and $t_{lastIAF}$ is the time since the last IAF flyover occured.

$$t_{IAF} = N * t_{holding} - t_{lastIAF} \tag{4}$$

6) Element 17 - IAF variability: A bar attached to the IAF flyover event serves as a visual representation of all possible shortenings that the IAF flyover timing can take. This will help ATCos interpret the constraints of the holding procedure in the one dimensional language of a timeline. The minimum holding procedure time is shown as a constraint for IAF variability. Figure 12 shows how the bar will decrease in size over the course of an aircraft's position.

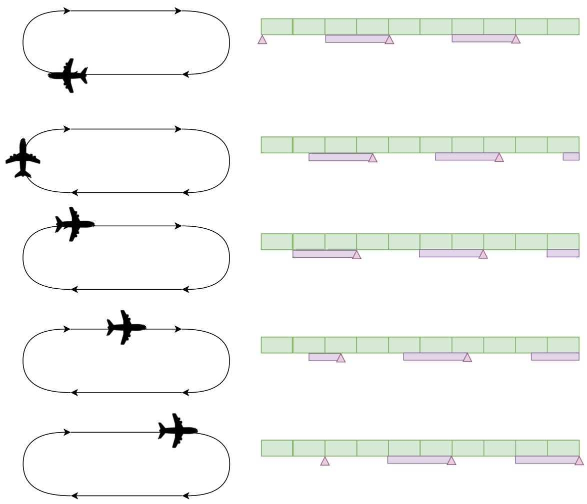

Figure 12. IAF events - Evolution of standard holding procedure

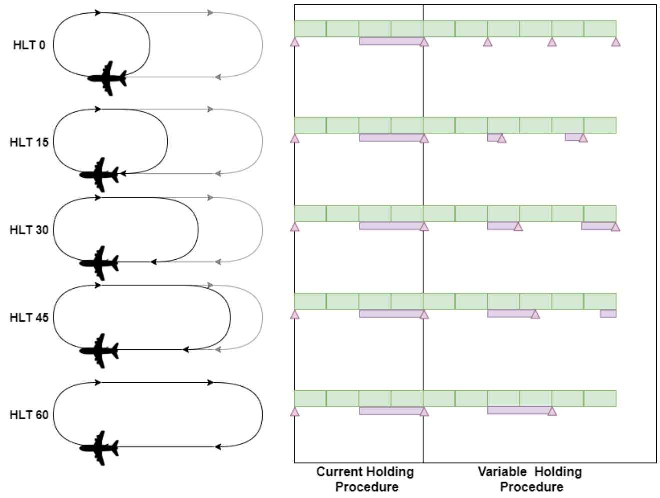

Figure 13. IAF events - variable HLT

Figure 13 shows five different HLT commands and how this command effects the holding procedure's shape and IAF variability. The timeline in the image is split in to two sections: Current holding procedure and variable holding procedure. This is because before a new holding leg time will be taken into effect, the current holding must first be completed. In this figure a standard four minute holding has just begun and after a standard holding procedure the new holding will take effect. In the Variable holding procedure section of the figure it can be seen how the HLT command effects the minimum duration of a holding procedure and in turn how the total duration of this holding procedure unfolds over time, well into the future. Notice how the holding procedure shape changes during the variable holding procedure section based on leg time.

Combining the information shown of the IAF flyover element with the IAF variability element of this display, a strategy can be formed and appropriate control actions can be executed to improve accuracy of delivery. In this version of the display, only a change in holding leg time is enough to reach an accurate delivery.

F. Concluding remarks

The goals of this display are to increase all KPAs. An improvement in accuracy of delivery, situation awareness, workload and system acceptance is desired. The baseline display has both control tasks of descending aircraft and accurate delivery requiring the air traffic controller to mentally align the aircraft with the exit time of the aircraft. Exit time must be aligned with both FL and EAT using knowledge-based behaviour. Using this novel display, each event is displayed on the timeline and both tasks become rule-based behaviour as the task is transformed into a one dimensional error handling control task. Rule-based is generally governed by IF-THEN rules, for example: IF timeline event symbols do not align, THEN execute holding leg time command to align symbols. Another example: IF arrival time at FL 70 event symbol is behind EAT AND EAT is within ROD fan, THEN execute a RoD command to move arrival event symbol in front of EAT event.

Experiment results and analysis in the final part of this paper will attempt to explain how effectively these tasks are supported.

IV. Experiment setup

The experiment conducted had a between-subjects design. The experiment was held with eleven participants. Five participants, experienced with an air traffic control course from NLR, were to use a baseline setup for holding stack control. Five other participants experienced with the same air traffic control course were to use the novel SP display for holding stack control. Finally a professional ACC used the SP display for holding stack control. The results and comments of a professional ACC are meant as a check that indeed the novel display fulfills the needs of a stack controller. Many insights can be brought to light that other participants may miss.

A. Participants, Instructions and Procedure

Participants with domain knowledge were conducting the experiment. Most participants never did any holding stack operations and had to learn desired goal states, available control actions and potential control strategies. This was done to eliminate any misunderstanding of display functionality both for baseline and SP displays. Control tasks and strategies were introduced as measures to achieving goal states using available control actions. This was done in form of a combination of explanations and test scenarios.

Three hours were allocated for experiment design. Most of the experiment time was dedicated to training as holding stack control is considered a complex task. Next to training, a main scenario was held for data collection. Because of the nature of holding procedures, a lot of time was dedicated to this section of the experiment per scenario to enable data collection of the main experiment. Also included in the experiment

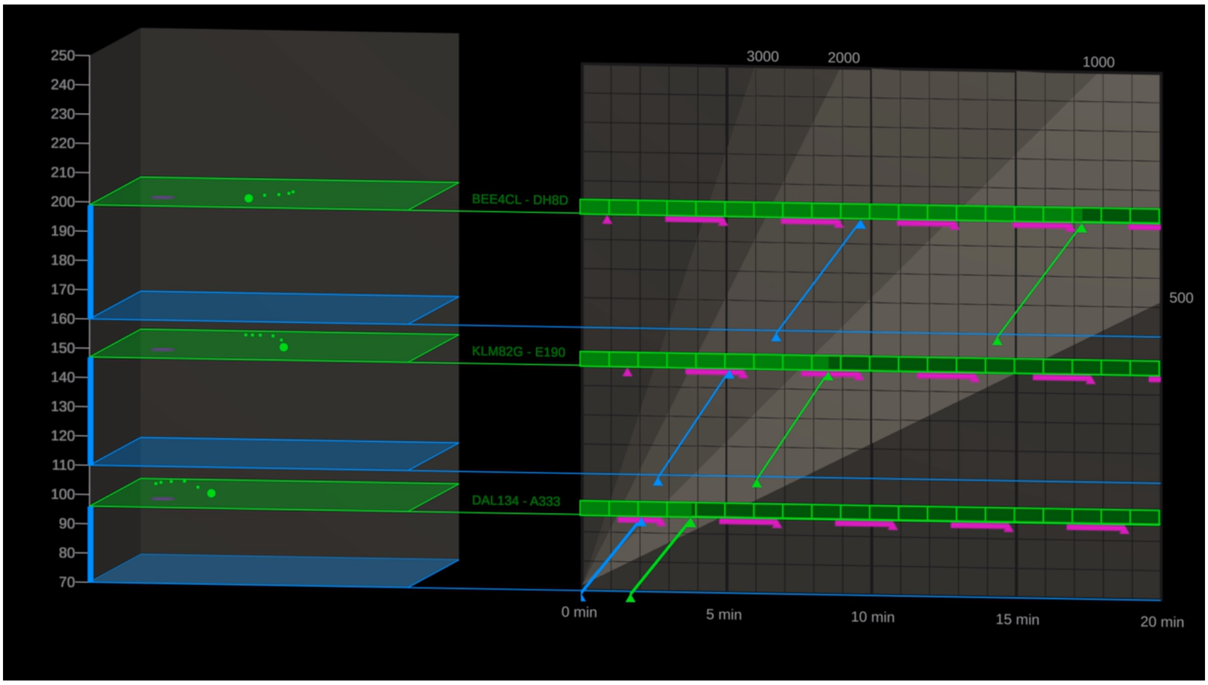

Figure 14. Screenshot of final display build

was a small amount of time for a short intro, some time for leniency in training and some time for a questionnaire after the data collection scenario has ended. The experiment procedure was held as follows for the baseline participants as well, the SP participants and the experienced ACC. The experiment training scenarios are divided into a scenario for introduction to controls, a scenario for introduction to vertical separation safety control task, a scenario for the accuracy of delivery control task and finally a scenario reflective of the data collection scenario of the experiment. The experiment structure used for both displays was as follows:

1) Introduction to experiment
2) Basic training presentation
3) Basic scenario for familiarizing with controls
4) Introduction to holding procedures and vertical control presentation
5) Training scenario on vertical descent, vertical separation and rate of descent
6) Presentation on accuracy of delivery control task for holding stack control
7) Training scenario on accuracy of delivery
8) Break / half way mark
9) Training scenario comparable to main scenario for data collection. Once participant is comfortable with this scenario, main scenario can be executed.
10) Main scenario
11) Questionnaire
12) End of experiment

Roughly two out of three hours of the experiment was spent on preparing the participant for the main scenario to minimize the learning effect.

B. Apparatus

The NARSIM environment developed by NLR is an high-fidelity air traffic control simulation environment. NARSIM is a research tool often used for concept development and validation, prototyping of new ATC systems and training [15]. In order to interface with NARSIM, new code has been developed in the C# programming language. This code allows the display to receive data from the NARSIM environment. The display has been developed in the Unity3D game engine, enabling 3D environments, shaders, camera projection type manipulation as well as many more options for future development including Virtual Reality (VR) and Augmented Reality (AR).

Baseline participants involved were seated with a mobile setup of NARSIM. SP participants had this mobile setup of NARSIM and the novel display situated next to the baseline display. Both participant groups had full view of LVNL's lateral radar display and LVNL's vertical view display situated on the same screen as the radar display.

Only the SP participant group had access to the novel SP display during the experiment. Participants used command inputs in order to control air traffic. Control actions were executed by inputting commands to NARSIM. This was done by selecting an aircraft with the mouse and then inputting a clearance with the terminal. The available control actions are:

- UCO: Take aircraft under control
- EFL: Clear aircraft forExecutive Flight Level
- ROD: Command Rate of Descent
- HLT: Holding leg time command
- HDG SPL: Exit aircraft from stack

Many of these control actions are familiar to all participants. Aircraft would respond to command inputs using NARSIM's simulation of an aircraft's autopilot system.

C. Scenarios

Under normal circumstances ATCos in the Netherlands have been trained to avoid the use of holding stacks. This is not in the best interest of conducting a feasibility study for this novel display which attempts measure KPAs during holding stack management. For the course of this experiment it was therefore reasonable to include an assumption which makes holding stack operations standard procedure. This was done for all incoming flights scheduled to land at Schiphol airport. During the experiment a single IAF was chosen above which all holding stack operations are conducted. The IAF in question is RIVER.

Because each test run may include multiple standard holding procedures with a duration of 4 minutes, the training and experiment duration was relatively long. For a single participant to guide multiple aircraft to the bottom of a holding stack took a fair amount of time. This was why only one scenario was possible for gathering data and why it was not feasible to train all participants for both displays.

The available control actions during this experiment included:

- Take an aircraft under control
- Clear aircraft for a FL
- Change an aircraft's holding leg time
- Exit an aircraft from a holding stack

When designing a scenario, the question "What is a challenging traffic scenario?" emerges. It was theorized that aircraft delivered at a specific time at IAF could have a paired EAT which requires little effort to solve as a stack controller. This can be done by extrapolating multiples of standard holding times of 4 minutes and then checking if the aircraft is approaching IAF near its EAT. It would effectively be in or near the solution space of a regular holding procedure without any timing input from a participant.

Likewise it could be made challenging by having the EAT occur outside of the solution space. Say if the aircraft without any timing input will have passed over the IAF 40 seconds before EAT. This would put the aircraft in an awkward exit strategy from a holding procedure. To prevent this scenario a participant would have to anticipate this and make corrective actions. This would be a more challenging scenario than when the EAT occurs inside the solution space.

As it was uncertain how complex a holding task would be for novice stack controllers who just learned to control aircraft in holding, a fairly simple scenario took place as the main data collection scenario. It was hypothesized that especially baseline participants would struggle to control for accuracy delivery without any support tool for accuracy of delivery.

The final scenario included a steady stream of incoming aircraft all which would spend approximately 15 minutes in a holding stack before exiting. The start of the scenario had only 1 aircraft in the stack. The experiment duration allowed for 5 aircraft to exit. What differed from conventional ATC compared to the experiment scenario is that aircraft would enter a holding stack as standard procedure, thus arriving at RIVER early and at a higher altitude. This was necessary to force usage of the novel tools available to participants.

D. Independent variables

The independent variables in the experiment for this paper define the factors with which the experiment is deliberately manipulated. The independent variables in the experiment were limited to a single between-participants variable: display type with BASE and SP.

E. Control variables

To remove experiment confounds, control variables were introduced, simplifying experiment parameters compared to real-world application. Control variables included:

- Simple weather conditions
- Aircraft will respond to controls exactly without time delays
- All aircraft in experiment have FMS and MCDU
- The altitude at which Aircraft are initialized
- Aircraft EAT
- Type of aircraft in experiment are limited to A320, A333, B737, B738, B763, DH8D, E190 and PC12 .
- Number of aircraft in scenario
- The IAF RIVER will be used for holding stack management
- Holding turn takes exactly 1 minute
- Flight computers are able to execute holding procedures exactly as defined. Four minute standard holding procedures and variations in leg time is executed exactly
- Aircraft will communicate programmed holding leg time. This is currently not done in industry.
- Holding stack is standard procedure

Simple weather conditions were defined as weather conditions with no wind, standard atmosphere and good visibility. These conditions are required for all aircraft to have similar Aerodrome operating minima, irrespective of aircraft type.

F. Dependent measures

A combination of subjective and objective dependent measurements were taken to gain insights on KPAs:

1) Objective variables
    - Interval between holding stack exit time and EAT
    - Type of control action taken by participant
    - Number of control actions taken by participant
    - Time at which control action is given
    - Aircraft attitude over time
2) Subjective variables
    - Situation awareness
    - Workload
    - System acceptance

A questionnaire was adapted from the Situation Awareness for SHAPE (SASHA) [16] questionnaire template to measure situation awareness. Rating Scale Mental Effort (RSME) [17] will be included to measure perceived workload. A modified Cooper Harper will be used to measure system acceptance using a Controller Acceptance Rating Scale (CARS) [18]. These methods of measurement have been adopted to this experiment and differ slightly from their origins. For example: the SASHA questionnaire has been altered to include feature-specific questions related to the novel SP display. Software will be able to measure objective data such accuracy of delivery. Feature-specific questions on the questionnaire differ slightly per experiment group as there are some features not present in the baseline but present in the SP. Most questions in the questionnaire are posed in the form of a Likert scale.

G. Hypotheses

The following hypotheses have been drawn on how KPAs change depending on which display is used:

- Situation awareness was predicted to increase for the SP display. There is a risk that SA is decreased due to display complexity and display clutter. The prediction, however, was that the added features would benefit the participant in a manner which will increase cognitive understanding of the system and therefore also benefit the participant's SA.
- Workload was predicted to instead of have a peak before an aircraft exits, flatten over the lifetime of this aircraft. Because the workload of the accuracy control task has been shifted from FL 70 to any FL, participants may have reduced workload once the aircraft reaches FL 70 but increased workload elsewhere. The participant is then able to choose when to execute their control actions and this will likely not be all at one peak.
- Controller acceptance was predicted to increase with the addition of the accuracy of delivery support in the SP.
- Accuracy of delivery was predicted to increase. Time between exit and EAT is predicted to go down as the novel display has a dedicated support tool for reduction of this interval. The lack of a support tool for ATCos when it comes to accuracy of delivery was one of the main drivers of this study. Current accuracy of delivery has a guideline of ± 2 minutes and is typically around 1 minute.

V. Results

Results are gathered from five baseline participants, five SP participants and one professional ATCo specialized in ACC. ATCo results will be considered separate from this comparison as the experience difference will be substantial. The results of the SP can in turn be compared with the results of the ATCo to see an effect due to experience. Due to such a small sample size, statistical analysis techniques reliant on normal distributions are avoided. Instead the statistical significance of the objective results are measured with a non-parametric, Mann-Whitney U test. For all tests a significance threshold of α = 0.05 is taken. No statistical test comparisons are done with the ATCo due to the participation of only one ATCo.

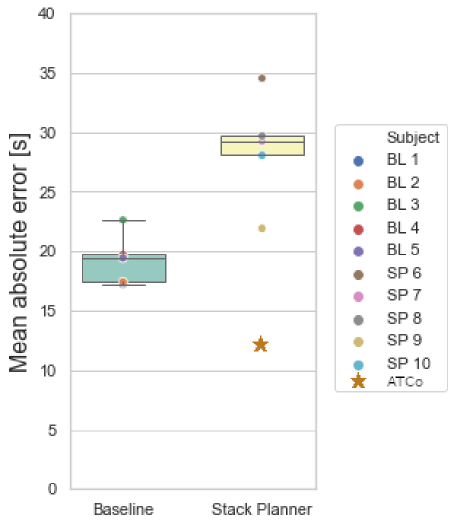

Figure 15. Accuracy of delivery

A. Control task results

To analyse the objective data from the experiments the data have been plotted in box plot format in addition to the Mann-Whitney U test. Accuracy of delivery is seen to degrade when using the novel SP display as seen in Figure 15. Furthermore the Mann-Whitney U test shows that there is a statistical significance in the degradation of accuracy (U = 1.000, p = 0.016). While the difference in accuracy is statistically significant, the baseline participants seem to have overperformed when considering an expected accuracy around 60 seconds as hypothesized. The chosen scenario was likely not complex enough, giving the baseline participants a chance to perform at a similar level to SP participants. Showing that SP participants managed to perform close to this impressive baseline performance shows, however, that the display is manageable given the chosen scenario. Considering the strategies used by both groups it was noted that baseline strategies relied on specific knowledge of a simple scenario. This strategy used Knowledge Based Behaviour to solve the accuracy control tasks while the SP strategies did not rely on the simplicity of the scenario. Instead, SP participant strategies relied on Rule Based Behaviour, letting the display organise complex information for the participant.

To get a better insight of the strategies used to control aircraft, the time of a given command can be analysed. Commands given to each individual aircraft are put on a normalized scale based on what time this command is received in the aircraft's lifetime. The formula for understanding a normalized command time is as follows:

$$t_{cn} = (t_c - t_{first_IAF})/(t_{last_IAF} - t_{first_IAF}) \qquad (5)$$

Where t_{cn} is the normalized command time, t_c is the command time, $t_{firstIAF}$ is the time at which the aircraft

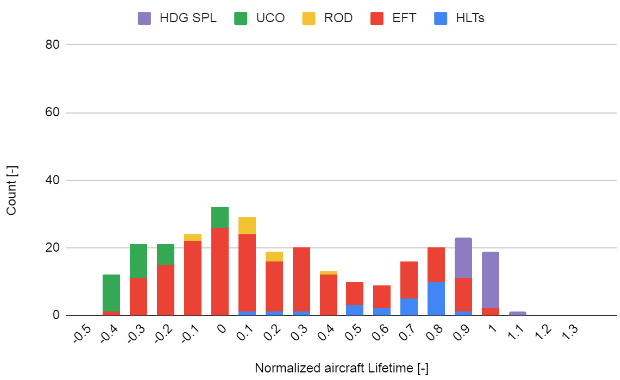

Figure 16. Number of commands over aircraft lifetime - Baseline

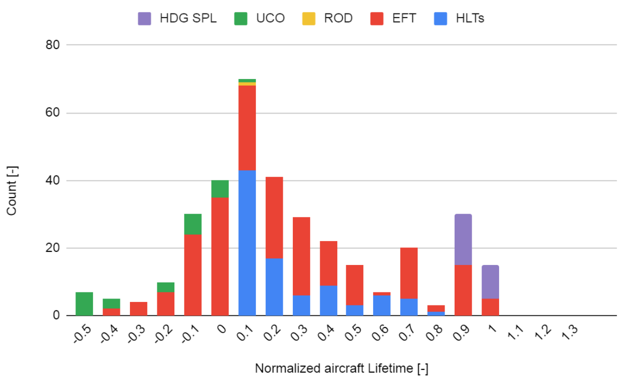

Figure 17. Number of commands over aircraft lifetime - Stack Planner

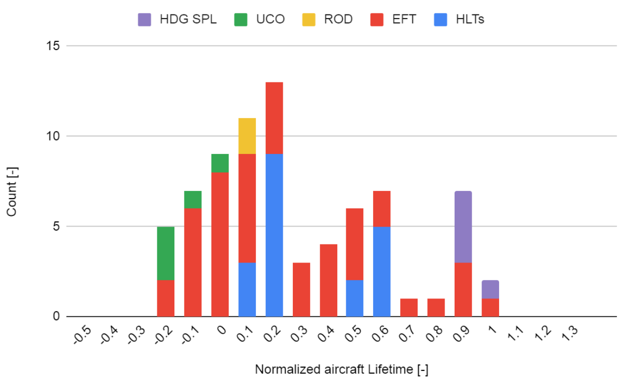

Figure 18. Number of commands over aircraft lifetime - ATCo

first flies over the IAF and $t_{lastIAF}$ is the time at which the aircraft last flies over the IAF on its way to approach.

Figures 16, 17 and 18 can be compared to see the times at which different commands are given. In these figures a histogram is shown where each color represents a different command given at a given interval in the aircraft's lifetime. No differentiation is made between participants within their group or aircraft in this histogram. Intervals are divided into buckets of 0.1 width along a normalized scale. The total time each aircraft spends in the holding stack varies slightly but is relatively close and has a mean time of 14.7 minutes, giving each bucket an approximate time of $\pm$ 1.47 minutes. When comparing the baseline graph to the SP graph, fairly similar patterns emerge concerning all commands except for one: HLT. The first point of attention must be drawn to the amount of HLT commands given during the SP experiment is far greater than that of the baseline. This is likely due to the design of the experiment and display where participants would probe a number of commands to see if their command achieves their goal. Commands are given freely and a system is likely necessary to reduce this command count due to probing. Next to this it seems that there is a difference between HLT peaks between the two displays where there is a peak near the end of life for the baseline and a peak near start of life for the SP. Here is observed that the baseline participants are solving the accuracy control task near the end of the aircraft's life which is very close to EAT. This leaves little room for error. The SP participants, however, were confident enough to make initial control actions related to the accuracy control task much earlier, often more than 10 minutes ahead of baseline participant HLT commands. This seems to show SP participants using a more holistic approach to holding stack control, performing control actions early in an aircraft's lifetime to improve the situation near the end of its lifetime. There is a lot of time to correct any mistakes made before the aircraft is near EAT and corrections are likely minor.

This notion is reinforced by the results from the ATCo whose strategy involved an early HLT command for an initial correction followed by a later command near EAT for a final correction if there were any inaccuracies that arose during the aircraft's lifetime shown clearly on Figure 18. This very same ATCo made suggestions on a potential new strategy which could be combined with the SP display. This suggestion strongly reflects how the aircraft were controlled in the experiment. It was suggested that an initial control action could be placed to give an initial nudge to place the EAT in the aircraft's solution space. Later errors may accumulate after which a final command could correct this with a minor alteration.

Comparison between command times are further analysed with box plots in Figure 19 as well as Mann-Whitney U tests as shown in Table III. Table III shows that the only measurements that have a difference between displays which is statistically significant is accuracy and mean HLT. Other measurements all have P-values above 0.05 which is not statistically significant. This was anticipated with the control strategies, tasks and actions being fairly similar between displays when operating outside of the accuracy control task. Referring back to Figure 18, it seems that the ATCo's control timings for these tasks do not deviate significantly from baseline or SP results. Finally the control action of ROD was barely used by any of the participants which was also anticipated as this scenario did not encourage such control actions. ROD commands therefore did not aid in controlling air traffic and was barely used.

Table III
MANN-WHITNEY U TEST RESULTS FOR OBJECTIVE DATA AND RSME

	Accuracy	Mean UCO	Mean EFL	Mean HLT	Mean HDG SPL	RSME
Mann-Whitney U	1.000	12.000	6.000	0.000	3.000	4.000
Z	-2.402	-0.104	-1.358	-2.611	-1.984	-1.786
P 2-tailed	**0.016**	1.000	0.222	**0.008**	0.056	0.095

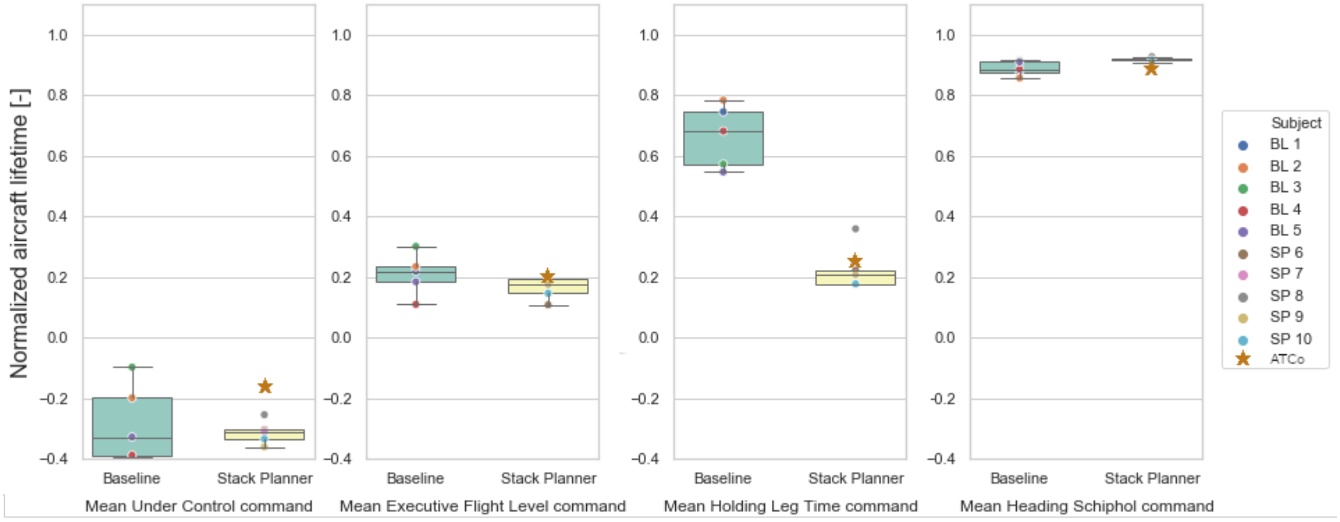

Figure 19. Commands over aircraft lifetime

B. *Controller acceptance*

Figure 26 shows results based on subjective data related to controller acceptance. It shows that both displays are fairly well designed for controller acceptance with only one outlier in the baseline who found the display difficult to use for stack control. This is an indicator that there are likely no major design flaws from a participant's perspective as they are able to use both displays for the intended purpose. There is, however, still room for improvement. The questionnaire filled in by baseline and SP participants cover individual display elements. One display element present in both display shares the purpose of helping a controller understand an aircraft's position and orientation. These display elements are the vertical view and the stack volume. Figure 27 shows that participants are using the stack volume for its intended purpose more than the vertical view. Notably the ATCo who had more experience controlling aircraft did not feel the need to use the stack volume for understanding aircraft attitude. This may be because prior training helped him understand this by other means.

Other useful display elements only present on the SP include the Timeline as seen in Figure 28, the cleared flight level as seen in Figure 29, and the IAF flyover frequency as seen in Figure 30. The main display element which proved to be unpopular regarding its intended purpose is the RoCD fan as can be seen in Figure 31. Display element RoCD fan also had mixed opinions about its usefulness as can be seen in Figure 20. Comments regarding the usefulness of this element however are mixed. What seemed to happen is that participants used the RoCD fan for a quick check if an aircraft would reach its cleared flight level on time in conjunction with the connection between timelines instead of its intended purpose of showing an aircraft's rate of descent. The opinions formed for this display element may be due to the simple traffic scenario where there was no incentive to change an aircraft's RoD. Future experiments may yield different results.

The display element "Connection between timelines" has proven to yield mixed results as can be seen in Figure 21. This is likely due to the close relationship with the RoCD fan and how this display element was received. Comments were very similar to comments received for RoCD fan, mentioning that it was being used as a quick visual check for timing rather than an understanding of RoD.

Overall the display elements of the SP seemed to be accepted by participants. This is reflected in both objective and subjective results.

C. *Workload*

In Table III it can be seen that the difference between the two groups regarding RSME are too small to be statistically significant. It is, however, clear that there is a higher workload for some participants of the baseline. This is backed up with comments from SP participants who found that they experienced an acceptable workload which was neither too high nor too low. When observing participants during the experiment there was a clear difference in body language where baseline participants seemed to be working harder than SP participants.

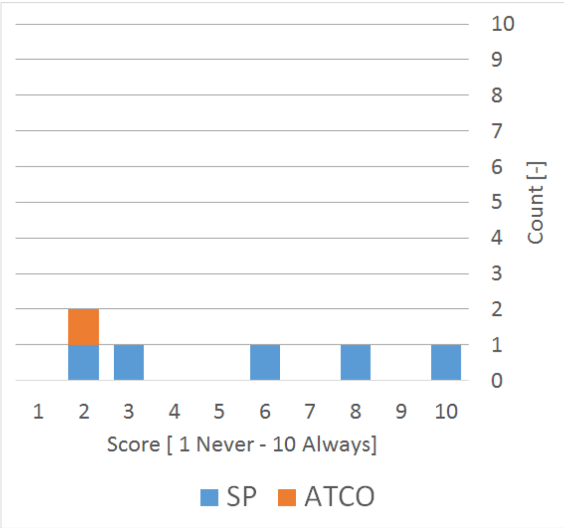

Figure 20. Do you think the RoCD fan provided you with useful information?

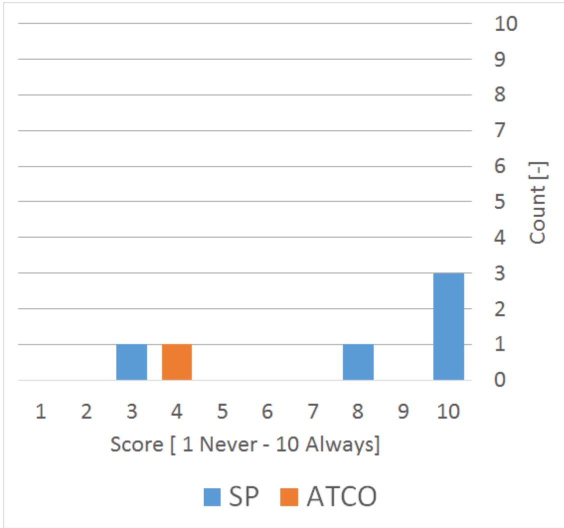

Figure 21. Did the connection between timelines help you to understand if the aircraft would reach FL 70 on time?

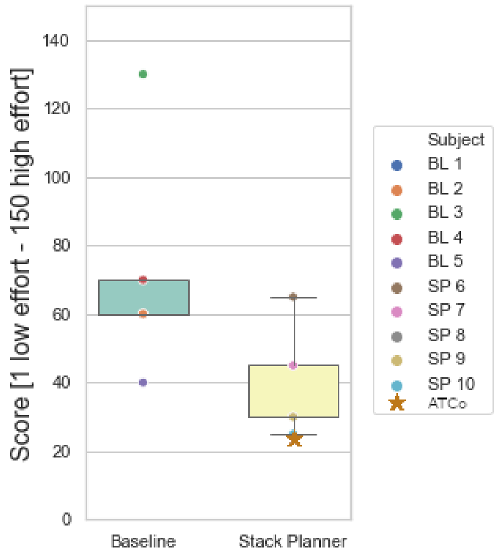

Figure 22. Rated Scale Mental Effort (RSME)

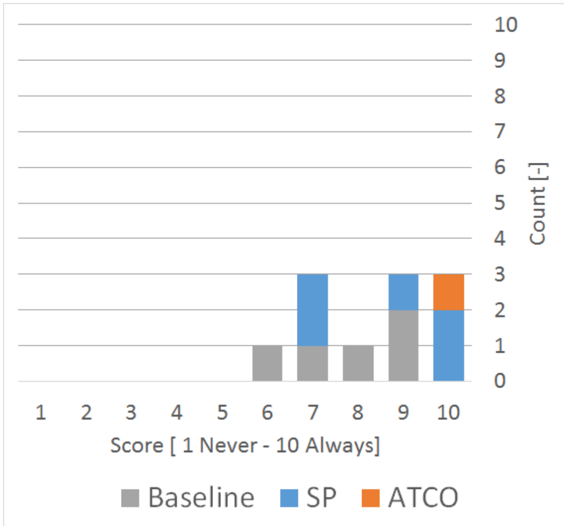

Figure 23. Did you have the feeling that you were ahead of the traffic, able to predict the evolution of the traffic?

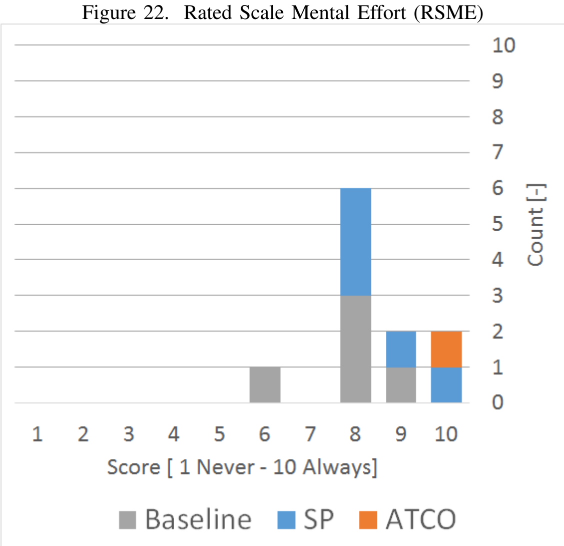

Figure 24. Did you have the feeling that you were able to plan and organise your work as you wanted?

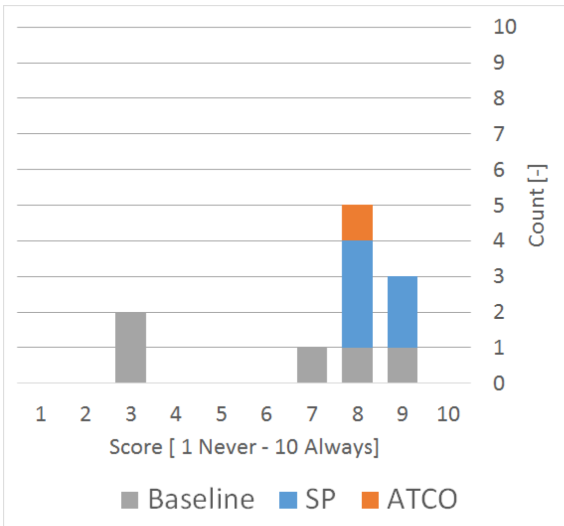

Figure 25. Were you able to avoid focussing too much on a single problem and/or aircraft?

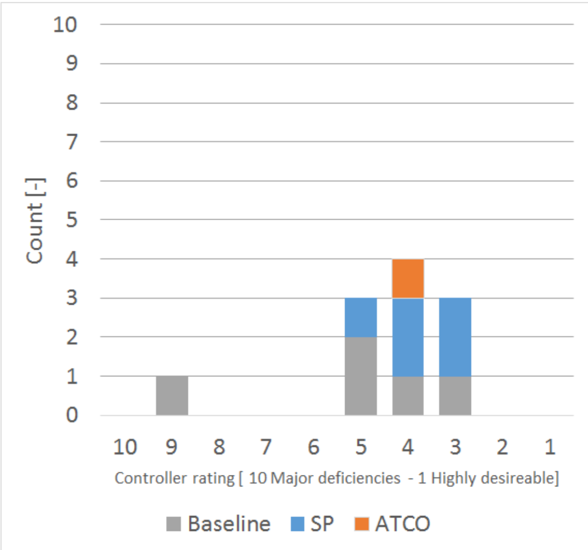

Figure 26. CARS - Controller Acceptance Rating Scale

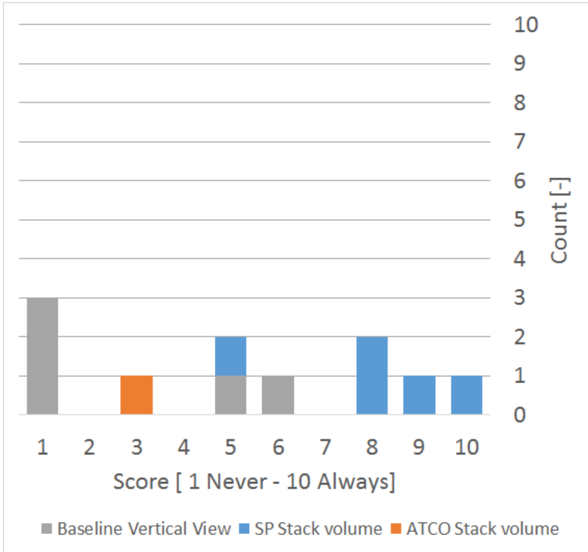

Figure 27. Did the Vertical view / Stack volume help you understand the spatial position and orientation of each aircraft in the stack?

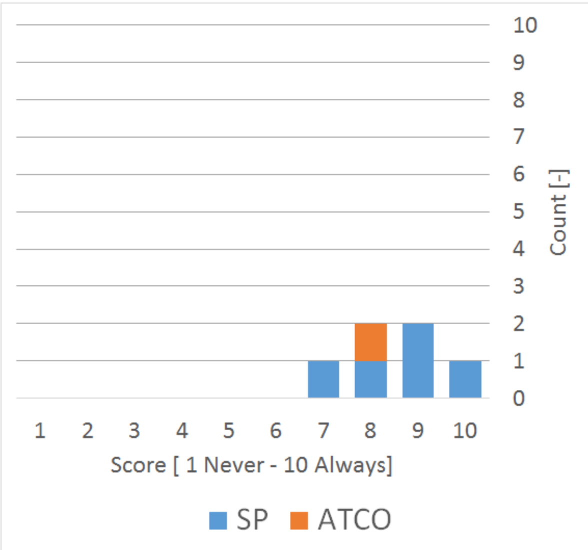

Figure 28. Did the Timeline help you understand future events for each aircraft?

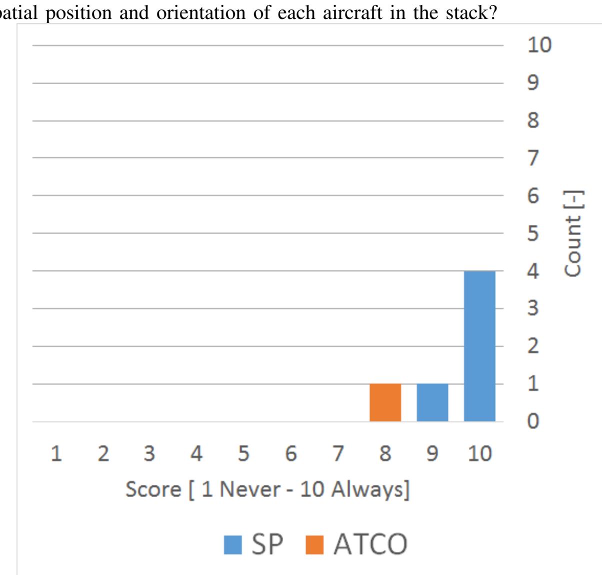

Figure 29. Did the cleared flight level help you to understand the aircraft's target flight level?

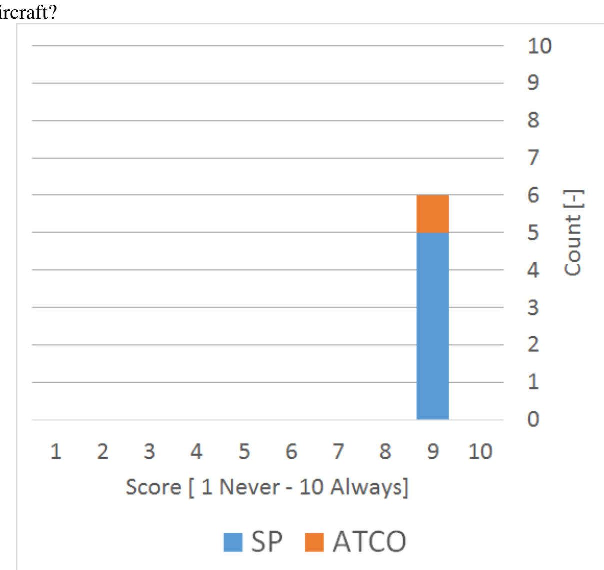

Figure 30. Did the IAF flyover frequency help you with a more precise exit?

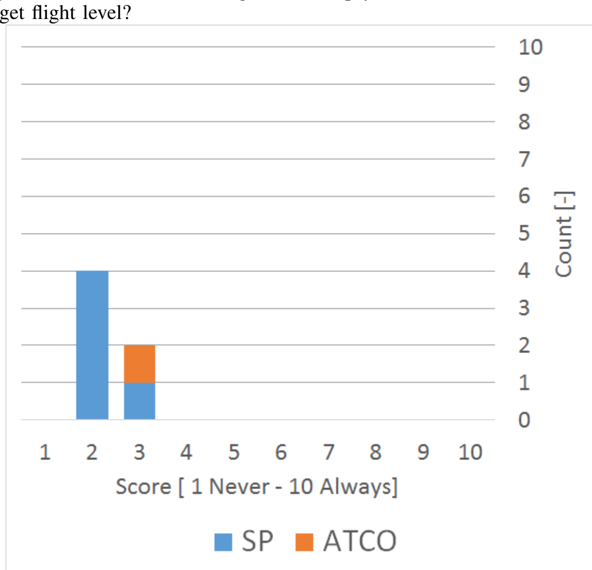

Figure 31. Did the RoCD fan help you plan vertical transition of aircraft?

Figure 22 shows box plots related to perceived workload measured with RSME. There was a case with one baseline participant where there was a safety violation close to the end of the experiment. The participant gave two aircraft the same FL clearance risking a catastrophic mid-air collision. This was not averted on time and the experiment ended around the same time. This is likely due to lack of experience in holding stack management using the baseline display.

D. Situation awareness

Figures 23 and 24 show results from the questionnaire where participants subjective perception of their situation awareness is captured. In both of these figures the participants perception of situation awareness is fairly high for both groups. Already presented results show that the SP display is able to help participants plan their traffic up to 10 minutes ahead of baseline participants. Knowing this, one may expect a larger gap between baseline and SP regarding situation awareness, yet the results are fairly close. Figure 25 shows some evidence of how participants may have been exposed to “attention spotlight”, a term used in ATC to describe using too much time to solve a single problem, ignoring other problems which are more urgent. Some baseline participants may have spent more time on a single problem than SP participants.

VI. Discussion

Due to the complexity of the task as well as the complexity of the support tools, it may still not have been enough to completely remove the learning effect from recorded data. It is likely that the SP participants may have needed more training than baseline participants as there are additional support features which the participant must learn compared to the baseline display.

Accuracy of delivery was predicted to increase with the use of the SP. This did not happen. Instead the participants using the baseline display managed to outperform the SP participants by a small, but statistically significant, margin. Based on live observations during the experiment, the manner in which the results were obtained leads to concerns for baseline participants in more complex scenarios. The experiment setup was likely too simple to show any difference between the two displays. Baseline results were expected to be upwards of one minute but both baseline and SP managed to produce accurate results. Regardless, it does seem that the SP display is able to achieve results under one minute which was expected. There was, however, a large increase in accuracy when a professional ATCo used the SP compared to any other results from both baseline and SP participants. The number of participants are small so no direct conclusions can be drawn but it may very well be that experience plays a large role in accuracy. It is now expected that SP display results will scale much better with scenario complexity than baseline results and this needs to be tested. For example: this could be tested with scenarios that include wind. Different aircraft types would have different performance when it comes to holding procedures as not all aircraft are able to fly four minute standard holding procedures and how their holding procedures vary will depend on their performance. This added complexity will be calculated by a prediction system in the case of the SP display but will have to be mentally calculated by baseline participants.

According the hypotheses, the situation awareness was predicted to increase when using the SP. Observing the control action timing back in figures 16, 17 and 18 it seems that participants using SP are executing control actions that influence timing much more in advance compared to the baseline. If it is the case that HLT actions taken earlier indicate a heightened situation awareness, then there is objective evidence that supports this hypothesis. An argument for this to be true is that when processing a control action and deciding upon it, usually this is done for unresolved issues. Control actions on already resolved issues are a waste of time and participants are likely uninterested in investing time and mental capacity solving an already solved issue. It then becomes clear that unresolved issues are the most likely candidate for attention regardless of which display is being used. If the previous is true then participants using the SP are aware of issues related to timing far ahead of baseline participants and have the ability to tackle these issues earlier. It may even lead to an increased situation awareness. This is based on an assumption that the controller has a good understanding of the problems that they are solving.

This may not be the case. An argument against an increased situation awareness is that a control action results from a decision. These decisions come at a cost on both time and workload. The Skill based behaviour, Rule based behaviour and Knowledge based behaviour from the SRK taxonomy [3] are three levels describing at what cognitive level an activity is being performed. A decision resulting from higher cognitive activity comes at a higher cost in both time and workload. Baseline control for accuracy of delivery is an activity which involves knowledge based behaviour, the most taxing cognitive activity.

SP control for accuracy of delivery, however, is an activity which involves rule based behaviour which comes at a lower cognitive cost than knowledge based behaviour. A behaviour which comes at a lower cognitive cost but also requires less problem solving and mental effort. The behaviour involved is a result of the design of each display. It seems that the further in time a participant of the baseline display tries to control for accuracy, the higher cognitive cost it has. This then results in either little or no commands given early in the aircraft’s lifetime. While information comes at a higher cognitive cost, there is a case to be made that this also improves situational awareness of the baseline controller as they are engaging with the problem. It is however undeniable that the cost for reading ahead of time for the SP is then much lower than the cost for reading ahead in time for the baseline display setup. This means that the baseline controllers have no ability to solve time-based problems early in an aircraft’s lifetime, before the problem becomes difficult to solve with added time pressure.

SP participants on the other hand can access time based control actions that look further in the future at a much lower cost than baseline participants. For baseline participants the cost of looking ahead more than four minutes seems to be too large and so control actions are taken much later in the aircraft's lifetime. With a reduced cost for acquiring such a decision for the SP display, it does not imply improved situation awareness and caution should be had when making such a claim. This is a typical danger when using rule-based behaviour for control. A controller may know what to do to let aircraft achieve their desired response but will not necessarily understand the effects behind their control actions on a deeper level. Controllers may even be at risk of becoming lazy or complacent, not utilizing their spare mental capacity to increase their situational awareness.

Subjective results from the questionnaire are not strong enough to support an increased situation awareness but based on comments it does seem that SP controllers an advantage over baseline participants. It was anticipated that results would show that SA increased when using the novel display but it seems that both subjective and objective results are inconclusive regarding SA.

Knowing that the accuracy of delivery control task involved for both displays requires different levels of cognitive activity discussed in the previous paragraph, one would expect ATCos to be able to manage their workload more easily with the SP. Workload was actually predicted to be flattened over an aircraft's lifetime. Workload would not necessarily increase or decrease but become more balanced by avoiding workload peaks near the end of an aircraft's lifetime. This expectation is related to the expectation of an increased situational awareness. participants will be able to manage their workload over the entire course of the aircraft's lifetime, not only right before EAT. A subjective questionnaire result yields no statistical evidence as the participant number is low but Figure 22 does seem to show a trend where participants using the baseline had higher workloads. Comments left by participants using the SP used language such as "Easy to use", "little effort" and "acceptable workload". In contrast, there were no comments left by baseline participants after giving a higher mean RSME score.

According to the hypothesis the CARS would increase when using the novel SP display. There was not enough evidence of this based on the subjective results of the questionnaire. Comments left by both groups varied and had feedback for multiple points of improvement on both displays. The comments left by participants were insightful but too broad to tell if one display was better in terms of controller acceptance. For the baseline display the most notable point of improvement was the clutter on the vertical view display where labels would overlap without the option to move the label. The main two points of improvement for the SP display was the lack of feedback on aircraft selection and the lack of feedback on the current HLT command. Another interesting point of feedback was the option of having a system which would somehow show what the solution input might be when choosing an HLT command. An example of how such a system might work would be to show a range of values inside the solution space which an ATCo can then choose according to their preference.

The expectation was that the control strategies used by SP participants will scale with the complexity of the scenario while the control strategies of the baseline participants will quickly need to be changed completely, likely resulting in a drastic decrease in accuracy of delivery unless the participant has a very strong understanding of the scenario and how this scenario effects their control inputs on the system. Increased complexity for this scenario can easily be done with any weather condition that makes a holding procedure differ from its standard holding duration or shape. This would need to be tested with a future experiment using a more complex scenario. It should also be noted that the experienced ATCo who participated in this experiment managed to get a mean accuracy of delivery of 13 seconds. This may indicate that the extra display elements on the SP that participants needed to learn during training may have affected how quickly they are able to reach a point where they are able to very accurately control the aircraft, giving baseline participants an advantage with less training material. Accuracy, however, can be improved with experience as shown with this experienced ATCo's result. This is likely true for both displays.

Given what is discussed, future efforts should be put in creating a more complex scenario when designing an experiment. EAT of aircraft can be planned outside of their solution space if left alone with regards to controlling accuracy of delivery. Furthermore IAF flyover related display elements can be further developed as there seems to be a lot of unexplored territory. Other novel timing based display elements may also prove useful.

VII. Conclusion

A novel holding stack support display was designed using Cognitive Work Analysis and Ecological Interface Design philosophies. The display aimed to improve accuracy of delivery, situation awareness, workload and controller acceptance. This display was then tested against current state of the art display technology in a proof-of-concept experiment. The results are promising, showing potential improvements in situation awareness, workload and controller acceptance. While improvements are anticipated in accuracy of delivery when tested under more complex experiment scenarios, the current accuracy of the SP design is under 30 seconds which is an improvement in accuracy from minute accuracy of $\pm$ 2 minutes to second accuracy of $\pm$ 30 seconds. Further improvements are observed when used by professionals. The technology readiness of this display is still in its infancy but large strides have been made in identifying the support required for holding stack management and some promising initial concepts have been tested to fill this requirement.

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Part II

Literature Review and Preliminary Research (Graded under AE4020)

1 | Introduction

In a report issued by Eurocontrol there is a growth scenario where air traffic within Europe will nearly double (184%) within the next 20 years [7], reaching 19.5 million flights per year. Air Traffic Control (ATC) procedures and tooling will need to evolve and grow to support this traffic. Challenges in ATC come from many angles with this predicted growth as traffic density in the sky increases. An example of such a challenge is when an aircraft is nearing the Terminal Manoeuvring Area (TMA) earlier than its Expected Approach Time (EAT). The aircraft may then arrive earlier than can be accommodated by approach controllers. This may lead to a necessity for adding a delay to this aircraft. There are many strategies when it comes to introducing a delay. This report will cover only one delay strategy called a "holding stack" and investigate how a controller can manage this strategy in their work environment.

1.1 Holding procedure and holding stack

A holding procedure is a path that an aircraft flies to maintain its position and altitude within certain bounds. The aircraft effectively flies in loops waiting for a follow up procedure. This can either come from ATC or the pilot can request one from ATC and divert. A holding procedure is given to a pilot by ATC to keep an aircraft in approximately the same longitude and latitude. A specific reference point is communicated to the pilot over which the holding procedure is executed. A stack emerges when multiple holding procedures are created on varying flight levels in the same position.

A need for holding stack support has been addressed in item 10.6 on page 47 in a report issued by the Knowledge Development Centre (KDC) [8]. In this report a desire for a tool that provides decision support for speed, timing and rate of turn while holding is expressed. It is also states that there is a goal to change holding operations so that it may "*lead to a better flow of traffic, less fuel flow and improve accurate delivery for approach Schiphol*". It is also stated that "Area controllers use only their expertise for efficient holding". From this report it is clear that there is a need for improving the current holding stack support tools or procedures available to stack controllers. Because flow of traffic and accuracy of delivery are interdependent, Only accuracy of delivery will be used as a measurement. Here accuracy of delivery is defined as the time between exit to approach and EAT Some Key Performance Area (KPA) in stack control are thus: **fuel flow** and **accuracy of delivery**. In the report, speed, timing and rate of turn are listed as control parameters while maintaining a separation minimum. Other additional KPA that are not mentioned in the report but that are also essential for ATC are **Situational Awareness (SA)**, **workload** and **system acceptance**.

It is important that a solution in ATC that is resilient to unforeseen situations is more important than the most efficient solution that fails catastrophically in some specific situation [9]. In this report a new ecological display design will be used in an attempt to improve one or more of these KPAs. A Cognitive Work Analysis (CWA) will be performed to understand the work domain of a stack controller and from this analysis an ecological display can be designed. This display is used in an experiment using Air Traffic Controller (ATCO)s in a realistic scenario linked to the NARSIM simulator of National Aerospace Laboratory of the Netherlands (NLR). Evidence in the form of experiment results and analysis will be created to either support or dissuade the use of the newly designed display. The KPAs mentioned will be used to determine the display's viability.

1.2 Research question

The research question posed in this master thesis project is defined as follows:

How will a dedicated holding stack display impact accuracy of delivery, fuel efficiency, SA, workload and system acceptance of the stack controller when compared to LVNL's state-of-the-art interface?

In this research question the previously mentioned KPAs are included, namely: an improvement in **fuel flow**, **accuracy of delivery**, **Situational Awareness**, **workload** or **system acceptance**. By asking this question it will become clear how this display design approach may influence these KPAs. Answering this question will require extensive analysis of the work domain as well as an experiment and analysis of resulting data.

Once this question has been answered there will be sufficient evidence to determine the display's viability compared to conventional display support tools used in holding stack control. ATCOs have used basic holding stack displays for many years. Little research has been done on how to improve the holding stack display and none of them have attempted to use EID as a framework for display design. This report will provide information in the field of ecological display design combined with holding stack display support tooling.

If a result is found which has an increase in KPAs without any drawbacks there is potential that interest is shown in this display support tool by ANSPs such as LVNL or NATS. If one or more of these ANSPs decide to proceed to implementation then it will have a direct impact on Area Control Center (ACC) as they will have to use the display. Further stakeholders who might be affected by this display are pilots if there turns out to be slightly different procedures.

1.3 Research approach and report structure

This report explains the procedures taken to arrive at a novel display design for a holding stack controller. The report has two main phases: Literature review and design. An extensive literature review spans four main chapters covering different aspects of holding stack management while a design phase is split into three main chapters. The main goal of the literature review is to gain a solid understanding of holding stack management which should strengthen any decisions made during design. The four main chapters that the literature review covers are: Current concept of operation, Novel display solutions, Case study and Cognitive Work Analysis. The main goal regarding design of a novel display is to harness the information gained in the literature review to answer the research question and improve on KPAs. The main chapters of the design phase consist of Display design, Experiment setup and conclusion and outlook. Here the main design outline is defined and the approach on how to analyse its feasibility is covered. The final conclusion and outlook chapter concludes the report.

2 | Concept of operation

Before starting design of a new display, it is important to understand what the current ConOps is. This section is meant to document procedures, responsibilities and tools currently available with entering, remaining in and leaving a holding procedure and/or holding stack. Compiling these subsections was done with source material from International Civil Aviation Society (ICAO) [1] [10], International Virtual Aviation Organization (IVAO) [11] [12], skybrary [13] and an NLR ATC training course [14]. Interviews with domain experts provided contextual knowledge to standard operational procedures [15].

2.1 holding procedure

A standard holding procedure is defined as follows: "A predetermined maneuver which keeps aircraft within a specified airspace while awaiting further clearance from air traffic control" [13]. Aircraft start their holding procedure at a holding fix which serves as a reference for both pilot and ATC. A holding fix is any VHF Omnidirectional Radar combined with a Distance Meseauring Equipment or other mutually understood navigation point used to communicate holding intent. For example in the Netherlands, 3 of the 4 predetermined standard holding patterns are above an initial approach fix VOR/DME (RIVER, ARTIP, SUGOL). All segments of holding pattern geometry can be linked in to this holding fix. If no operational considerations prevail, right turns holding patterns should be established by the pilot. For this reason, right turn holding patterns will be discussed in this report. Left hand turn holding patterns have symmetric properties of that of right turn holding procedures. In the case of holding on VHF Omnidirectional Radar intersections or VOR/DME fixes, entries will be limited to the radials [1].

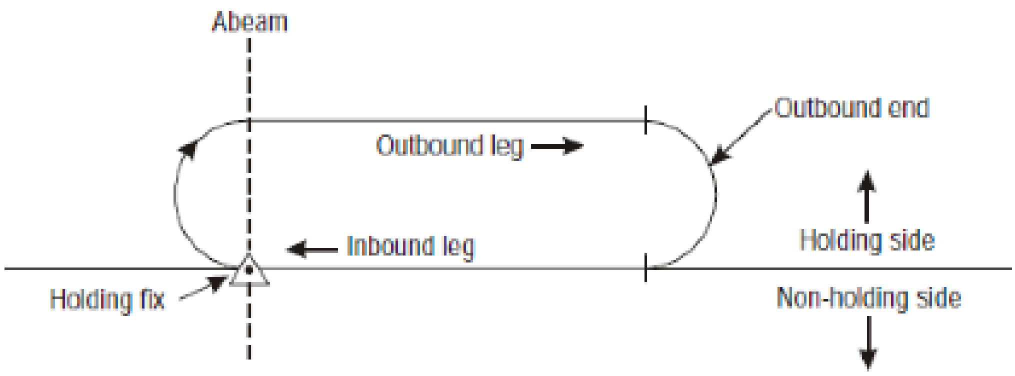


Figure 2.1: Holding procedure and terminology [1]

As can be seen in Figure 2.1, the geometry of a holding procedure has four segments:

- Inbound leg
- First half turn
- Outbound leg

- Second half turn

Each segment of a holding procedure is bound by the Initial Approach Fix (IAF). A standard holding procedure describes each leg to take 1 minute to fly if the aircraft is situated below 14000 ft and 1.5 minutes to complete when above 14000 ft [1]. Turns are done at either a bank angle of 25° or at a rate of 3° per second, whichever has a lower bank angle and will take approximately 1 minute. In practice the time it takes to fly these segments may vary as duration is a function of aircraft type, altitude and temperature [15]. However, nearly all commercial aircraft fly holding patterns with flight computers which tend to produce fairly accurate timings.

When a pilot uses a flight computer there are some options available when flying a holding procedure. In Figure 2.2 a holding page is shown on a flight computer. Leg distance or leg time can be entered, influencing the duration of a holding procedure. If a leg time is entered then a speed will be tied to the total holding procedure time. If a leg distance is used as an input then the total time will vary based on the most fuel efficient speed to fly at that flight level, automatically decided by the flight computer. Expected Further Clearance (EFC) is entered once the aircraft has initiated the holding procedure.

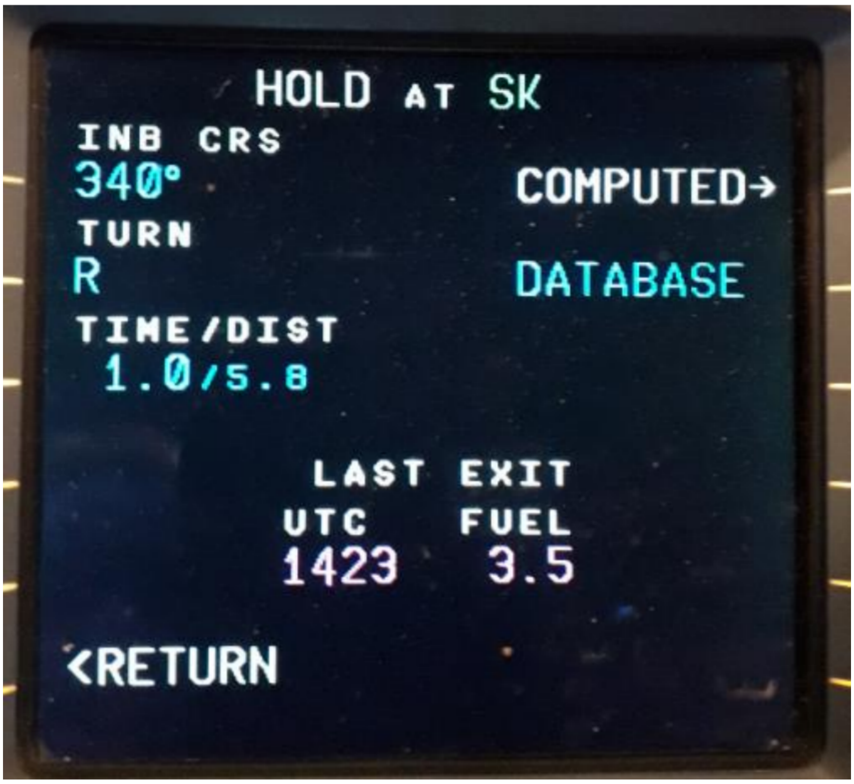


Figure 2.2: Holding procedure page on an A320 flight computer [2]

In Figure 2.3 a holding geometry is shown. In it can be seen how it will vary based on the leg time. It can also be seen that at the minimum leg time of 0 minutes, a 2 minute holding procedure will be flown which is essentially shaped as a circle.

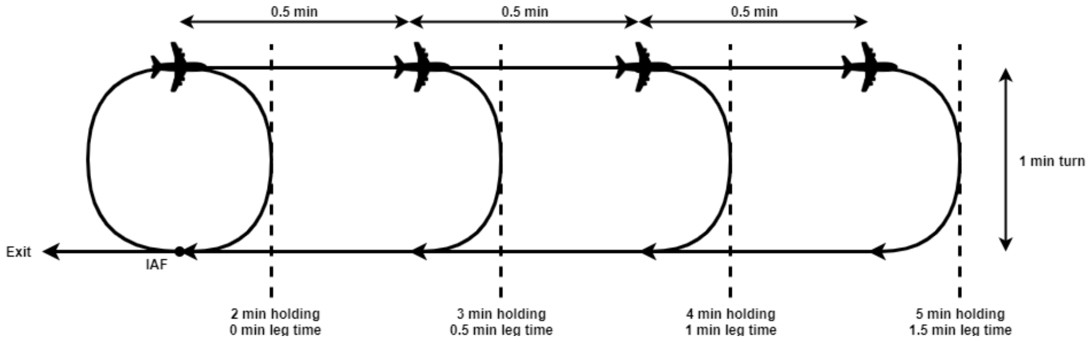


Figure 2.3: Variability of holding procedure timings. Image adapted from [1]

From this it is clear that if a controller will anticipate needing to delay an aircraft for less than 2 minutes, a holding procedure is not a good option. However, if a delay greater than 2 minutes is required then a holding procedure becomes a viable option.

$$holding\ procedure\ duration = 2 * (turn\ duration) + 2 * (leg\ duration) \tag{2.1}$$

2.1.1 Outbound parameters

Outbound timing begins over or Abeam the IAF, *whichever occurs later*. If the Abeam position cannot be determined, the pilot shall start timing when the outbound turn is completed. If the outbound leg is based on the DME distance, then the outbound leg terminates as soon as the limiting DME distance is reached. Every reference is in relation to the VOR/DME. Figure 2.4 shows the DME reference points for the outbound leg.

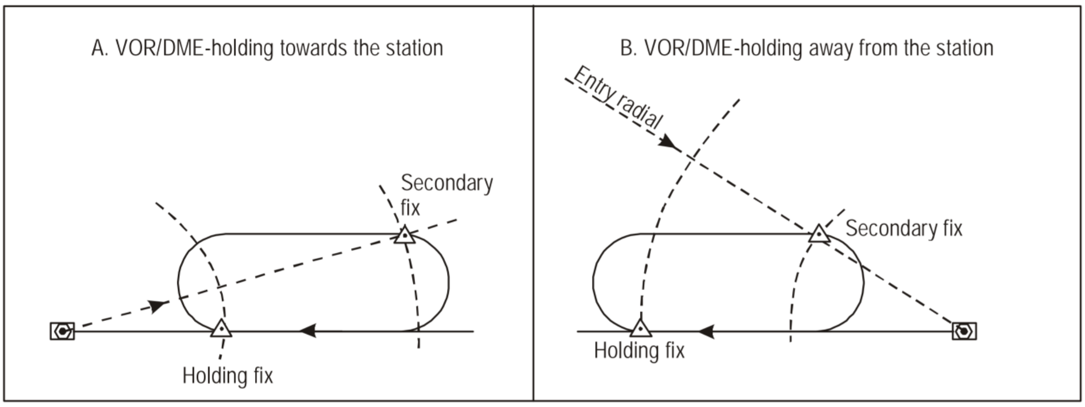


Figure 2.4: Holding procedure's outbound parameters [1]

In PAN-OPS document item 3.4.5 on outbound time [1] suggests that the outbound part of a holding procedure may vary between 1 and 3 minutes in half-minute intervals. This means that outbound leg + outbound turn may not exceed 3 minutes. Because a turn should be 1 minute, the maximum leg time is 2 minutes, which brings the maximum holding procedure duration to 6 minutes. Figure 2.3 shows how half minute intervals affect the holding procedure duration.

2.2 Speed restrictions

Pilots are responsible for wind corrections to maintain the track and make allowances by controlling heading and speed. Aircraft entering the holding pattern shall be flying at or below the

Table 2.1: Holding speeds [1]

Altitude	Under normal conditions	Under turbulent conditions
A < 14000 ft A < 4250 m	IAS = 230 KT or 425 km/h	IAS 280 KT or 315 km/h
14000 ft < A < 20000 ft 4250 m < A < 6100 m	IAS = 240 KT or 445 km/h	IAS = 280 KT or 520 km/h or 0.80 Mach, whichever is less
20000 ft < A < 34000 ft 6100 m < A < 10350 m	IAS 265 KT or 490 km/h	IAS = 280 KT or 520 km/h or 0.80 Mach, whichever is less
A > 34000 ft A > 10350 ft	IAS = 0.83 Mach	IAS = 0.83 Mach

airspeeds given in Table 2.1. There are different holding speeds for category A and B aircraft as well as helicopters but this thesis will not cover these cases so they are left out.

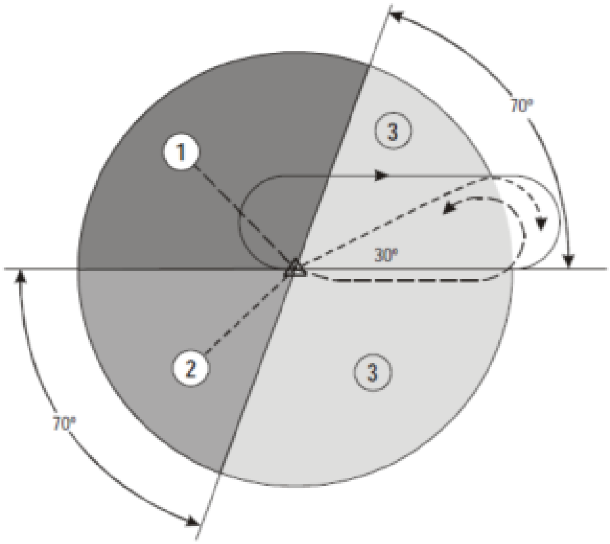


Figure 2.5: Entry procedures for a holding procedure [1]

2.3 Holding pattern entries

In Figure 2.5 can be seen the multiple entries available to start a holding pattern depending on the direction of approach to the holding fix reference. Available entries include:

1. Parallel entry
2. Teardrop entry
3. Direct entry

There is a flexibility of 5° on either side of the direction boundaries for the pilot but all standard entries will fly over the holding fix. Variations of the basic entry procedures may be made to meet local conditions after appropriate consultation with concerned operators [1].

Before a holding is authorized the following must be communicated to the pilot by an area controller [16]:

- the holding fix or IAF
- the heading of the holding direction
- if RNAV or DME is used, leg length (if none is specified a standard 1 minute leg is assumed)
- direction of turn (if none is specified right turn is assumed)
- Expected Further Clearance (EFC)

2.4 Holding stack

Holding procedures have now been covered. Next topic to cover is the concept of a holding stack: "A number of aircraft holding at a common fix with vertical separation" [17]. As holding stack control is not covered in ICAO documents in Aircraft Operations - Flight Procedures volume 1 or volume 2, instead the reference material almost solely consists of material from IVAO [11] [12]. Figure 2.6 shows a visualization of a holding stack and its surrounding airspace. In this figure can be seen the structure of a holding stack above an IAF. The subsequent airspace sections that an aircraft will pass through after exiting a holding stack is also visualized.

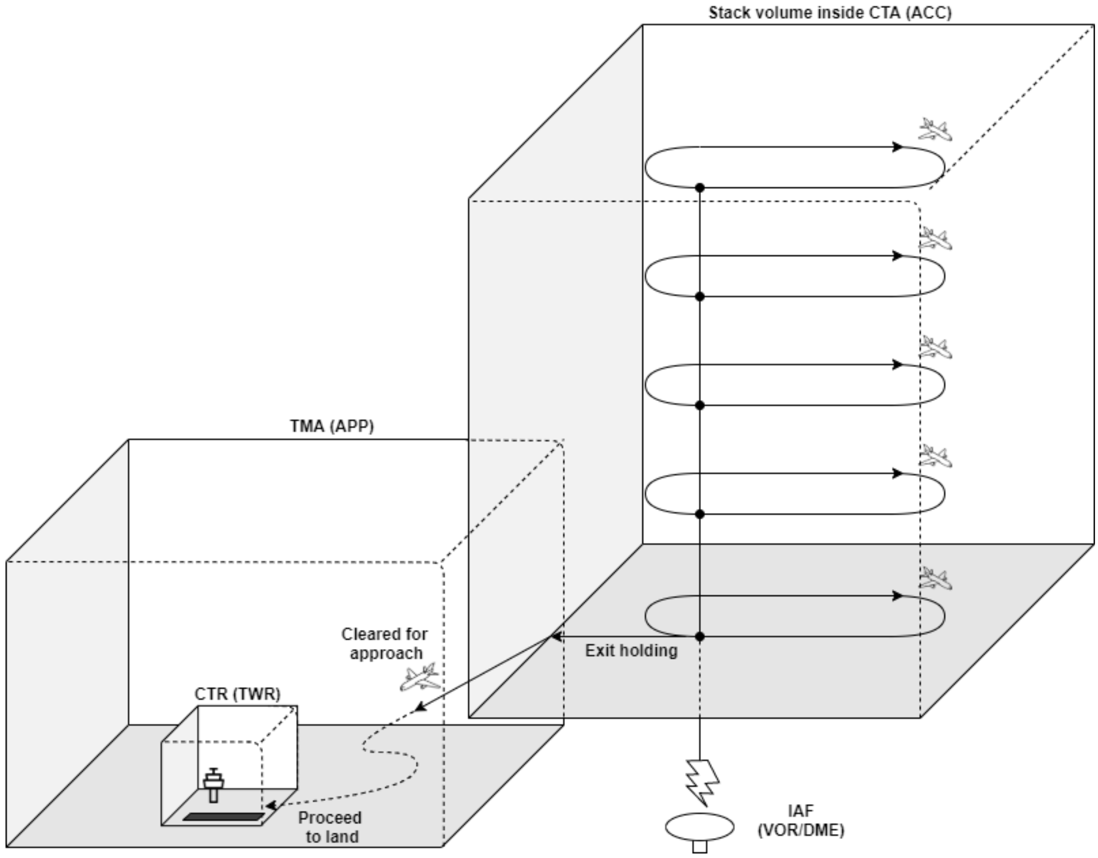


Figure 2.6: Airspace where holding is executed (not to scale)

2.4.1 Filling a holding stack

A holding stack is managed with the First-In First-Out (FIFO) principle [12]. An ATCO will put aircraft in the stack in order of arrival, the latter at a higher FL maintaining a separation of

10 FL, and remove them from the stack in the same order. A more familiar example of FIFO is standing in line for groceries.

2.4.2 Emptying a holding stack

Aircraft may leave the stack and begin approach only at predetermined FLs, usually situated near the minimum holding stack FL. In the Netherlands these values are between 70 and 100 FLs. This means that if an ATCO plans to release an aircraft from the holding stack for approach, it must be guided to the bottom of the stack first.

Aircraft are preferably removed from the holding stack when on the inbound leg [12]. This will ensure a straight flight over the IAF which is more efficient and easier to predict. This aircraft will then start the approach sequence after entering the TMA and control is handed over to Approach control (APP). After the lowest level aircraft has been removed from the holding stack the holding stack must be reorganized. The air traffic controller will descend each aircraft one by one to a lower flight level. The aircraft above the descending aircraft may not be cleared for descent until minimum vertical separation will be guaranteed by the air traffic controller. Once all of the aircraft in the stack descend one level, this frees up space higher up for new aircraft to join the holding stack.

Aircraft controllers may anticipate the descent but may not forget about aircraft's performance or pilot's speed of response [12]. The holding procedures are separated by 10 FL which is the minimum vertical separation used for holding procedures. Figure 2.7 shows the minimum separation to be adhered to by ATCOs for holding stack operations.

In Figure 2.6 a holding stack and its stack volume is shown. In this volume are aircraft flying holding patterns at different FLs. At the bottom, aircraft exit the holding stack and enter TMA to begin approach followed by a landing. In it is also shown the different airspace types that it must pass through before it lands.

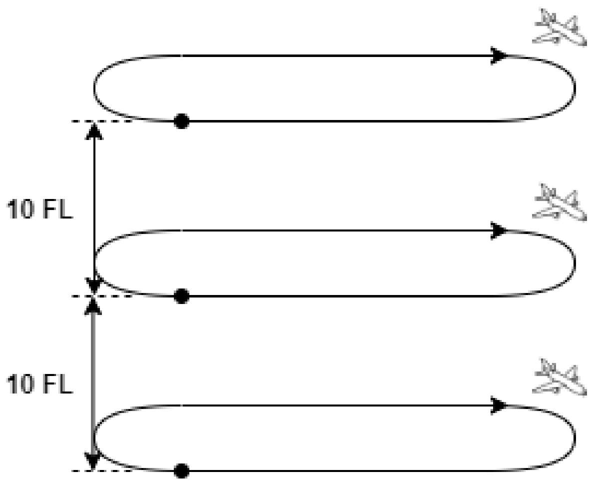


Figure 2.7: Minimum separation to be kept by ATCO (not to scale)

2.5 Human responsibilities tied to a holding procedure

Next to all of the technicalities of holding procedures and holding stacks there is also a human factors aspect. If holding stack control is seen as a system it quickly becomes clear that humans are deeply rooted in this system. If a successful display is to be designed, it is detrimental that a good understanding of human responsibilities is reached. In this section the responsibilities of human actors is covered. An expert holding stack controller from LVNL was able to provide valuable insight for this chapter [15].

2.5.1 Pilot in command (Captain)

A pilot is responsible for their aircraft and passengers. The pilot will fly a route given by an air traffic controller and may make requests if they deem it necessary. A pilot may for example make an Expected Further Clearance request to determine they need to divert to alternate. A pilot will tend to fly efficiently to conserve fuel. They may make requests or give reminders to ATCO so as to increase flight efficiency. Pilots are also responsible for the flying comfort of their passengers.

2.5.2 First officer

Sitting next to the pilot is the co-pilot. A co-pilot will have all the training necessary to complete the tasks that a pilot will be able to execute but will have less experience. The co-pilot will in general help the pilot complete all their tasks and help manage control of the aircraft. In emergency situations where the pilot is no longer able to control the aircraft, a co-pilot will take over control. A co-pilot will listen in on all of the information exchange between pilot and Area Control Center.

2.5.3 Area Control Center

An area controller is an executive controller. Before entering a holding stack, an aircraft is guided by an area controller. Area controllers are responsible for aircraft in their sector. They are also responsible for clearing aircraft for approach. This means that if TMA is not able to accommodate any new aircraft that a delay must be introduced by the area controller to aircraft which are destined for approach. This can be done a number of ways, one of which is clearing them for a holding procedure above an IAF. Depending on the traffic conditions there may already be an air traffic controller assigned as a holding stack controller. If there is need for a holding stack, depending on the size of a holding stack, an area controller will handle a holding stack if it is small but will not be allowed to use a vertical view display. If the stack is predicted to be large, there is the option to use a standby controller as a holding stack controller as described in Section 2.5.4. If there is no need for holding stack control then the area controller will continue to guide this aircraft to approach.

2.5.4 Holding stack controller

The holding stack controller is responsible for all aircraft which are cleared for holding. Aircraft are cleared for holding by executive controllers. An area controller and a holding stack controller will have separate radio frequencies to communicate with aircraft under their control. Holding stack controllers are responsible for all aircraft cleared for holding. All aircraft in a holding stack are descended in an orderly fashion and cleared for approach.

Holding stack controllers will abide by ICAO regulation when possible. When an unforeseen situation occurs, holding stack controllers are permitted to use creative solutions. Control actions are carried out verbally over radio frequency in the form of a command to the pilot in command. Available control actions include: new FL descent clearance command, speed command, expedite descent command, exit holding command, cleared for approach command and direct to command.

The displays available to a holding stack controller may vary depending on which ANSP is the employer. Figure 2.8 for example shows a section of an LVNL holding stack display while Figure 2.9 shows a NATS holding stack display. These displays are support tools available to holding stack controllers. Currently ATCOs are meant to use the radar display to understand an aircraft's lateral position and the holding stack display to understand vertical positions and timings. Two separate displays are forming their cognitive understanding of the system.

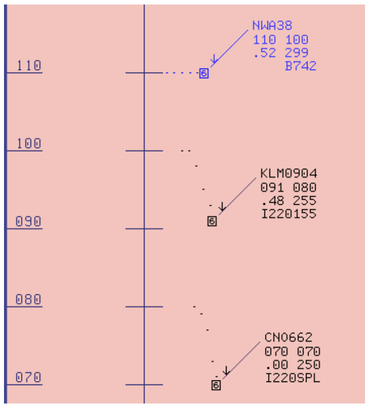


Figure 2.8: Snapshot of the "Vertical View". A holding stack display support tool for LVNL ATCOs [3]. The colours in this figure have been altered for readability.

Figure 2.9: Snapshot of the "Vertical Stack List". A holding stack display support tool for NATS ATCOs [4].

2.5.5 Standby controller

Standby controllers are assigned for every X controllers. The amount X may differ depending on what the supervisor deems necessary. Their responsibilities are to support active controllers as well as provide redundancy. If there is a need for a holding stack controller, usually a standby controller will become a holding stack controller.

2.5.6 Supervisor

A supervisor plays an important role in a control center. They will ensure safe conduct of a watch, check flight plans and slots, communicate with centers, and airlines as well as handle, supervise and support emergencies. Supervisors are responsible for daily staff management and controller management (breaks, time working etc.). They are responsible for making sure that all of the staff can collaborate and focus on their tasks.

2.5.7 Planner

A planner will not communicate with pilots but coordinate traffic with ATCOs and supervisors. They are responsible for smooth traffic transition between sectors.

3 | Case study

After documentation of ConOps is covered some real life examples are examined to see how closely ConOps relates to practice potentially revealing information that may have escaped documentation. Because ConOps is different depending on which ANSP is under control of air traffic a couple holding procedures from different ANSPs are covered. A case is taken during the same time of day, with similar traffic density for comparison between the two.

Heathrow's standard operating procedures will incorporate a holding stack in all weather conditions so ANSP NATS's holding stack management will be the first choice when covering a holding procedure. Because of this it is safe to assume that NATS has valuable experience when it comes to holding stack management and may have gained insights and experience that other ANSPs may may not have when it comes to holding stack management.

The second ANSP which will be covered will be LVNL. Expert ATCOs controllers from LVNL have provided insight into ATC. Understanding how LVNL operates holding stacks will provide valuable insight during analysis of experiment results. LVNL does not use holding stacks under normal weather conditions [8]. The chosen day and time to analyse holding stack control for both NATS and LVNL will be 02-01-2020 between 11:00 and 12:00 CET. Figure 3.1 shows a screenshot of Windy [18] during this time. Weather conditions in the Netherlands were foggy with a slight wind coming from the South and in the United Kingdom weather conditions were partly sunny with a firm southern wind [19].

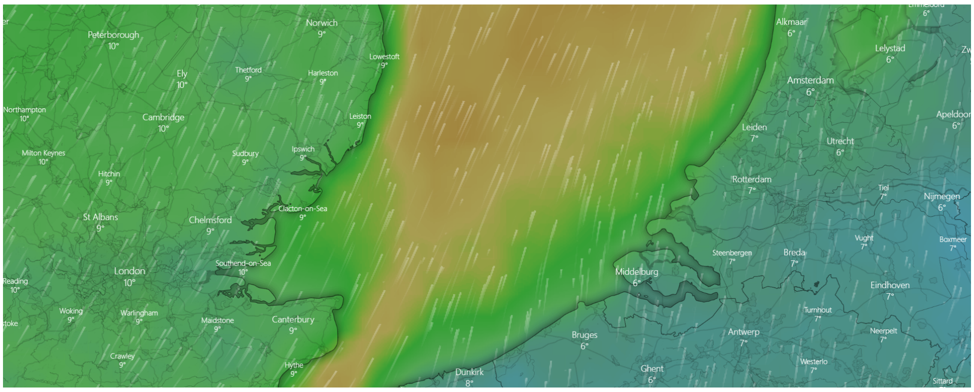


Figure 3.1: Wind conditions above Amsterdam and London on 02-01-2020 at 12:00

3.1 Holding vs conventional approach

Before analysis of holding procedures of these two ANSPs some considerations of holding procedures must be covered. A holding procedure is essentially a storage space. Where storage takes place and how will have an effect on timing and efficiency. If a holding procedure is done at a high altitude, an aircraft is able to fly more efficiently but the predictability of approach time decreases. There are other methods for aircraft storage. Tromboning will help an air traffic controller manage arrival times when an accurate timing is needed and vectoring will help when accuracy is a little less tight.

In general, holdings are flown at relatively low altitude compared to conventional approaches, reducing efficiency. Holding procedures also incorporate more turns than conventional approaches, reducing efficiency as the aircraft sacrifices some lift when at a bank angle. Another factor that must be considered is safety. All procedures whether it be conventional approach or holding stack incorporation must adhere to safety standards. In this case study is shown two very different approaches to holding procedures. NATS incorporates holding procedures to increase capacity at the cost of efficiency while LVNL avoids holding procedures increasing efficiency at the cost of capacity.

3.2 National Air Traffic Control Services (NATS) practices

NATS is responsible for Heathrow airport's ATC. In Figure 3.2 is a screenshot form Flightradar taken above Heathrow airport on 02-01-2020 at 12:09. Here is shown the flight history of 6 aircraft, revealing the 4 holding procedures that take place above the four different IAFs surrounding London as well as the approach route that follows after exiting a holding procedure. These are meant to coincide with the STAR chart. Using these four holding stacks, aircraft from any holding stack can be chosen to join a sequence of aircraft landings by an ATC.

In Figure 3.2 this is seen in practice. Aircraft all line up neatly for landing after being exiting different holding stacks. A likely scenario is that a stack controller is given ETAs of each aircraft in the stack. The stack controller then communicates with the pilots of each aircraft, lowering their flight level in the stack so as to let the aircraft exit as near to the given time as possible and at the correct flight level. This is done with the control actions available to a stack controller covered in Section 2.5.4.

Figure 3.2: Holding stacks for storage above Heathrow airport

In Figure 3.3 a closer look at one of the holding stacks is shown. As can be seen, aircraft will leave the stack in orderly fashion while their timings are corrected after exiting the holding stack by tromboning. With so much space available for time correction after the holding procedure then it could be argued that the control variable of holding procedure size may not be necessary. It is however still used as shown in Figures 3.2 and 3.3. Waypoint LAM North-East of Heathrow communicates a Left-handed turn holding procedure. This is likely a conscious result of airspace management.

Another noteworthy observation is that the holding turn size and leg length are all slightly different. Holding procedure geometry are affected slightly by factors such as altitude, temperature and aircraft type. They do however all converge on the inbound leg and IAF.

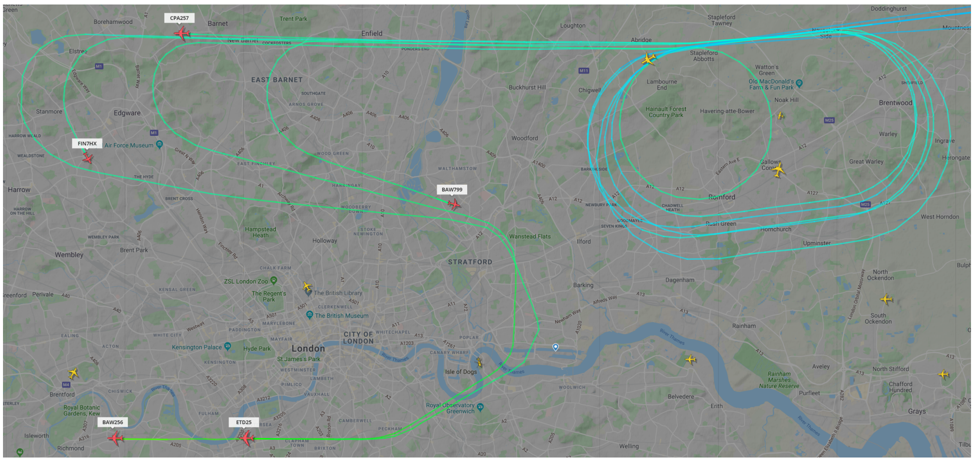


Figure 3.3: Holding procedures above waypoint LAM positioned North of Heathrow airport showing how approach timing is managed after exiting a holding with the use of tromboning

3.3 Luchtverkeersleiding Nederland (LVNL) practices

LVNL as an ANSP will avoid holding stacks and holding procedures when they possible [8]. During the chosen time of day holding stacks exist but only for a short period between 11:00 and 12:00 EST. This is due to the "non-nominal" situation mentioned in the KDC report [8]. The weather was foggy which is the "adverse weather" condition that the KDC report mentions.

Here there is a difference between the goal of a holding stack compared to that of NATS. Holding stacks, when used by LVNL, have a sole purpose of solving a difference between high capacity demand and low capacity availability. Already mentioned in 3.1 there is a trade for efficiency vs flexibility. The sole purpose is to

Figure 3.4 shows conventional approach procedures above LVNL. It is a screenshot of flightradar at 16:04 CET. Here multiple clean vectoring and approach procedures are shown. Aircraft are directed towards ARTIP by ACC and cleared for approach before being handed over to TMA. This is a result of air traffic management long before arrival at ARTIP. Conventional ATC above the Netherlands uses a combination of tromboning, speed alteration and vectoring. In nominal weather conditions this is sufficient.

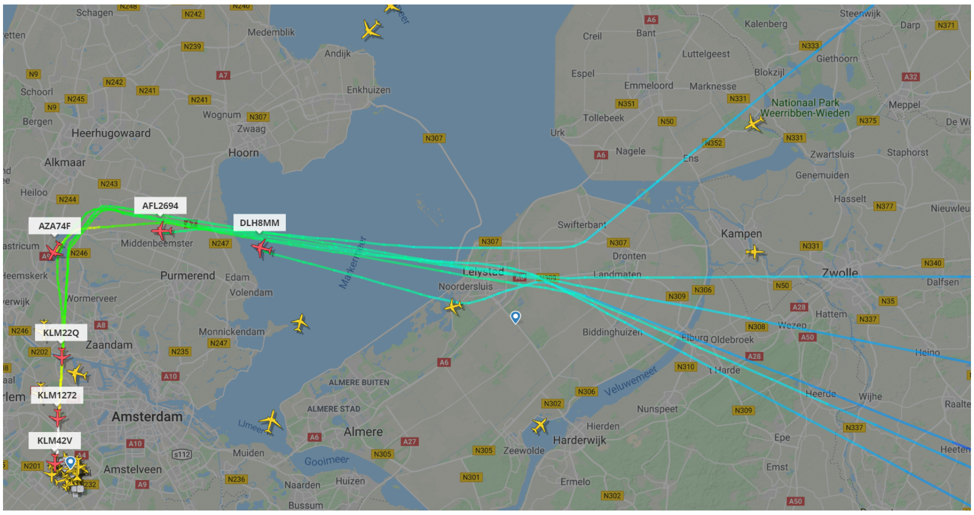


Figure 3.4: Schiphol's nominal arrival traffic conditions via ARTIP

LVNL will switch to holding procedures during adverse weather conditions. Figure 3.5 shows a screenshot of air traffic above the Netherlands on 02-01-2020 at 11:43 CET. This was taken when the weather above the Netherlands was foggy, meeting the "non-nominal" condition. ATCO's strategy then needs to change from conventional approach to holding procedures and holding stack management. Once a peak in delays has passed in which ATCOs are using holding procedures, ATCOs return to conventional ATC in which no holding procedures take place.

Figure 3.5: Holding stacks for storage above Schiphol airport

In Figure 3.6 is shown how one aircraft is given the command to exit the holding procedure while still in a turn. The pilot will put a "Direct to ARTIP" command in their flight computer after which the aircraft will exit the holding and recalculate how to fly to the ARTIP waypoint using its current attitude.

Figure 3.6: Direct to exit command while in a holding

In Figure 3.7 the approach procedures for inbound aircraft from the east under foggy weather conditions is captured. When taking a closer look at a single holding stack above SUGOL in Figure 3.7 it can be seen that the length of the leg of each holding procedure may vary. In Section 2.5.4, leg time is considered to be a control variable. This helps an ATCO give an exit time closer to the ETA. Variations in leg time are shown clearly in Figure 3.7. Turn radius and time remains near constant while leg time governs a holding procedure's duration. In Figure 3.8 two aircraft are controlled with variable holding timings. It can be seen in this figure that aircraft "KLM66H" which is ahead of "KLM1486" exits the holding stack first after flying 2 holding procedures, of which the latter holding geometry is a circle with a leg time of zero. The second aircraft "KLM1486" is neatly controlled to exit the stack with longer holding procedure leg duration. The aircraft exits after this one holding procedure resulting in both aircraft exiting the stack with a managed time interval.

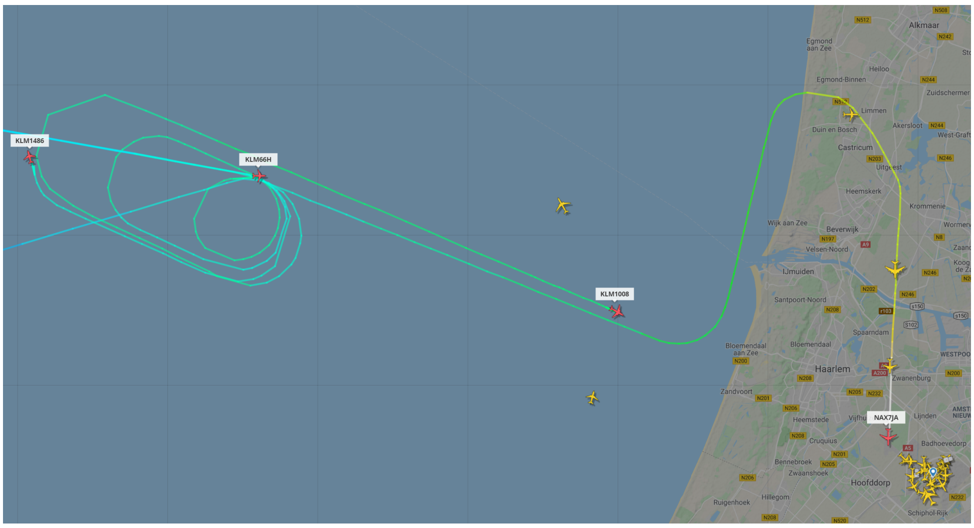


Figure 3.7: Approach under foggy weather conditions via SUGOL

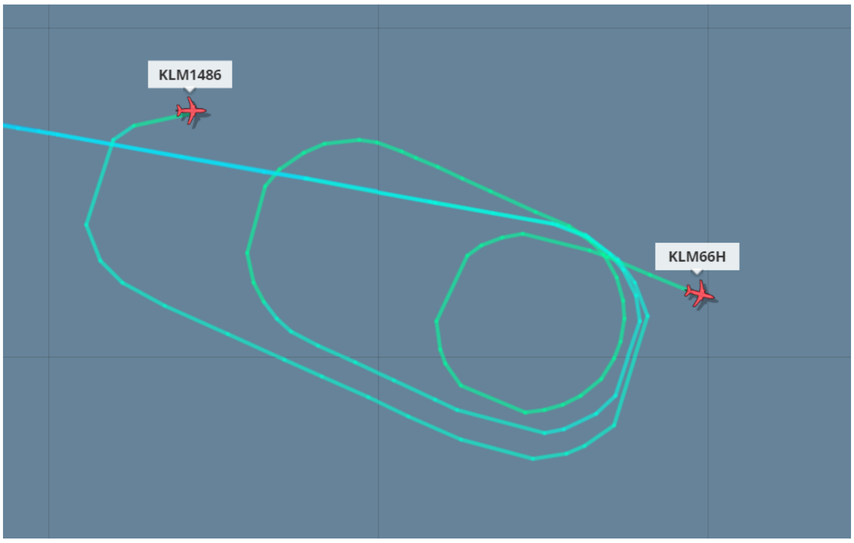


Figure 3.8: Holding stack procedures in LVNL

Further investigation of this holding stack management is shown in Figures 3.9 and 3.10. These two figures are snapshots of both aircraft shortly after they left the holding stack. Exact timings of the holding stack have proven difficult to retrieve but the first holding procedure starts around 11:28 for aircraft "KLM66H" and the second holding ended about 11:42. Also can be seen that the aircraft descends while in the holding stack and while in the holding stack turn. The aircraft descended to about FL 70 before doing its second holding procedure followed by exiting and starting approach. The total holding time of the aircraft was approximately 12 minutes. The timings of "KLM1486" are estimated to have holding entrance time of be 11:36 its exit at 11:45. The second aircraft likely got a holding command slightly before the pilot entered it into his/her FMS at 11:31 where a kink can be seen in the altitude over time graph. After this the aircraft descended to FL 90 and entered the holding procedure all using the on-board flight computer. Important is that the two aircraft in the holding stack fly at different altitudes. After KLM 1486 exits the holding stack, air traffic density via SUGOL subsided and conventional procedures are restored.

Figure 3.9: Altitude and speed over time of KL1486

Figure 3.10: Altitude and speed over time of KL1534

Knowing the approximate timings and the kinks in the altitude over time graphs it can be deducted that when the holding stack was created by the first aircraft, this was input right before the waypoint was reached. When the second aircraft was cleared for holding there was a bit more time available to enter it into the flight computer. This is, however, speculation as the timings on flight radar are not accurate enough to draw concrete conclusions. Regardless, valuable insight is provided from this case study in holding stack management. What is most telling about this methodology is that the aircraft before and after the two studied in this case study both did not fly any holding procedures. The holding stack procedure was spontaneously created because it was deemed necessary by an area controller and then released when deemed unnecessary. The holding stack lasted around 15 minutes and was likely unplanned, only used as a backup strategy.

3.4 Case study conclusion

LVNL uses holding procedures to store air traffic unable to proceed to approach and is undesired due to efficiency concerns while NATS uses holding procedures in standard operating conditions in an attempt to maximize capacity. A holding procedure's leg time is extended or shortened to improve accurate delivery to approach. Currently there are no support tools to help air traffic controllers with timing an exit and all control actions are based on cognitive understanding of the system combined with their expertise. In the following chapter this will be understood as "knowledge based behaviour" which is the most mentally demanding type of control task. A dedicated support tool may alleviate the workload required to perform such a control task accurately. Sections 4.5 and 5.4.12 will discuss this further.

4 | Cognitive Work Analysis

CWA is a methodology developed in 1999 by Kim Vicente in an attempt to tackle Human Machine Interface (HMI) for complex sociotechnical systems [20]. Nearly all aspects of the work domain have been covered in Part 2. In this chapter knowledge gained from Part 2 will be analysed with the CWA methodology, revealing all constraints imposed on the ATCO as well as their available control actions, tasks and strategies.

4.1 Rasmussen's Abstraction Hierarchy (AH)

In Figure 4.1 an abstraction hierarchy of holding stack control is shown. In it are outlined all of the "why", "what" and "how" interactions related to a holding stack inside ACC. Storage is the primary reason for a holding stack to exist which is listed as a general function. A holding stack is a physical function and has a physical form consisting of geometry and Holding aircraft state values.

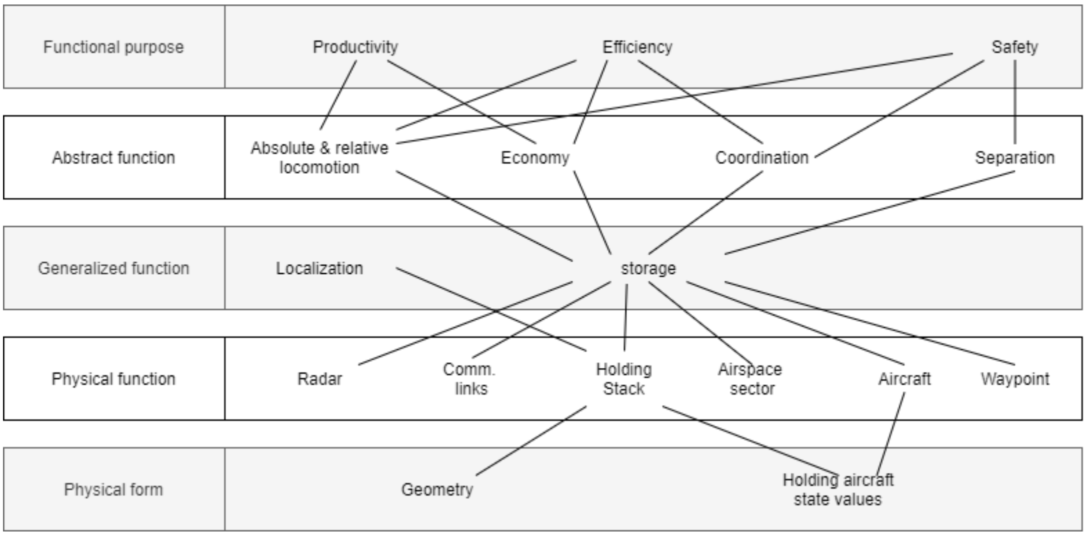


Figure 4.1: Abstraction Hierarchy of holding stack control

4.2 Control Task Analysis

In this section analysis is performed on two control tasks that a holding stack controller is expected to encounter. Three main control actions and two control tasks have been identified after analysis of the work environment in Part 2. The three main control actions are:

1. Lowering aircraft altitude using FL clearances
2. Extending or reducing holding procedure time by shortening or extending an aircraft holding procedure's leg time
3. Clear aircraft for approach

Using these control actions the following control tasks are executed:

1. Lower aircraft to appropriate FL before clearing aircraft for approach in time for EAT
2. Align aircraft holding procedure with EAT using leg time variation

Under current circumstances the second control task has no support tool. Holding stack controllers have to mentally align their aircraft's exit time with EAT before performing a control action. As will become clear in Section 4.5, this is knowledge-based behaviour and requires a higher cognitive load. Fortunately support tools already exist which help with the first control task. Such tools are the Vertical view displays covered in Section 2.5.4.

In Figure 4.2 a decision ladder is shown for an aircraft in a holding stack which must be guided to FL 70. Table 4.1 explains each step taken in Figure 4.2. Vertical separation must be maintained and the aircraft must reach its exit FL close to its EAT. Furthermore the preferred attitude of the aircraft at its exit FL when near EAT is that of an aircraft approaching the IAF so that its exit time is as close to its EAT as possible.

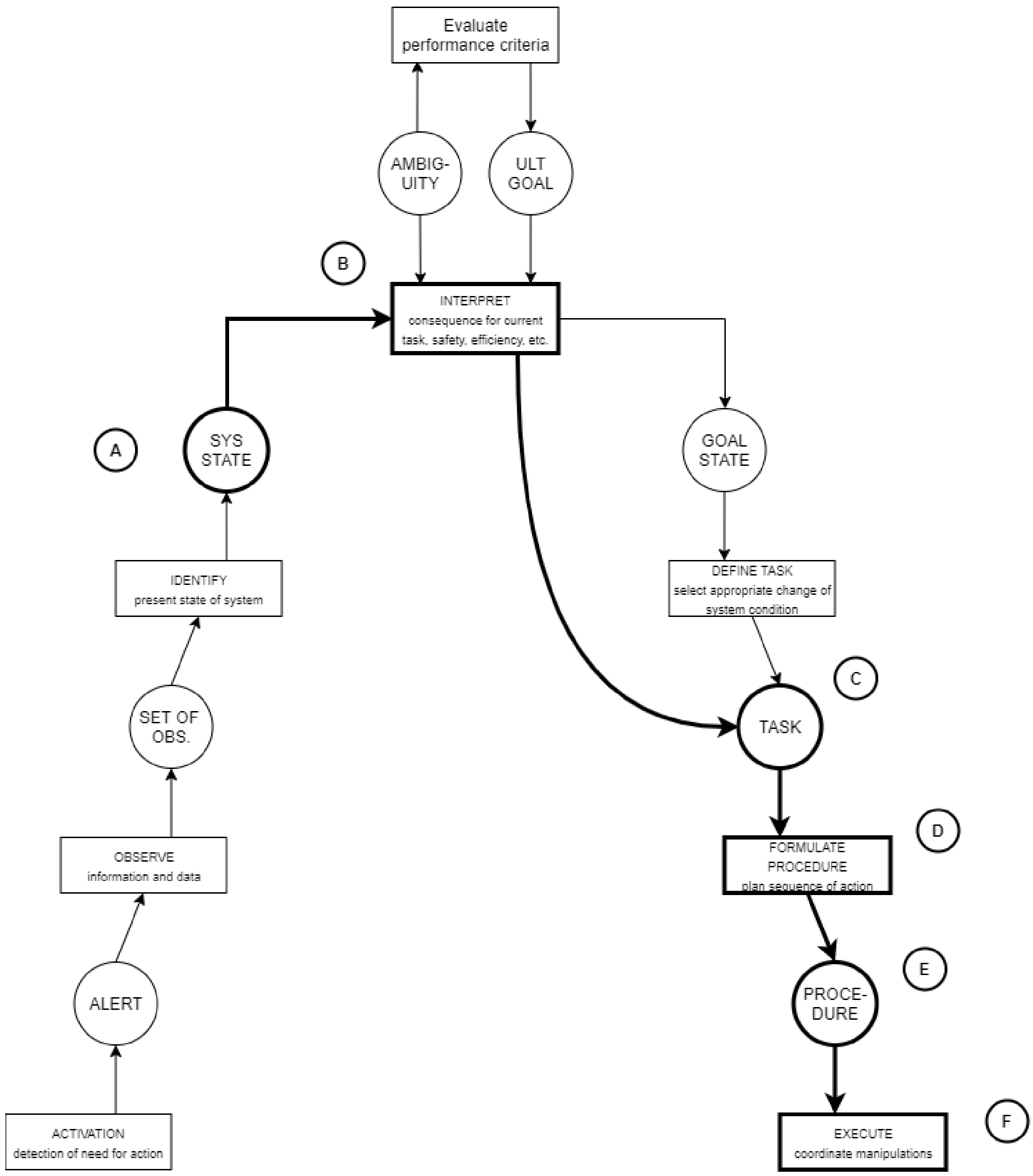


Figure 4.2: Decision ladder for ATCOs

State	Description	Type	Ladder Code	Abstraction Level
A	Knowledge of aircraft in the holding stack and knowledge of their EATs	Knowledge State	System State	Functional Purpose
B	Determine criticality of FL versus EAT and if occupied FLs prevent descent	InformationProcessing Activity	Interpret	Abstract Function
C	Knowledge of which flight level clearance(s) must be modified to descend aircraft to desired flight levels	Knowledge State	Task	Generalized Function
D	Select specific strategy for accomplishing redistribution of aircraft in holding stack	InformationProcessing Activity	FormulateProcedure	Generalized Function
E	Knowledge of desired aircraft distribution strategy	Knowledge State	Procedure	Physical Function
F	Convey series of flight modifications (plan) to aircraft for execution	Activity	Execute	Physical Form

Table 4.1: This table refers to figure 4.2

4.3 Strategies Analysis

Strategies analysis analyzes how tasks are performed, irrespective of who is performing them. In the case of holding stack control, aircraft are first given a holding clearance before they are allowed to enter the holding stack. Aircraft in the stack have a cleared FL. This cleared FL is reduced when there are unoccupied FLs below. This is repeated until the aircraft reaches its exit FL where it is further cleared for approach near its EAT. Figure 4.3 shows two examples of tasks that an ATCO may take to control an aircraft in the form of an information flow map.

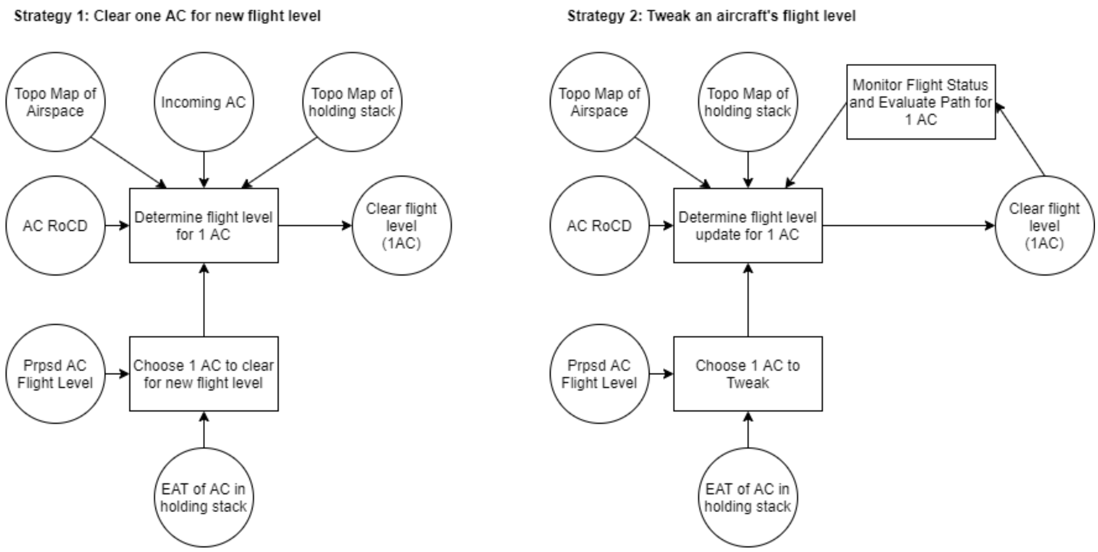


Figure 4.3: Information flow map for stack management

Noticeable when studying area control is how an ATCO might simplify a complex traffic problem by reducing dimensions. Examples of this include making aircraft fly at the same speed, the same heading or by separating their FLs. All these strategies used by ATCOs tend to steer a complex problem to a more manageable problem. A holding stack is another such simplification of a complex problem. By removing lateral control, only one spacial dimension remains (namely vertical separation), the problem no longer requires control for lateral separation. This allows the controller to focus on controlling aircraft to their exit altitude and exiting the aircraft at the desired EAT. Noteworthy is that time as a control variable requires less immediate action when a holding stack is created. Delays are effectively only limited by fuel reserves. There are however sacrifices made when utilising a holding stack as mentioned in Chapter 3 where two delay strategies are compared.

4.4 Social Organization

In this section the responsibilities of the computer systems and human actors are analysed. Figure 4.4 again shows two examples of tasks that a controller may take to move an aircraft in a holding stack. In this figure, responsibilities are distributed between human and computer. Responsibilities of human actors are colored dark gray, computer responsibilities are colored in white and shared responsibilities are colored light gray. Here can be seen that computer responsibilities include visualization of all information while human actors are responsible for decisions based on displayed. Because a computer will be able quickly and easily reorganize information in a way that a human will be able to interpret and, if done correctly, form a cognitive understanding of the system as a whole. Responsibilities of a stack controller are explained in more detail in Section 2.5.

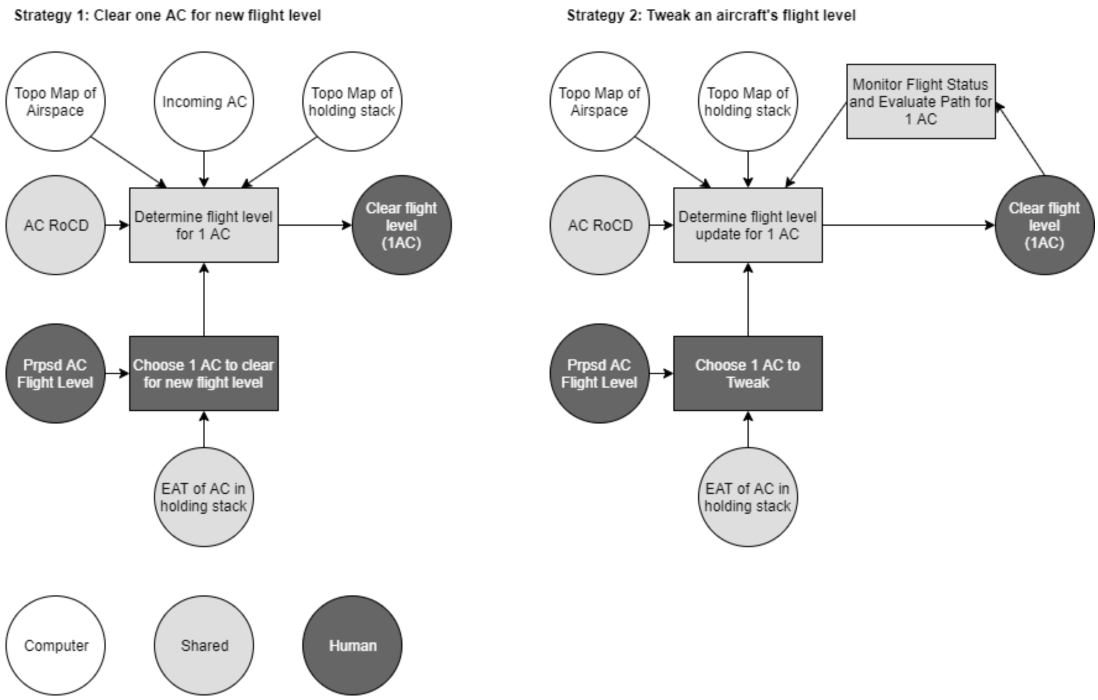


Figure 4.4: Information flow map with human-computer task allocation for stack management

4.5 Worker Competencies Analysis

Worker competencies analysis is an analysis investigating the level of cognitive load required to complete the identified control tasks in Section 4.2. Analysis is done using the Skills, Rules and Knowledge based behaviour (SRK) taxonomy developed by Rasmussen in 1983 [21]. Using SRK categories as worker competency levels, insight is gained into the level of cognitive load each task may require from a controller. According to Rasmussen, levels of cognitive load can be divided into three main behaviours: skill-based behaviour, rule-based behaviour and knowledge-based behaviour. Each behaviour is linked to a manner in which information is interpreted. The three types of information are Signals, Signs and Symbols respectively. Table 4.2 has a worker competency breakdown of all information processing done in a sample control task of a holding stack controller.

Information Process Step	Resultant Knowledge State	Skill-Based Behaviour	Rule-Based Behaviour	Knowledge-Based Behaviour
1 - Scan for aircraft cleared for holding zone	2 - Knowledge of all aircraft in holding zone	Monitoring of time-based spatial representations of aircraft cleared for holding zone	Perceive explicit indication multiple aircraft are currently cleared for holding	Reason, based on proposed flight plans, that multiple aircraft may have to be present in holding zone within similar time frame
3 - Determine which aircraft are descending	4 - Whether aircraft are descending or level	Perceiving how aircraft's RoCD and IAF line up with EAT	Use heuristics to determine whether RoCD lines and IAF line up with EAT	Reason based on geospacial knowledge of to/from points timings and capable RoCD for aircraft type for each flight, that RoCD and IAF are lining up with EAT
5 - Predict future time-based state of holding space for each aircraft	6 – Whether aircraft will arrive at flight level 70 within a reasonable time compared to EAT	Perceive arrival time at FL 70 for each aircraft based on spatial representations of heading and speed	Use heuristics to estimate whether aircraft will arrive at flight level 70 within a reasonable time compared to EAT	Calculating using RoCD, orientation in holding race-track and flight level of each aircraft, when aircraft is able to leave the holding stack
7 - Determine criticality of future state, distance between AC and time between EAT and IAF	8 - Whether future distances between aircraft and time between EAT and IAF is acceptable	Perceive whether the IAF and RoCD will line up with EAT	Use heuristics to determine if the stack exit time is acceptable	Calculate time between each aircraft and their EAT at their future states and compare with the minimum acceptable / possible time difference

Table 4.2: Worker competencies required to complete a task divided into Skills, Rules and Knowledge

5 | Display design

In this chapter a novel display is introduced. The novel display is made up of 20 separate elements. Elements of the display are divided into 3 main sections. Namely the static elements, dynamic elements on the left hand side of the display and dynamic elements on right hand side of the display. For each element the shape will be described and reasoning for each will be elaborated upon. The goal of this novel display design is to make improvements to the identified KPAs. Display design features are therefore guided by the thirteen display design principles from the book "An Introduction to Human Factors Engineering" [22]. Before discussing each display element individually, an explanation of colour language and a display overview is presented.

5.1 Colour language

Colour language is split into five main categories: **Background, Static elements, Aircraft related elements, Clearance related elements and IAF related elements**. A legend of these categories and their corresponding colours is shown in Figure 5.1. The display background colour in this report has been altered from the chosen background colour for readability purposes.

5.1.1 Background colour

The chosen background colour is black as to remain consistent with LVNL's radar display which also has a black background and is to be used in tandem with this novel display. This decision is driven by the principle of consistency. In this report the background colour will be displayed in white for readability purposes.

5.1.2 Static elements

Pale tints of gray are used for static elements of the display as these elements do not require immediate attention and are always available in the same position on the display. This is in line with the display principle of making the display legible and the principle of reducing information access cost of other signals on the display.

5.1.3 Aircraft related elements

Shades of green are chosen for aircraft related elements. This is again for the principle of consistency with LVNL's radar display. Green also has great contrast with the black background colour.

5.1.4 Aircraft clearance related elements

For the aircraft clearance related elements of the display a blue is chosen. This colour is chosen using the principle of discriminability and the principle of making the display legible. The chosen shades of blue will not have similar appearing signals. To indicate a future state of an aircraft a different colour language will help distinguish with aircraft related elements while a similar shape language will show the similarities between the two.

5.1.5 IAF related elements

IAF related elements are derived from the principles of discriminability and making the display legible just as the clearance related elements.With only five colour categories, this display adheres to the principle of avoiding absolute judgement limits.

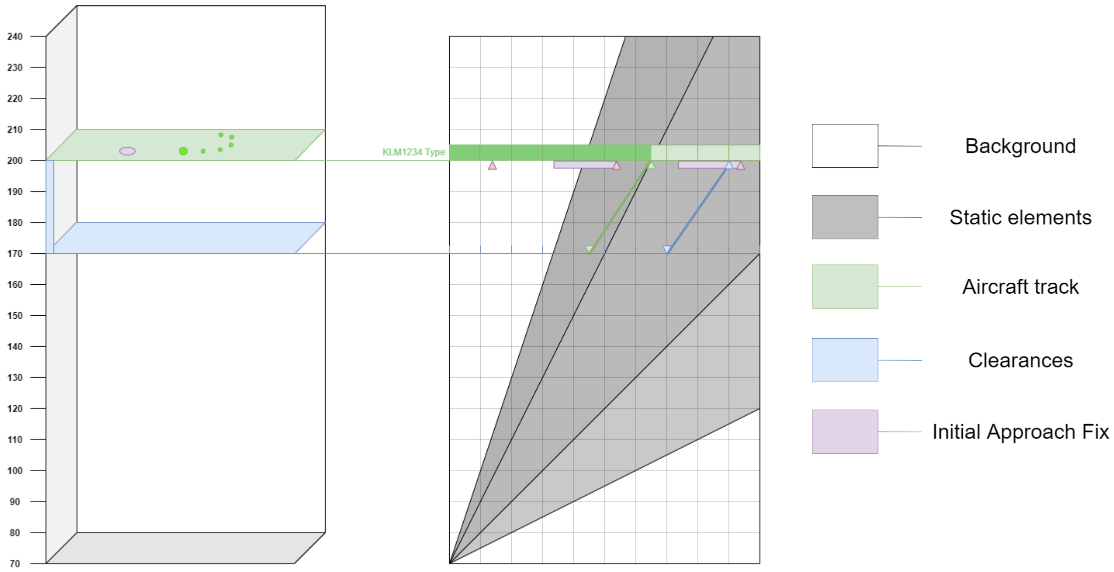


Figure 5.1: Final display design with colour language legend

5.2 Display overview

A short overview is given of all display elements. Figure 4.1 showed the abstraction hierarchy of this display, Figure 5.2 shows the final display with numbering of each display element and Table 5.1 gives a short description of each display element, corresponding to Figure 5.2.

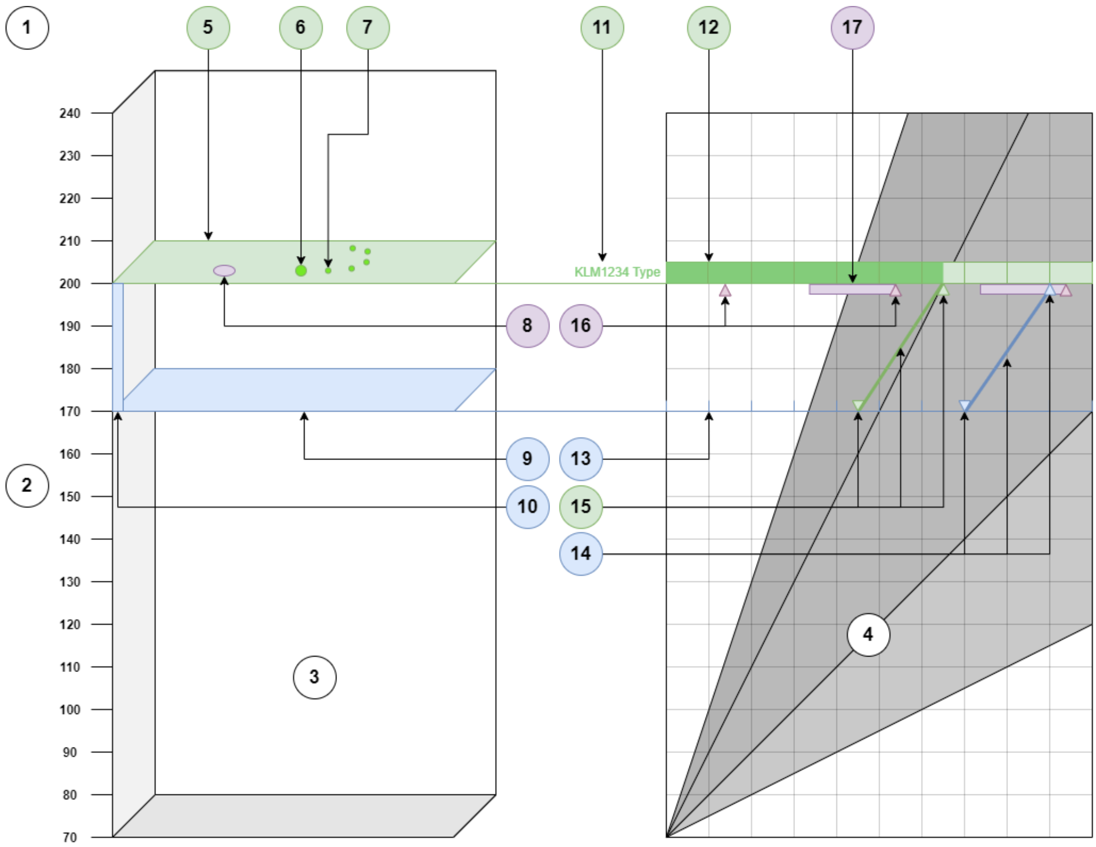


Figure 5.2: Final display design with display element number references

#	Element name	Colour language	Element description
1	Background	Background	A background colour
2	FL indicator	static	Scale of flight levels in the vertical axis ranging from 70 to 240
3	Stack volume	static	Three planes which cover the backdrop of a holding volume
4	RoCD fan	static	Rectangle with grid. Large triangles situated within rectangle
5	Aircraft plane	Aircraft	A lateral plane within the stack volume intersecting aircraft position
6	Aircraft blip	Aircraft	Position of aircraft track within the stack volume
7	Velocity dots	Aircraft	Trail of dots left behind by aircraft track updates
8	IAF marker	IAF	Lateral IAF position within the stack volume
9	Cleared plane	Cleared	A lateral plane within the stack volume intersecting the aircraft's cleared flight level
10	Occupied flight levels	Cleared	A bar stuck to the FL indicator, the aircraft plane and the cleared plane
11	Aircraft information	Aircraft	Information on aircraft callsign and type
12	Aircraft timeline	Aircraft	Timeline situated on top of RoCD fan and connected to aircraft plane
13	Cleared timeline	Cleared	A timeline situated on top of RoCD fan and connected to the cleared plane
14	RoCD markers	Cleared	An event intersecting both timelines with a line connecting the two. Gradient is determined by RoCD
15	EAT	Aircraft	An event present on both timelines with a line connecting the two. The gradient is determined by the RoCD
16	IAF flyover	IAF	Repeating event markers with frequency equal to holding procedure duration
17	IAF flyover variability	IAF	A bar connected to the IAF event which stretches to the left. It will only stretch to 2 minutes after the previous IAF event and/or 2 minutes after the left side of the RoCD fan

Table 5.1: Overview of all display elements

5.3 Static display elements

Static elements of the display do not change over time. Information is presented as a backdrop and is meant to help an ATCO understand exact measurements of dynamic elements if they are required. In Figure 5.2, numbers 1,2,3,4 are all static elements. Because Element 1 has already been elaborated upon, it will not have a dedicated subsection. Elements 2-4 will be explained in this section.

5.3.1 Element 2 - Stack volume

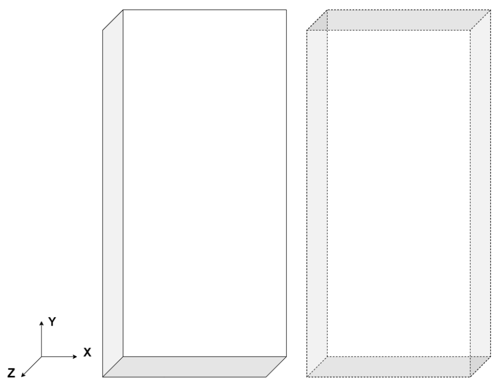


Figure 5.3: Left: axis definitions, Mid: Stack volume, Right: volume shape encapsulated by stack volume

The stack volume is a volume represented with three surfaces as a backdrop of the XY, YZ and XZ planes. The holding airspace is meant to be encapsulated by this stack volume representation. The plane at the bottom of the stack volume represents the lateral plane which will overlap with the radar display. Other planes contain the altitude information. Aircraft cleared for holding will show a plane as described in Section5.4.1. Aircraft cleared for holding AND within the holding airspace will show an aircraft blip and velocity dots as described in Sections 5.4.5 and 5.4.2. The scale of x,y and z are not one to one. An emphasis is lain on visualization of vertical separation, so the Y-axis will have scaling to help visualization. Lateral scaling will be one to one. The shape of the stack volume is viewed in an isometric projection camera frustum. The camera angle used to view the stack volume is chosen such that the depth of the aircraft plane described in Section 5.4.1 will never overlap when tracks have a separation of 10 FLs. Lateral position information on the holding display is not shown before the aircraft's position is within the holding airspace as it is deemed not useful until the aircraft has already established a holding procedure and is situated in the holding stack. Lateral position information is used to understand the aircraft's position in a holding procedure and helps the ATCO with their leg time variation control task. Showing aircraft in the stack volume is meant to visualize constraints based on the holding airspace. Aircraft flying within this zone should appear in this volume. If they do not then they are violating the holding airspace constraint. These violations will not occur during the experiment however. ATCOs will also be able to improve their 3D understanding of the actual airspace they are responsible for.

5.3.2 Element 3 - FL scale indicator

On the front left side of the stack volume, flight level indicators are shown with a scale from 70 to 240 (representative of Dutch airspace holding stack). These FL indications must be legible to the ATCO.

This will help ATCOs determine exactly at what flight level an aircraft is flying. Other holding stack display strategies also use this technique in various means, such as holding stack support tools used by NATS described in Figure 2.9 and vertical display support tool as used by LVNL described in Figure 2.8. This is likely due to the importance of vertical separation in holding stack control. Holding stack controllers must control vertical separation much more precisely than lateral separation. The FL indicator will help controllers understand an aircraft's FL just as in the already implemented holding stack support tools. Flight level scale range corresponds with minimum and maximum holding flight levels within the controlled airspace. The chosen camera projection in the display is the orthographic projection method. The reason for this is that the camera projection ensures constant shape language regardless of Flight level. This is not true for the more common perspective projection method.

5.3.3 Element 4 - FL/time grid with RoCD fan

Using a time axis in the X-axis and a vertical displacement in the Y-axis, a grid is displayed upon a plane named the FL/time. The grid units are 1 minute in the X-axis and 10 FLs in the Y-axis. Using these scales a gradient is drawn that represents a Rate of Climb/Descent (RoCD). Four typical RoCDs are drawn to show the RoCD of 500 ft/min, 1000 ft/min, 2000 ft/min and 3000 ft/min. Each of these RoCDs are drawn from the point of t=0 and FL 70. These gradients are called the "RoCD fan". Minutes on the x-axis are measured as "time from now until a given event". Figure 5.4 shows these RoCDs In bold. This is are temporarily shown as ATCOs will quickly be able to pick up the meaning behind these four angles. Being a background display element, shades of gray are used for lines and areas. The RoCDs are shown darkening with each increasing step. RoCD below 500 and above 3000 ft/min are given a larger contrast colour to differentiate from a normal descent. Using this FL/time grid, a rate of climb provides information about how long an aircraft will take to reach FL 70 given different descent profiles.

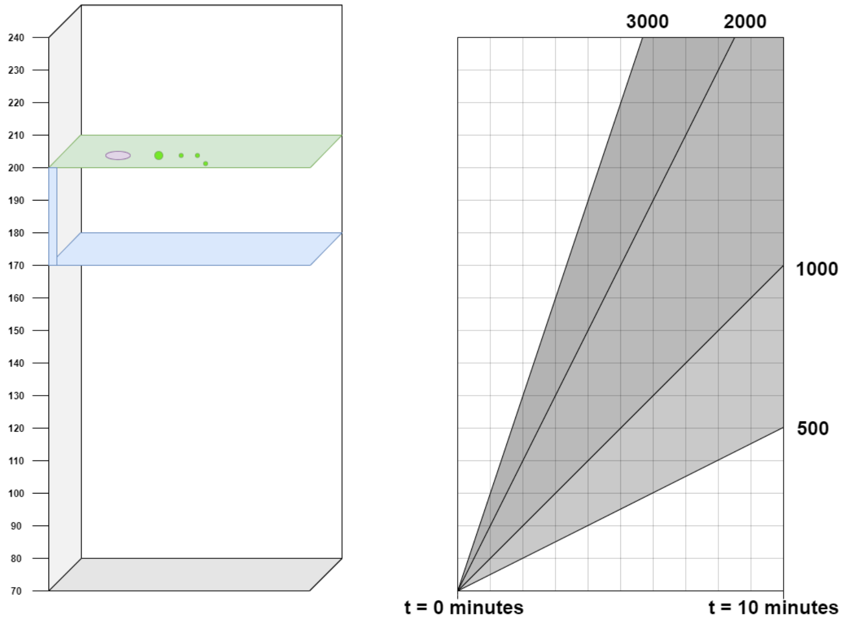


Figure 5.4: RoCD fan

The chosen RoCD profiles are chosen because they represent a range of RoCDs that an average commercial airline might use to descend within an ACC sector. A graph is shown in Figure 5.5 which displays descent capabilities of common commercial jet aircraft. ATCOs can use these gradients to plan when their aircraft arrive at FL 70 based on when their given events occur. This element was added as an attempt to show the physical constraints of aircraft. This does not show exact physical constraints of aircraft but it does show a range of common profiles. This should be sufficient for an ATCO to understand what is a normal descent and if more communication in required.

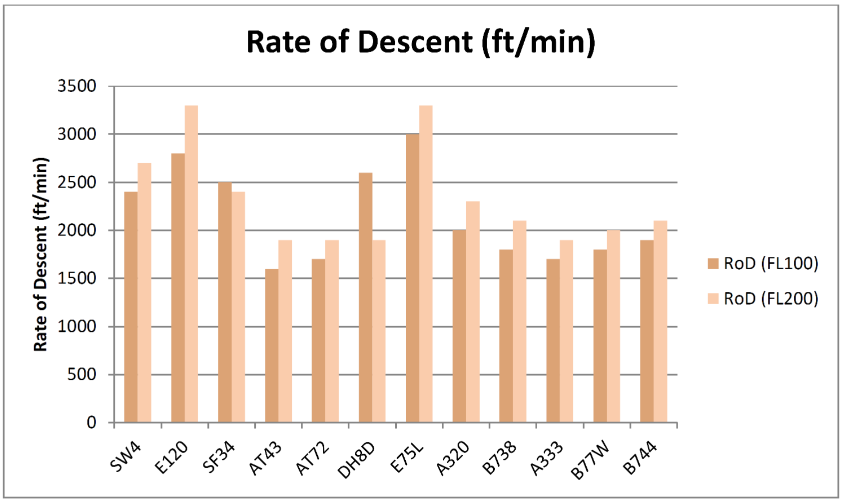


Figure 5.5: Typical RoCD of aircraft [5]

5.4 Dynamic display elements

Many dynamic display elements are included in this display. All dynamic elements will change position on the display over time. Some will change shape. Each element described in the following subsections will belong to only one instance of an aircraft. Each of the dynamic elements of the display will therefore be duplicated by the number of aircraft on the screen. There is one exception related to the clearances. If an aircraft reaches its clearance then the clearance related elements will disappear.

5.4.1 Element 5 - Aircraft plane

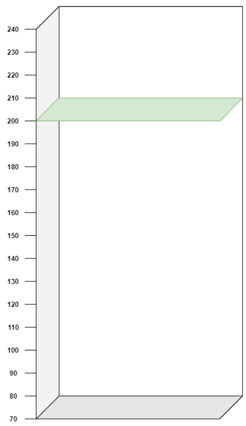


Figure 5.6: Slice of airspace showing the aircraft plane

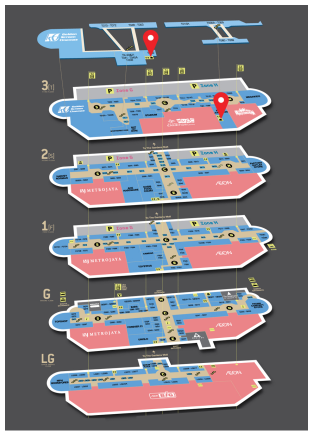


Figure 5.7: Map of Mid-valley mega mall [6]

A cross-section of the aircraft track's vertical position. The aircraft plane will move with each track update, following the aircraft's track signal. Slight transparency in the plane will allow the controller to see the corners of the stack volume through the plane. A controller will be able to read an exact measurement of the aircraft FL when looking at the intersections between the track actual plane and the FL scale indicator. This design is inspired by a common application of 3D navigation support often found in multistory shopping malls. An example is shown in Figure 5.7. In a shopping mall there will often be a map to guide shoppers to their desired shopping destinations. On this map can be found a lateral plane for each story. It is on the plane that the lateral information is found. If a shopper wishes to navigate to a shop on another story, there will be multiple steps to reach such a destination. First the shopper must navigate to the escalator/elevator. This is lateral navigation. Secondly the shopper must navigate to the correct floor. This is vertical navigation. Then the shopper must again navigate laterally again to their final destination.

This simplifies a 3D spatial navigation problem into simpler 1D and 2D spatial navigation problems. An example is shown in Figure 5.7. This design attempts to make use of this simplification to provide 3D spatial information at a lower cognitive cost. Understanding what FLs aircraft fly at is the most important feature of any holding stack display. If FL information is obscured, then the vertical separation constraint may be at risk. This is absolutely unacceptable for safety. Because of the orthographic projection, each distance has consistent representation no matter the position in the display. Because of the chosen camera angle described in Section 5.3.1, aircraft planes will never overlap if separation constraints are met.

5.4.2 Elements 6 and 7 - Track blip with velocity dots

A similar indicator shape as that used on the radar screen will be used to represent an aircraft track's position. Velocity dots will trail from this position to indicate an aircraft's speed with the same rate as on the radar screen. The indicator will coincide with the track actual plane. The velocity dots will be projected onto the aircraft plane. With respect to the AH these elements show updates of the spacial states of the aircraft. A controller will be able to interpret past present and, to an extent, future states.

Track updates are given at very low frequencies of the order 0.1 - 0.3 Hz. This hampers intuitive understanding of aircraft speed and direction. Velocity dots help the ATCO perceive speed and direction as well as improve cognition of the system. Keeping similar shape and colour language helps consistency when ATCOs switch between displays.

5.4.3 Element 8 - IAF marker

A circle projected onto the aircraft plane represents the IAF lateral position. This circle represents the relative position of the holding procedure compared to the stack volume. Aircraft are expected to fly over this point in the cross section once per holding. The position of this marker will depend on right hand turn or left hand turn holding stacks. The position of the waypoint will be placed so that the aircraft is in line of exiting either on the right side of the stack volume.

5.4.4 Element 9 - Aircraft cleared plane

A plane with identical features to the aircraft plane is situated on the intersection of the cleared flight level of the aircraft. This acts as a virtual image showing a prediction of where the aircraft will be once it reaches its cleared flight level. There is only a difference in colour language and Y-axis position. The transparency of the plane will fade from 0.3 to 0 when the aircraft plane moves close to the cleared plane.

5.4.5 Element 10 - Occupied flight levels

A bar connecting aircraft plane and aircraft cleared plane. This bar is attached to the FL indicator. This cleared connection is a representation of the flight levels that are unavailable for other aircraft. Any flight level next to this bar is unavailable for other aircraft to be cleared for. Other aircraft may also not be cleared within 10 flight levels of this indicator.

5.4.6 Element 11 - Aircraft information

Connection between aircraft plane on left side of display and time relevant information of that aircraft on right side of display. Additional information containing aircraft callsign, aircraft type and flight level are displayed hovering above this line.

All of the information on the left side of the display is connected to the right side of the RoCD fan. A connection will help ATCOs to manage the distance between the two representations of information. A similar line connection without aircraft information connects the aircraft cleared plane with the cleared timeline.

5.4.7 Element 12 - Aircraft timeline

The aircraft timeline is positioned at the same FL as the aircraft's track information and represents the aircraft's timeline. The timeline is linked to the left side display with a connection line as described in Section 5.4.6. The "now" time of the display is shown on the left hand side of the grid and the timeline moves to the left at a rate of 1 unit per minute. Each event on the timeline will follow Equation 5.1. Important events on the timeline are EAT, IAF flyover and time until FL 70 is reached.

$$time\ until\ event\ =: t_{event} - t_{now} \tag{5.1}$$

Relevant events to control of the aircraft will be displayed on this timeline as it moves in the stack display and progresses through time. This representation of time will prove to be useful for ATCOs to plan their control actions. The RoCD fan will help the controller understand how the current RoCD will effect the aircraft's future states. This is further explained in Section 5.4.10. It will also show how long it will take to reach FL 70. If an aircraft is descending too slow or too fast, an ATCO can give commands accordingly. The contrast order of darker to lighter based on gradient for the RoCD fan is chosen based on subjective appeal.

5.4.8 Element 13 - Cleared timeline

A timeline showing a predicted future state of the aircraft once it reaches its cleared FL. To reduce the complexity of the display, this timeline has been kept simple and will only show two events. Namely: EAT and time until FL 70.

5.4.9 Element 14 - RoCD timing

A calculation is made using current RoCD revealing how long the descent may take to reach FL 70 from current FL if uninterrupted. This calculation can be done for any FL using Equation 5.2 where RoCD is positive in climb and negative in descent. The RoCD marker will appear as a triangle underneath the cleared timeline, marking the predicted duration that it will take to reach FL 70. A similar calculation is made for the time to reach the cleared flight level. A RoCD marker is displayed on the cleared timeline as an event representing time to reach FL 70 after the cleared flight level is reached. A line connects the RoCD event on the aircraft timeline and the cleared timeline. The gradient of this line will match the RoCD fan perfectly.

$$time\ until\ target\ flight\ level\ = (FL_{target} - FL_{current})/RoCD \tag{5.2}$$

The RoCD fan will help the ATCO understand what that RoCD is approximately without having to read exact values. When the aircraft approaches level flight, its rate of descent will be near zero. As a result, the gradient of the RoCD will end as a straight line and the marker will tend to infinity. This is desirable because then the ATCO will not be able to see a RoCD marker (as it is off screen) when an aircraft is at level flight. The ATCO will then be able to quickly conclude that the aircraft has RoCD of near zero if there is no marker present. There is also a transition period between level flight, communication and then descent but this will be relatively small.

5.4.10 Element 15 - Expected Approach Time (EAT)

This is one of the most important events on the aircraft timeline, as this is the time at which the aircraft is to leave the holding stack. It is the main time when considering all control tasks listed in Section 4.2. With this event displayed on the timeline, ATCOs are able to perform control actions to shift other events in favour of EAT. EAT events are shown on the aircraft timeline and the cleared timeline. They are connected with a line, just as the RoCD timing, but this line does not follow the RoCD fan. Instead it follows with a gradient equal to that of the RoCD timing.

5.4.11 Element 16 - IAF flyover timing

An event displayed on the aircraft timeline. This event represents each time the aircraft is planned to fly over the IAF. Because of the nature of a holding procedure, the flyover time will repeat itself with a frequency equal to the holding procedure duration. The duration of a holding procedure is predominantly reliant on leg time and is described in Equation 5.3 where N represents the holding procedure sequence number.

$$time\,until\,IAF\,flyover = N * holding\,procedure\,duration - time\,since\,last\,flyover \tag{5.3}$$

5.4.12 Element 17 - IAF variability

A bar attached to the IAF flyover timing serves as a visual representation of all possible shortenings that the IAF flyover timing can take. This will help ATCOs interpret the constraints of the holding procedure in the one dimensional language of a timeline. The minimum duration of a holding procedure is two minutes as shown in Figure 2.3. Only the minimum holding procedure time is shown as a constraint for IAF variability. Maximum constraint was decided to be excluded as it could end up overlapping with the next IAF flyover event, cluttering the aircraft timeline solution space.

5.5 Concluding remarks

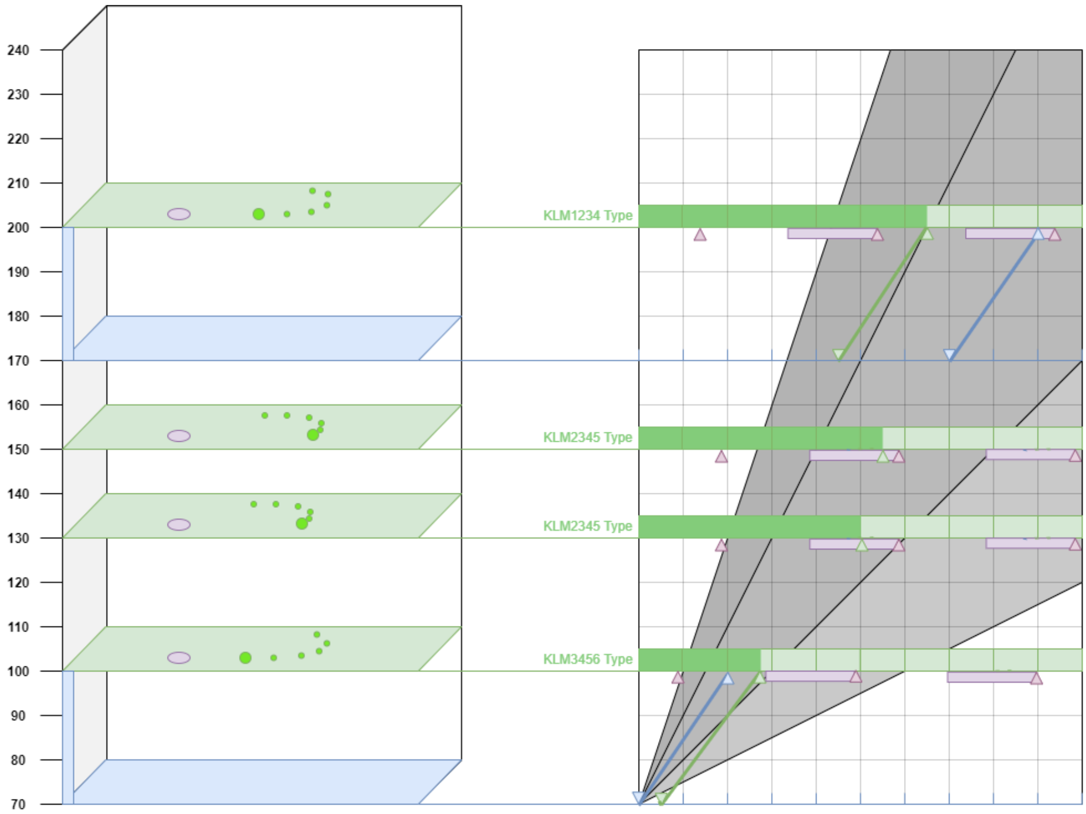


Figure 5.8: Final design of display

As discussed in Section 1.1, the goals of this display are to increase at least one of the KPAs. An improvement in **fuel flow**, **accuracy of delivery**, **situation awareness**, **workload** or **system acceptance**. With the help of CWA, display elements have been identified and designed to support control tasks and cognition. For example: both control tasks described in 4.2 require the air traffic controller to mentally align the ETA with the exit time of the aircraft. Exit time must be aligned with both FL and holding procedure timing using knowledge-based behaviour. Using this novel display, each event is displayed on the timeline and both tasks become rule-based behaviour as the task is transformed into a one dimensional error handling control task. IF: events do not align as desired, THEN: use control actions to align events. This result was achieved by mapping the physical forms of geometry and holding aircraft state values from the AH to the interface.

6 | Experiment setup

Evaluation of the display design will be done by means of an experiment. The experiment will be used as a measure for addressing the research question defined in Section 1.2. KPAs will be used for performance measurements in this experiment. Evaluation of KPAs must be enabled by analysis of the data generated in the experiment.

6.1 Participants and explanation to participants

Participants that have domain knowledge will be invited as participating controllers in the experiment. Participants involved with holding stack control will be asked to fill in a questionnaire beforehand to see how many hours have been spent controlling aircraft in and outside of holding stack management. This could be used to spot outliers. A fair amount of time will be dedicated to training air traffic controllers desired goal states and available control actions. This is done to eliminate any misunderstanding of display functionality. Control tasks and strategies will be introduced as measures to achieving goal states using available control actions. Examples will be used during training to test the knowledge of each participant before continuing to data collection.

After training, two different scenarios will be used to gather data on the display. These scenarios are further explained in Section 6.3. Due to time constraints explained in this section, participants are divided in two main groups; an experiment group and a control group. The experiment group will conduct the experiment with the novel display while the control group will use a standard LVNL setup

6.2 Apparatus

The NARSIM environment developed by NLR is an advanced air traffic control simulation environment. NARSIM is a research tool often used for concept development and validation, prototyping of new ATC systems and training [23]. NARSIM will be the environment used for modeling air traffic in the experiment. In order to interface with NARSIM, new code has been developed in the C# programming language. This code allows the display to receive data from the NARSIM environment. The display has been developed in the Unity3D game engine, enabling 3D environments, shaders, camera projection type manipulation as well as many more features for future development including Virtual Reality (VR) and Augmented Reality (AR). Regarding the code, a Unified Modeling Language (UML) diagram is shown in Figure E.3 and two sequence diagrams are shown in figures E.1 and E.2. All are found in the appendix.

Participants involved will be seated with a mobile setup of NARSIM and the novel display. They will have full view of the lateral radar display. Next to the radar display will be the newly developed holding stack display support tool. Test participants will have access to both screens during the experiment while control participants will only have access to the radar display with LVNL's vertical view. Participants will use command inputs in order to control air traffic. Aircraft will respond to command inputs using NARSIM's simulation of an aircraft's autopilot system. This is done by selecting an aircraft with the mouse and then inputting a clearance with the terminal.

		Runs	
		1	2
ATCOs	1	D1S1	D1S2
	2	D2S1	D2S2

Table 6.1: Balanced latin square distribution of display type (D) and scenario complexity (S)

6.3 Scenarios

Under normal circumstances ATCOs in the Netherlands have been trained to avoid the use of holding stacks. This is not in the best interest of conducting a feasibility study for this novel display which attempts measure KPAs during holding stack management. For the course of this experiment it is therefore reasonable to include an assumption which makes holding stack operations standard procedure. This is done for all incoming flights scheduled to land at Schiphol airport. During the experiment a single IAF is chosen above which all holding stack operations are conducted. Scenarios will be divided in two complexity levels. Complexity will be varied using air traffic density and aircraft type.

Because each test run may include multiple standard holding procedures with a duration of 4 minutes, the experiment duration will be long. Preliminary estimates permit 30 minutes per experiment run. This is a conservative estimate. For this reason each scenario will have a long duration and only two scenarios are able to be conducted after training per participant.

6.4 Independent variables

The independent variables in the experiment for this report define the factors with which the experiment is deliberately manipulated. The independent variables will be: the two available displays and two yet to be defined complexity levels:

1. Display options:
    - Regular display setup of a typical LVNL ATCO.
    - New display setup
2. Scenario complexity options:
    - Non-challenging low complexity traffic scenario
    - Challenging high complexity traffic scenario

When deciding on independent variables, the question "What is a challenging traffic scenario?" emerges. A domain expert will be consulted for defining what a "challenging traffic scenario" is. With this setup a latin square distribution can be set up as shown in Table 6.1. Participant test groups will therefore have to be a multiple of 4.

6.5 Control variables

To remove experiment confounds, control variables are introduced, simplifying experiment parameters compared to real-world application. Control variables will include:

- Simple weather conditions

- Aircraft will respond to controls exactly
- All aircraft in experiment have FMS and MCDU
- The same IAF will be used for holding stack management
- Holding turn takes exactly 1 minute
- Flight computers are able to execute holding procedures exactly as defined. Four minute standard holding procedures and variations in leg time is executed exactly
- Aircraft will communicate programmed holding leg time
- Holding stack is standard procedure

Simple weather conditions are defined as weather conditions with no wind, standard atmosphere and good visibility.

6.6 Dependent variables

Dependent variables are split in to two categories: objective and subjective variables. Dependent variables are values that are expected to change when independent variables are manipulated. The following dependent variables will be measured during the experiment.

1. Objective variables
    - Fuel flow
    - Interval between holding stack exit time and EAT
    - Control actions taken by controller
    - Time at which control action is given
    - Aircraft attitude over time
    - Stack throughput
2. Subjective variables
    - Situational Awareness (SA)
    - Workload
    - System acceptance

A questionnaire will be adapted from the Situational Awareness for SHAPE (SASHA) [24] questionnaire template to measure situational awareness. A questionnaire from NASA's Task Load Index (TLX) [25] will be included to measure perceived workload. A modified Cooper Harper will be used to measure system acceptance using Controller Acceptance Rating Scale (CARS) [26]. Software will be set up to measure objective data such as Fuel efficiency and Accuracy of delivery.

6.7 Experiment procedure

A short chronological list of time estimates are given with a total budgeted time of 2 and a half hours for each participant:

- Intro questionnaire - 10 min
- briefing - 15 min
- training sessions - 30 min
- Question round / knowledge test - 15 min
- Scenario 1 - 30 min
- Scenario 2 - 30 min
- Exit questionnaire - 20 min

This will give enough time for participants to try two scenarios with varied complexity while still reserving a large amount of time for explanation, training and gathering subjective data. A decision could be made to try to fit both displays per participant but the total budgeted time per participant would have to be near doubled as each display requires different training.

6.8 Hypothesis

While results are still pending a hypothesis is drawn.

Predictions are drawn on how KPAs change depending on which display is used. The following points are made as a prediction to pending results.

- SA is predicted to increase for the new display. There is a risk that SA is decreased due to display complexity and display clutter. The prediction however is that the added features will benefit the controller in a manner which will increase cognitive understanding of the system and therefore also benefit the controller's SA.
- Workload is predicted to shift to a different point in time and remain manageable. The principal behind EID is not to minimize workload but instead to increase a controller's cognition. With an increased cognition a controller is then able to make more informed control actions. Because the workload of synchronizing the holding procedure's IAF flyover with the aircraft's EAT has been shifted from FL 70 to a any FL, controllers may have reduced workload once the aircraft reaches FL 70 but increased workload elsewhere.
- Accuracy of delivery is predicted to increase. Time between exit and EAT is predicted to go down as the novel display has a dedicated support tool for reduction of this interval. The lack of a support tool for ATCOs when it comes to accuracy of delivery was one of the main drivers of this study.
- Fuel efficiency has the potential to increase with new strategies such as higher FL control task management. Fuel efficiency is however predicted not to vary much. Novel strategies to take advantages of all the display features must be developed before a significant increase can be seen. Fuel efficiency is not the main goal of holding stack control but is a KPA nonetheless.

6.9 Data analysis

Analysis of the data will be conducted as a feasibility analysis. Because the population will consist of domain experts, the number of participants will not reach the necessary minimum to draw conclusions. According to the central limit theorem a minimum of 30 participants would be needed to draw conclusions and because the participant groups are split in two, a minimum of 60 participants would be needed to draw conclusions. This is infeasible for the scope of this experiment.

6.10 Conclusion and Outlook

In this preliminary report work up until the experiment phase has been conducted. A literature study has been conducted in Part 2. In this literature study the ConOps of an ATCO involved with holding stack management is presented. A CWA has been performed in Chapter 4. In this CWA many constraints of the system are revealed and a knowledge based behaviour requirement was identified for a control task. A novel display design has been presented in Chapter 5 enabling a control task to be changed from knowledge-based behaviour to rule-based behaviour. Other aspects of the system constraints are also visualized. A preliminary experiment setup has been proposed in Chapter 6. In this experiment setup proposal a predicted answer to the research question is given in the form of a hypothesis in Section 6.8.

In order to test this hypothesis the experiment must be conducted. After the experiment is conducted enough data should be available to compare with the hypothesis and answer the research question. Before the experiment can be conducted the display software must be refined and tested to ensure a smooth experiment procedure. Once the answer is available, further judgements regarding display feasibility can be drawn.

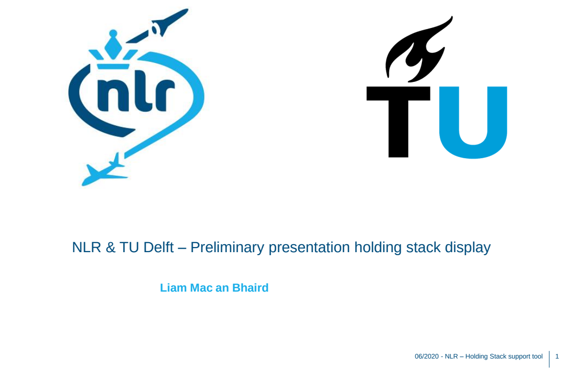
Part III

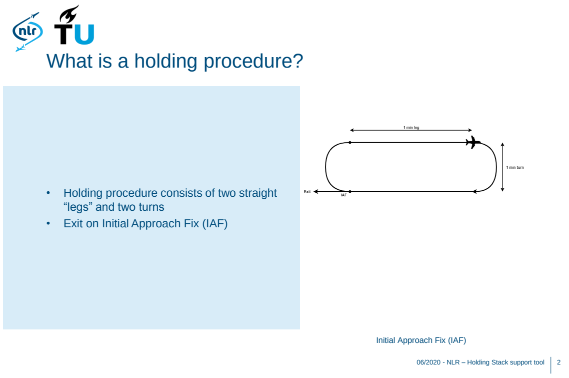
Book of Appendices

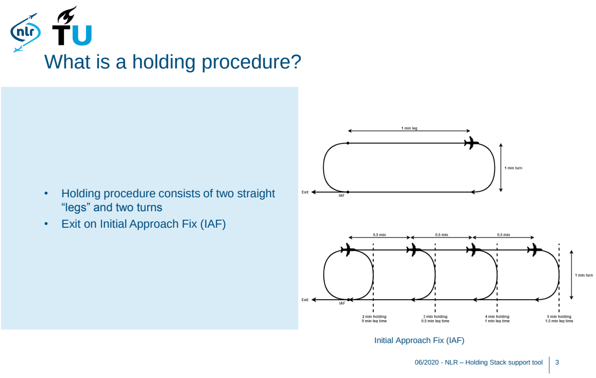
A | Experiment

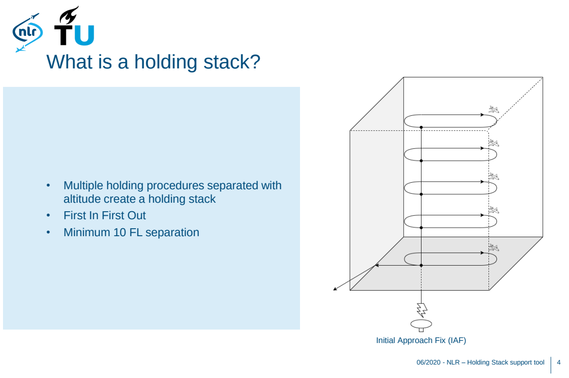
A.1 Briefing - Baseline

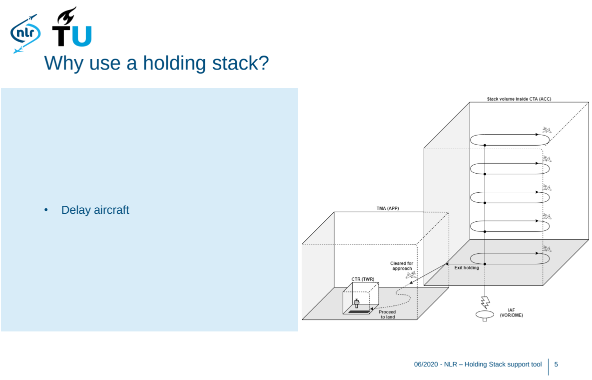
Experiment briefing is done in a powerpoint presentation format. The goal is to have all participants be comfortable with the test experiment before conducting the final experiment.

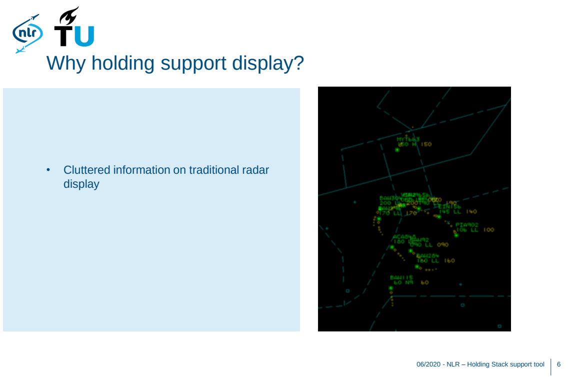






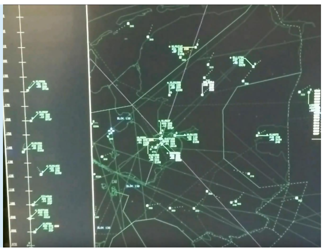




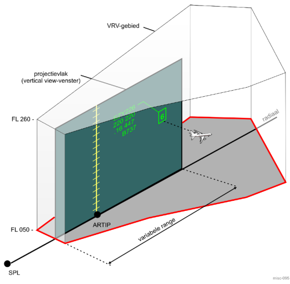


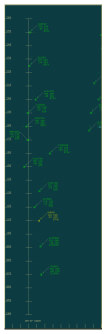
Current holding stack support tools - LVNL

- LVNL uses vertical view display

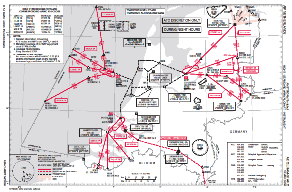


LVNL Holding

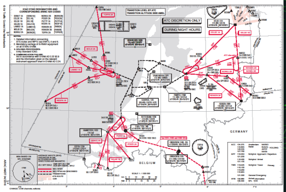


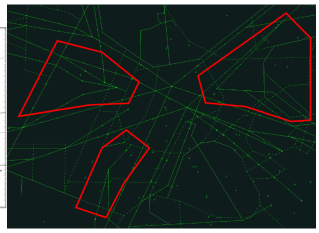


LVNL Holding



LVNL Holding



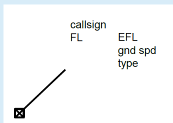


TASK - Basic

- Select aircraft in radar display
- Move label
- Select aircraft in Vertical view

TASK - Basic

- Select aircraft in radar display
- Move label
- Aircraft can also be selected in the vertical view
- Discuss label



TASK - Basic

- Give invalid command “ABC” and press ENTER
- Give valid command “EFL 160” and press ENTER
- Take selected aircraft under control “UCO” and press ENTER
- Give valid command “EFL160” and press ENTER

TASK – Descent

- Clear aircraft to FL 70
- FFW to aircraft reaching bottom of stack
- Exit holding stack using “HDG SPL” when aircraft is between FL 70 and 100

TASK – Descent

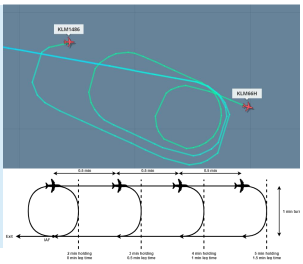
- FFW to multiple aircraft
- Take control of all aircraft by pressing F1 and then ENTER
- Clear all aircraft to next free FL, maintain 10 FL separation
- Standard FL commands are given in multiples of 10
- Exit aircraft “DAL134” between FL 70 and 100 by pressing F3 and ENTER

TASK – HLT change

- Increase simulation speed
- Change it’s holding leg time with “HLT 0” and ENTER
- Wait for a holding procedure
- Clear the aircraft to exit with “HDG SPL”

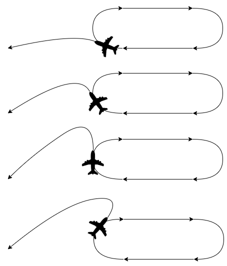
Holding leg time & Accuracy of delivery

- Aircraft must pass over Initial Approach Fix waypoint RIVER at EAT
- Change holding leg time to increase accuracy



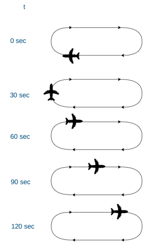
Holding leg time & Accuracy of delivery

- Bad exits for accurate delivery



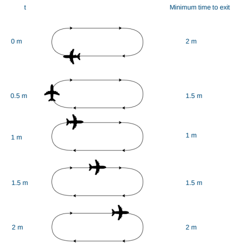
Holding leg time & Accuracy of delivery

- Positions during a 4 minute holding



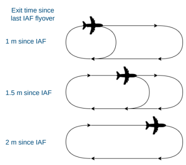
Holding leg time & Accuracy of delivery

- Minimum time to exit decreases until 1 minute into holding procedure
- After 1 minute the minimum time to exit will increase by one seconds for every one second flown
- After completing the outbound leg, the aircraft will return to the waypoint
- An exit command given after this point will follow the remaining holding procedure precisely



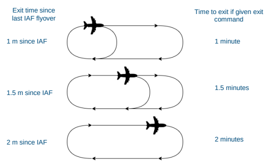
Holding leg time & Accuracy of delivery

- Manual exit timings



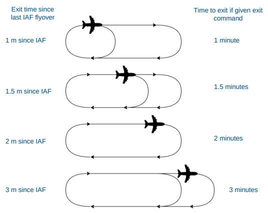
Holding leg time & Accuracy of delivery

- Manual exit timings



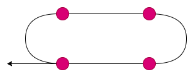
Holding leg time & Accuracy of delivery

- Manual exit timings
- Longer HLTs



Holding leg time & Accuracy of delivery

- Manual exit timings
- Longer HLTs



TASK – Accurate delivery

- Resume and feel free to ask for speed up
- Control aircraft to exit IAF near EAT
- Use "HDG SPL" or F3 and ENTER to exit when desired

06/2020 - NLR – Holding Stack support tool | 25

- BREAK

06/2020 - NLR – Holding Stack support tool | 26

TASK – Test run

- Maintain 10 FL separation
- Move aircraft to the bottom of the stack
- Release aircraft near EAT between FLs 70 and 100

06/2020 - NLR – Holding Stack support tool | 27

Experiment run

- Maintain 10 FL separation
- Move aircraft to the bottom of the stack
- Release aircraft near EAT between FLs 70 and 100

06/2020 - NLR – Holding Stack support tool | 28

Questionnaire

- Fill in google form

06/2020 - NLR – Holding Stack support tool | 29

Thank you for participating!

06/2020 - NLR – Holding Stack support tool | 30

A.2 Briefing - Stack Planner

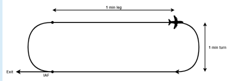
NLR & TU Delft – Preliminary presentation holding stack display

Liam Mac an Bhaird

06/2020 - NLR – Holding Stack support tool | 1

What is a holding procedure?

- Holding procedure consists of two straight "legs" and two turns
- Exit on Initial Approach Fix (IAF)

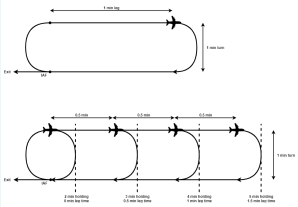


Initial Approach Fix (IAF)

06/2020 - NLR – Holding Stack support tool | 2

What is a holding procedure?

- Holding procedure consists of two straight "legs" and two turns
- Exit on Initial Approach Fix (IAF)

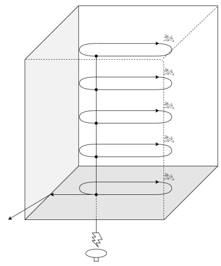


Initial Approach Fix (IAF)

06/2020 - NLR – Holding Stack support tool | 3

What is a holding stack?

- Multiple holding procedures separated with altitude create a holding stack
- First In First Out
- Minimum 10 FL separation

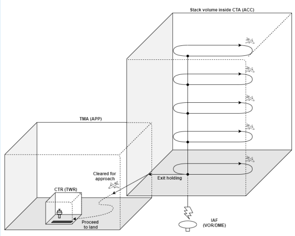


Initial Approach Fix (IAF)

06/2020 - NLR – Holding Stack support tool | 4

Why use a holding stack?

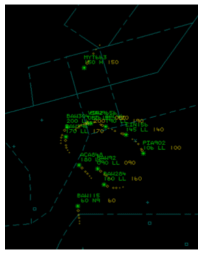
- Delay aircraft



06/2020 - NLR – Holding Stack support tool | 5

Why holding support display?

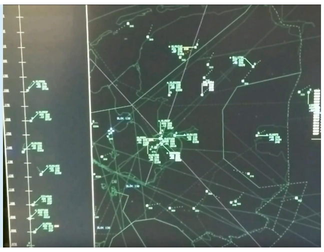
- Cluttered information on traditional radar display



06/2020 - NLR – Holding Stack support tool | 6

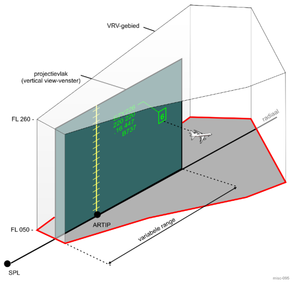
Current holding stack support tools - LVNL

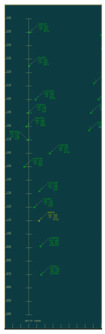
- LVNL uses vertical view display



06/2020 - NLR – Holding Stack support tool | 7

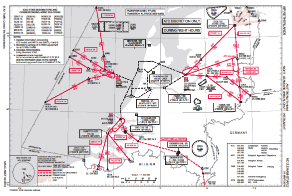
LVNL Holding





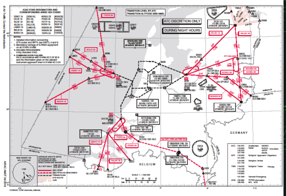
06/2020 - NLR – Holding Stack support tool | 8

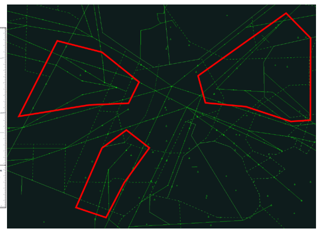
LVNL Holding



06/2020 - NLR – Holding Stack support tool | 9

LVNL Holding





06/2020 - NLR – Holding Stack support tool | 10

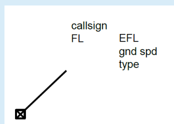
TASK - Basic

- Select aircraft in radar display
- Move label
- Select aircraft in Vertical view

06/2020 - NLR – Holding Stack support tool | 11

TASK - Basic

- Select aircraft in radar display
- Move label
- Select aircraft in Vertical view
- Discuss label



06/2020 - NLR – Holding Stack support tool | 12

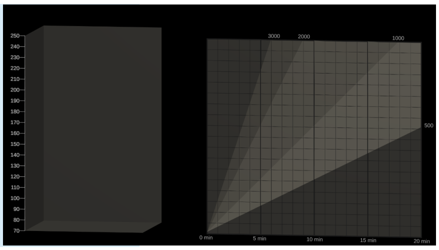
TASK - Basic

- Give invalid command “ABC” and press ENTER
- Give valid command “EFL 160” and press ENTER
- Take selected aircraft under control “UCO” and press ENTER
- Give valid command “EFL160” and press ENTER

Display – Background

Features Left:
- Holding stack volume
- FL indicator

Features Right:
- Grid
- RoCD fan

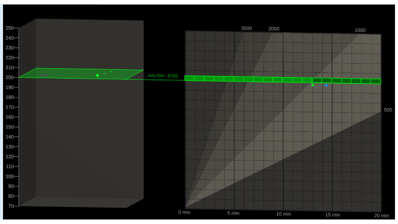


Display – Aircraft information

Features Left:
- Plane on which A/C intersects altitude
- A/C lateral position
- Velocity dots

Features mid:
- A/C info

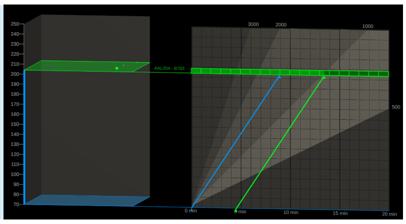
Features Right:
- A/C timeline
- Events on timeline



Display – Clearances

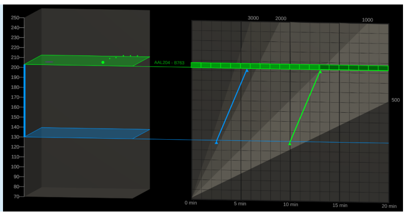
Features Left:
- Cleared FL
- Occupied FLs

Features Right:
- Timeline when Cleared flight level is reached



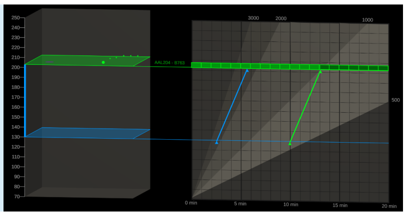
Question – Timeline Events

- Given current ROD, will the aircraft arrive on time for EAT if cleared for FL 70?



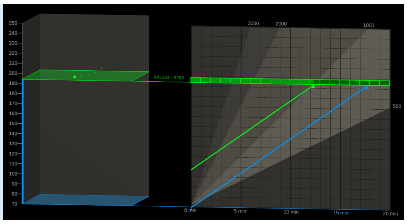
Question – Timeline Events

- How long will it take to reach FL 70 if cleared for FL 70?



Question – Timeline Events

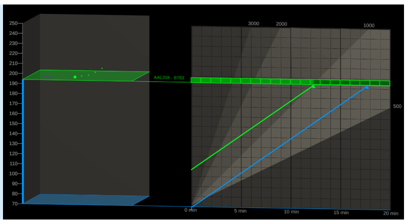
- Given current ROD, will the aircraft reach FL 70 on time for EAT?



06/2020 - NLR – Holding Stack support tool | 19

Question – Timeline Events

- How late will the aircraft be at FL 70 given current ROD?



06/2020 - NLR – Holding Stack support tool | 20

TASK – RoCD fan

- Clear aircraft to FL 70
- Change Rate Of Descent with “ROD 500”
- Change ROD with “ROD 3000”
- FFW to aircraft reaching bottom of stack
- Exit holding stack using “HDG SPL”

06/2020 - NLR – Holding Stack support tool | 21

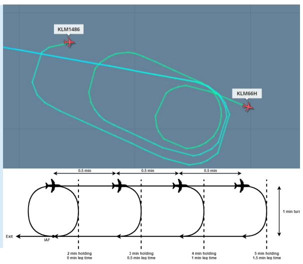
TASK – RoCD fan

- FFW to multiple aircraft
- Clear all aircraft to next free FL, maintain 10 FL separation
- Discuss which aircraft will make it on time for EAT

06/2020 - NLR – Holding Stack support tool | 22

Holding leg time & Accuracy of delivery

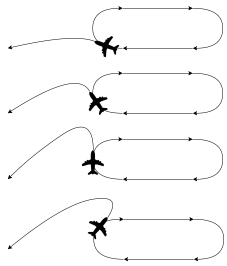
- Aircraft must pass over Initial Approach Fix waypoint RIVER at EAT
- Change holding leg time to increase accuracy



06/2020 - NLR – Holding Stack support tool | 23

Holding leg time & Accuracy of delivery

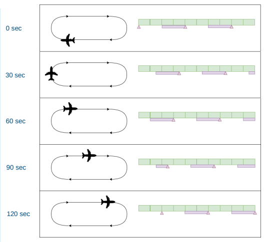
- Bad exits for accurate delivery



06/2020 - NLR – Holding Stack support tool | 24

Holding leg time & Accuracy of delivery

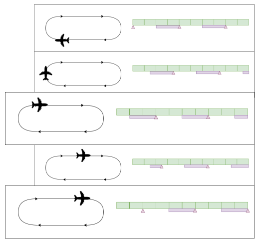
- IAF flyover timings for a 4 minute holding



06/2020 - NLR – Holding Stack support tool | 25

Holding leg time & Accuracy of delivery

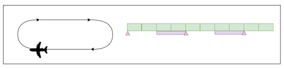
- No change in timeline until 1 minute into holding procedure
- After 1 minute the minimum duration until exit will increase by two seconds for every one second flown
- After completing the outbound leg, the minimum time to exit is fixed



13/05 /2020 - NLR – Holding Stack Update | 26

Holding leg time & Accuracy of delivery

- No change in timeline until 1 minute into holding procedure
- After 1 minute the minimum duration until exit will increase by two seconds for every one second flown
- After completing the outbound leg, the minimum time to exit is fixed

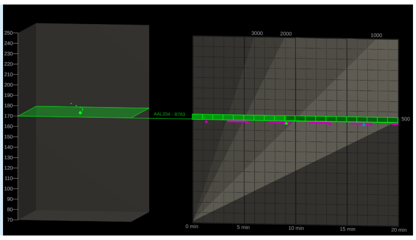


13/05 /2020 - NLR – Holding Stack Update | 27

Design – Initial Approach Fix (IAF)

Features Left:
- Lateral position of IAF

Features Right
- IAF flyover timings
- IAF changes in flyover timings



06/2020 - NLR – Holding Stack support tool | 28

TASK – IAF timings

- Take control of all aircraft with F1 one by one
- Select bottom aircraft
- Change bottom aircraft's holding leg time with "HLT 120" (120 seconds)
- Pause and discuss

06/2020 - NLR – Holding Stack support tool | 29

TASK – IAF timings

- Resume and feel free to ask for speed up
- Change the holding leg times of aircraft so that their EAT nearly matches their IAF flyover time
- Release aircraft at desired times with "HDG SPL" or F3 and ENTER

06/2020 - NLR – Holding Stack support tool | 30

- BREAK

06/2020 - NLR – Holding Stack support tool | 31

TASK – Test run

- Maintain 10 FL separation
- Move aircraft to the bottom of the stack
- Release aircraft near EAT between FLs 70 and 100

06/2020 - NLR – Holding Stack support tool | 32

Experiment run

- Maintain 10 FL separation
- Move aircraft to the bottom of the stack
- Release aircraft near EAT between FLs 70 and 100

06/2020 - NLR – Holding Stack support tool | 33

Questionnaire

- Fill in google form

06/2020 - NLR – Holding Stack support tool | 34

Thank you for participating!

06/2020 - NLR – Holding Stack support tool | 35

A.3 Experiment timeline

The experiment timeline lasted 3 hours and had the following structure:

Hour 1
00-15 Introduction and start up
15-30 Presentation Holding stack
30-45 Presentation vertical control
45-00 Practice vertical control
Hour 2
00-15 Presentation accuracy control
15-30 Practice accuracy control
30-45 Practice comparable to experiment
45-00 Practice comparable to experiment
Hour 3
00-15 Break
15-30 Experiment
30-45 Experiment
45-00 Questionnaire

A.4 Scenario design

Scenario design is done with a method to determine how densely the holding stack would be populated with aircraft using Figure A.1. This figure shows how aircraft can be planned into the scenario with a steady inflow. First flyover can be estimated and EAT can be set. A cross section on a point in time of all the aircraft will show how densely populated the holding stack is. A steady traffic density of 4-5 aircraft at a time in the holding stack was chosen for this study. Future studies can use the IAF flyover interval as an additional metric for adding difficulty to the scenario.

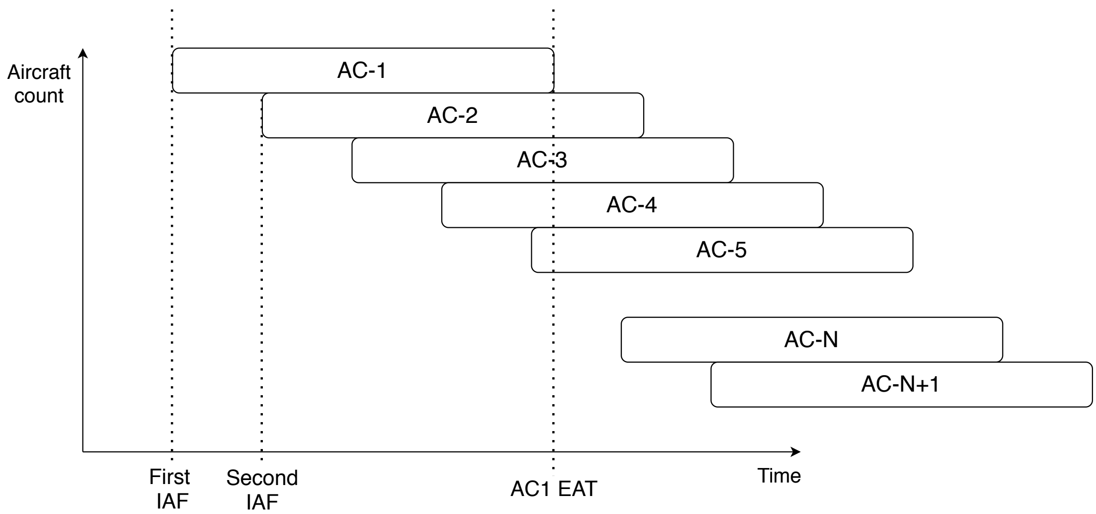


Figure A.1: Traffic density design

A.5 Participant command Quick reference card

All participants received a Quick reference card so that they can easily recap any command that they wish to perform. Figure A.2 shows this Quick reference card.

Quick Reference Card

Screens:

Radar display	**LEFT** screen
Vertical view	**LEFT** sub screen
Holding Stack Display	**RIGHT** screen

Aircraft Manipulation:

LMB	Select aircraft	
RMB	Change info tag location	
UCO	Take control of aircraft	**F1**
ENTER	Execute	

Control Actions:

EFL ___	Flight level	**F4**
ROD ___	Rate of Descent in ft/min	**F8**
HLT ___	Holding leg time in s	**F12**
HDG SPL	Release aircraft	**F3**
ENTER	Execute	

F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12
UCO + ENTER	Release control	HDG SPL	EFL	ROD 1000	ROD 1500	ROD 2000	ROD	HLT 30	HLT 60	HLT 90	HLT

Goals:

- Minimum vertical separation of 10 flight levels
- Move aircraft to bottom of stack
- Release aircraft near EAT between FLs 70 and 100.

Figure A.2: Quick reference card

B | Baseline results

The following pages will show a compilation of raw data gathered from the post-experiment google questionnaire. Each participant filled out a combination of mandatory questions with the option of adding comments for supplementary information. Figures B.2 and B.3 are used in both baseline and SP questionnaires. Figure B.1 is used in the baseline questionnaire and Figure C.1 is used in the SP questionnaire.

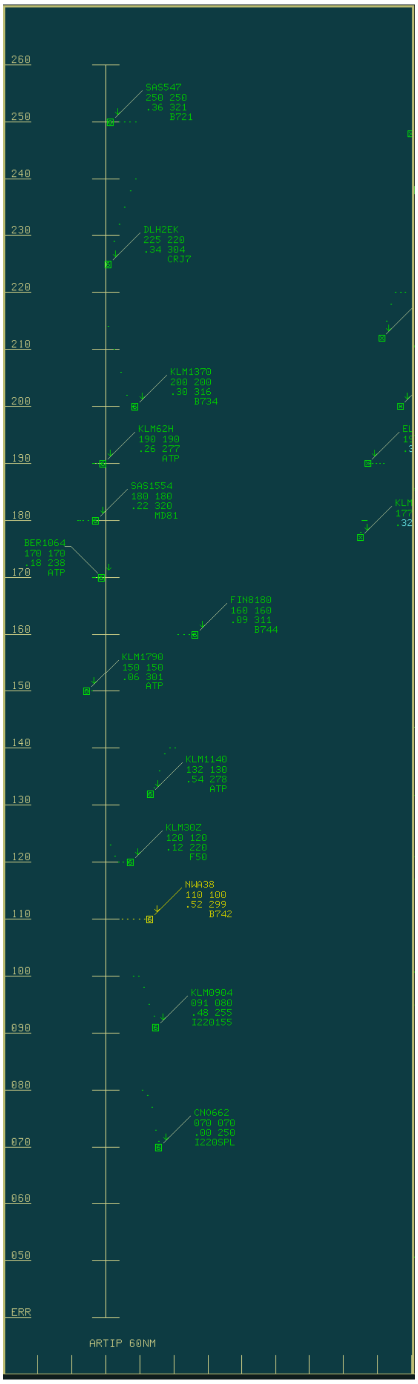


Figure B.1: Vertical View baseline display

Holding Procedure Support tool

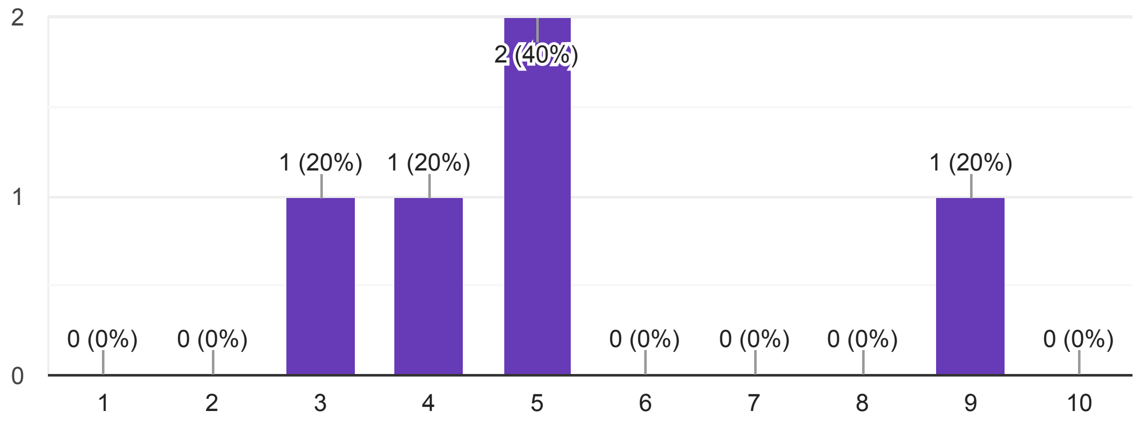
5 responses

Publish analytics

Controller Acceptance Rating Scale

Controller Acceptance Rating Scale

5 responses



Comments

4 responses

UI (like label decluttering, possible in RDS, not possible in VRV). EAT timings are done "from memory"

lack of sufficient overview and too many labels which makes it easy to not notice certain aircraft and their properties

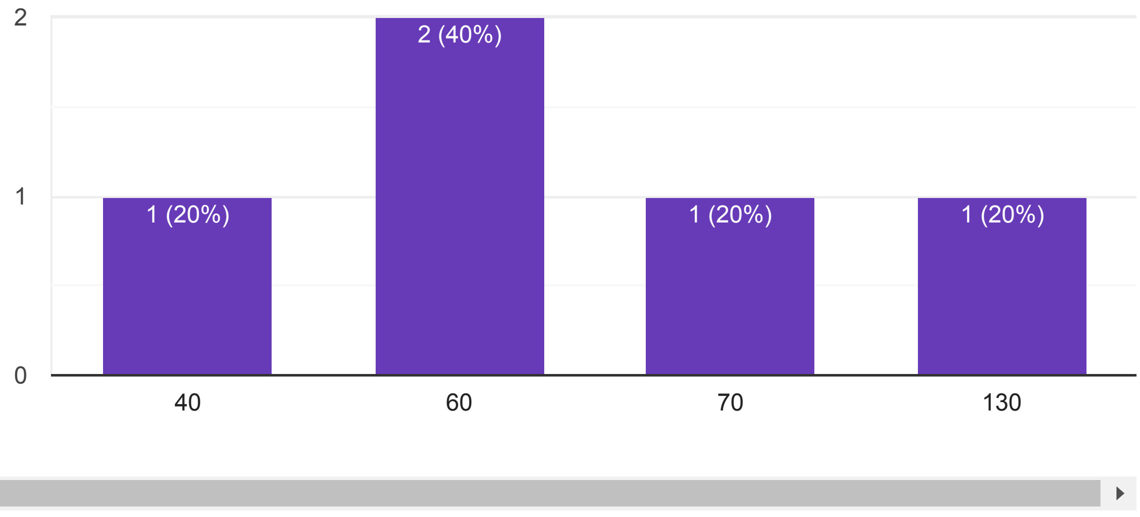
Vertical view is very cluttered and hardly usable because of this.
It is annoying to constantly have to declutter the labels in the plan view.

I can work with this, for the traffic levels simulated, quite well. I would have liked to have more supportin timing though, which was now all done in my head.

Rating Scale Mental Effort

Please indicate, by entering a number below how much effort it took for you to complete the task you've just finished. Choose between 0 and 150

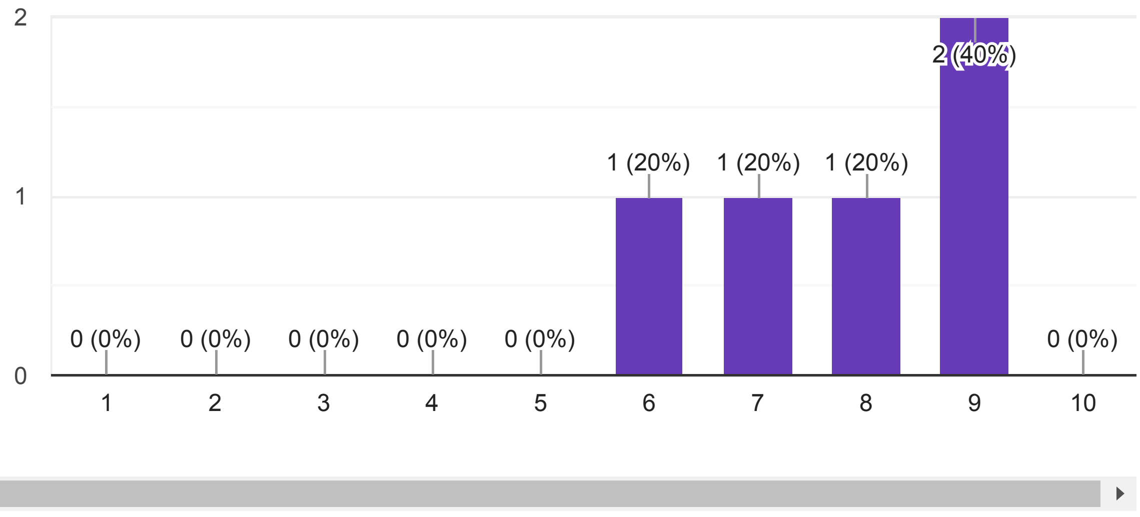
5 responses



SASHA - General

Q1: - Did you have the feeling that you were ahead of the traffic, able to predict the evolution of the traffic?

5 responses



Comments

3 responses

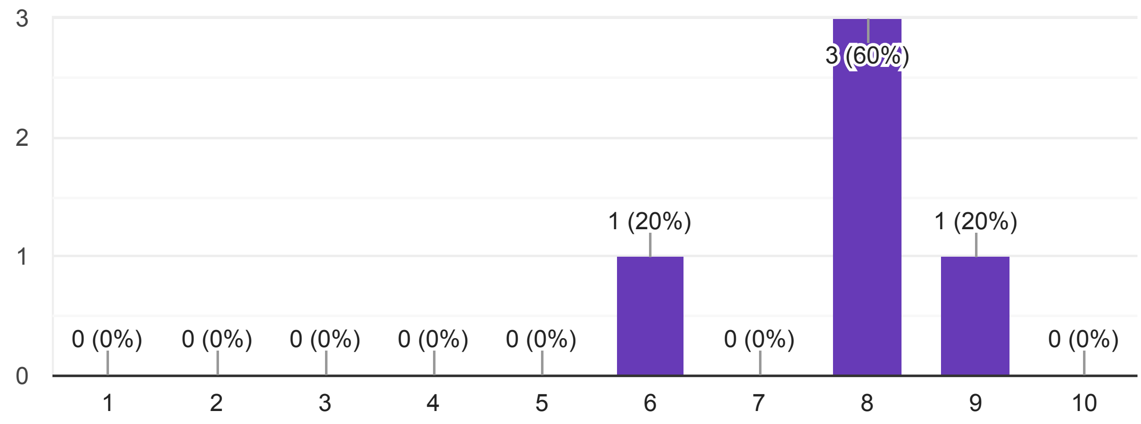
Although traffic was very "clean" and my strategy worked out because all EAT's we're within EAT planning interval.

up untill the last point it was fine, however a loss of vertical separation occured at the end. Reasons were most likely loss of concentration and loss of overview of all the different labels. When aircraft were separated only FL10 from each other, the labels stack up eachother making it difficult to quickly spot possible attention zones.

Traffic was nicely separated in time so I had sufficient time to work on each aircraft.

Q2: - Did you have the feeling that you were able to plan and organize your work as you wanted?

5 responses



Comments

3 responses

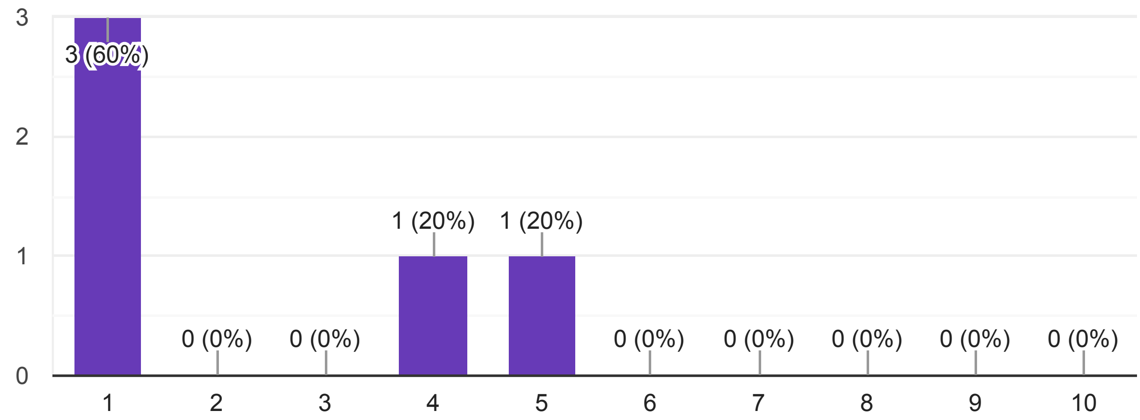
Yes, see previous comment (sample was perhaps a bit too clean and biased towards EAT's within EAT intervals)

yes, but the traffic was already well spaced when it entered my sector, making the subsequent control rather straightforward.

Overall, yes. I would have liked some more support in timing but could do w/o as well with current traffic levels.

Q3: - Have you been surprised by aircraft behavior that you were not expecting?

5 responses



Comments

3 responses

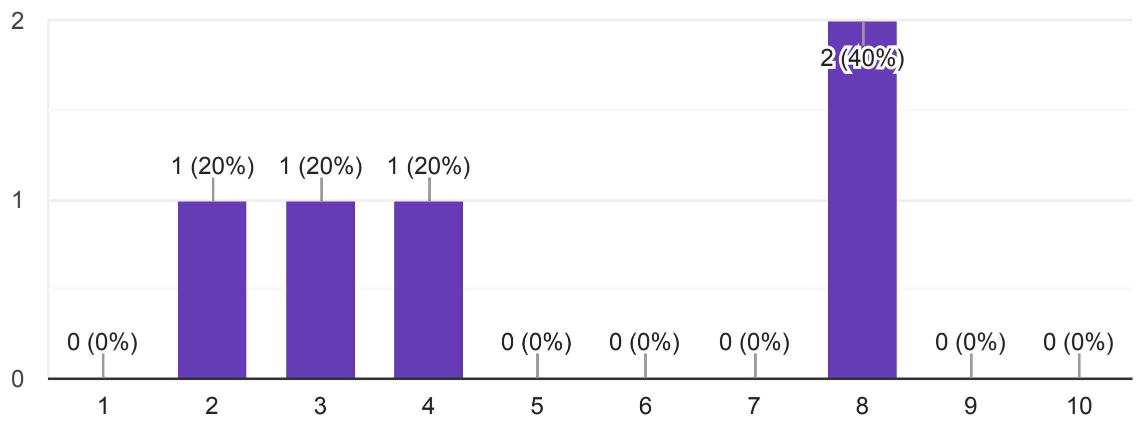
I built the thing :-)

no pilot deviations at all

I found that because a/c are all descending and decelerating my initial estimate of time to EAT was off with 30-100 seconds. However, I could generally compensate for that in the end. So the ' surprise' is about my predictions which were not all good at all times. Theyhad no consequence however as far as I can see.

Q4: - Did you have the feeling of starting to focus too much on a single problem and/or aircraft?

5 responses



Comments

3 responses

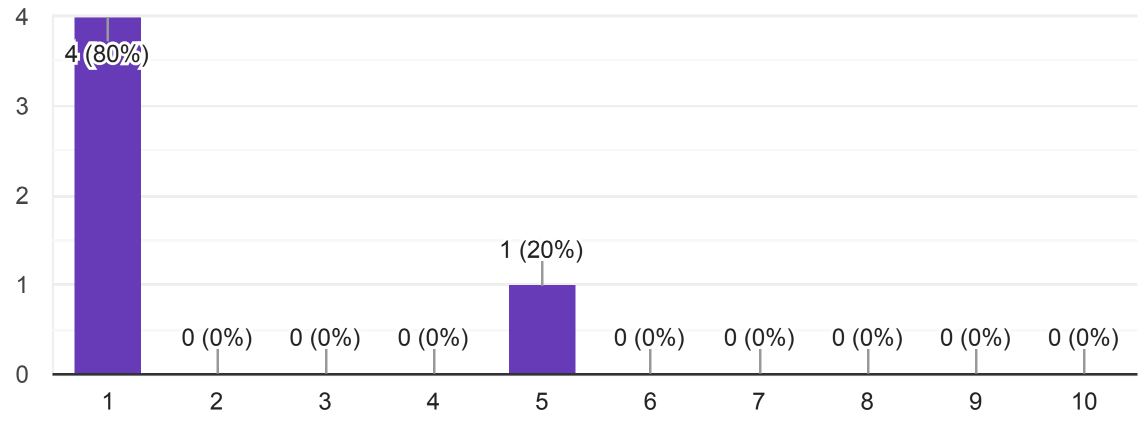
When it was time to exit. Given the strategy of solving everything in the last outwards leg, I started to focus on the exiting aircraft to give the command 'on time', losing focus on the other aircraft

often focussing on the lowest aircraft, calculating when and how it should exit, possibly forgetting aircraft above. Focus starts only at the second to last orbit from the lowest aircraft.

Because a/c/ were well separated you could work with them on their EAT one at the time. And then occasionally just give the whole sequence FL commands to get them down. The latter task was easy though.

Q5: - Did you forget to transfer any aircraft?

5 responses



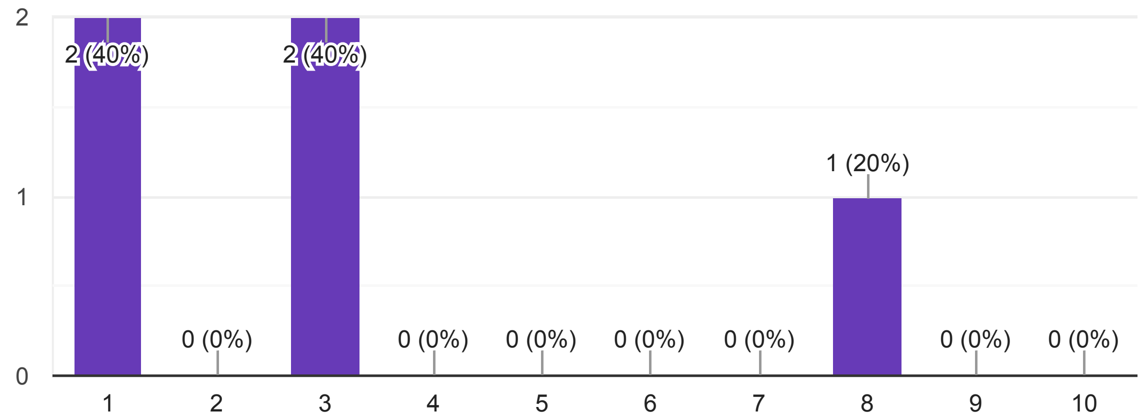
Comments

1 response

I think not. Plenty of time to manage these levels.

Q6: - Did you have any difficulty finding any static information? (information displayed in the background)

5 responses



Comments

3 responses

label cluttering makes it difficult to find static info

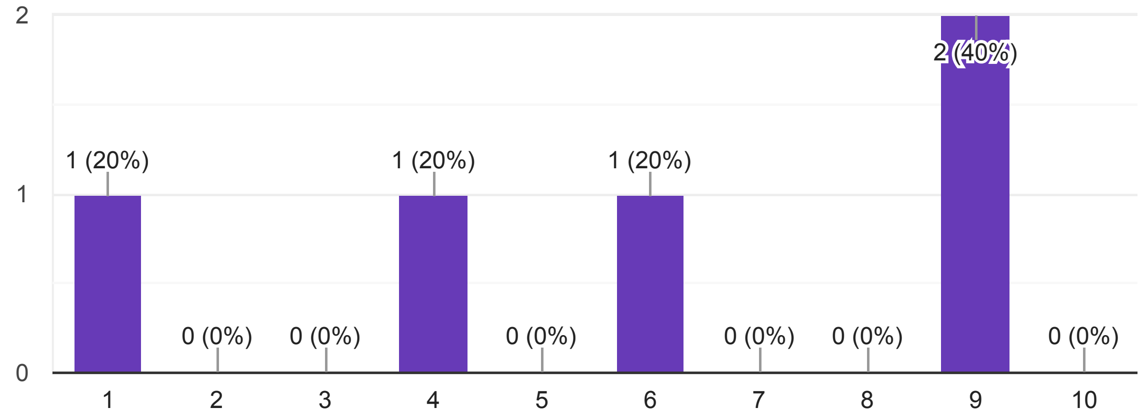
I did not, nor did I need any particalr background information. Only exception is that I would have preferred to have a more clear indication of waypoint RIVER. Now, I had to deduct its location from where the aircraft were turning outbound.

Only the labels were annoying.

SASHA - Vertical View

Q7: - Do you think the Vertical View provided you with useful information?

5 responses



Comments

4 responses

Only used vertical view for finding free flightlevels (although I've used the RDS for it as well)

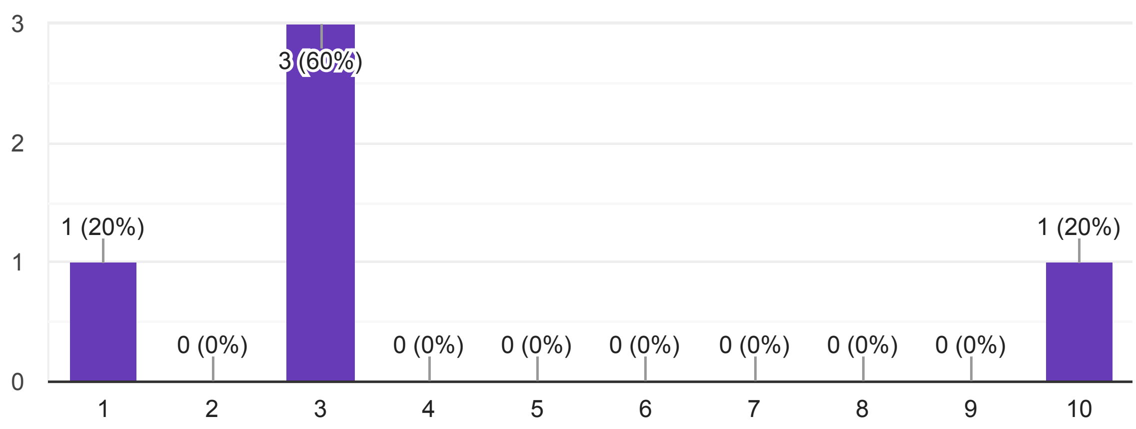
vertical view is handy, however it should be possible to move labels as well, like in the lateral view.

Because the labels were constantly overlapping, I found the vertical view unusable.

yes, I used it mostly to separate the a/c in altitude (which I would find difficult from just the radar screen). And from the Vertical View you could also select the 'lowest' aircraft immediately to get its EAT right.

Q8: - Were you paying too much attention to the Vertical View?

5 responses



Comments

3 responses

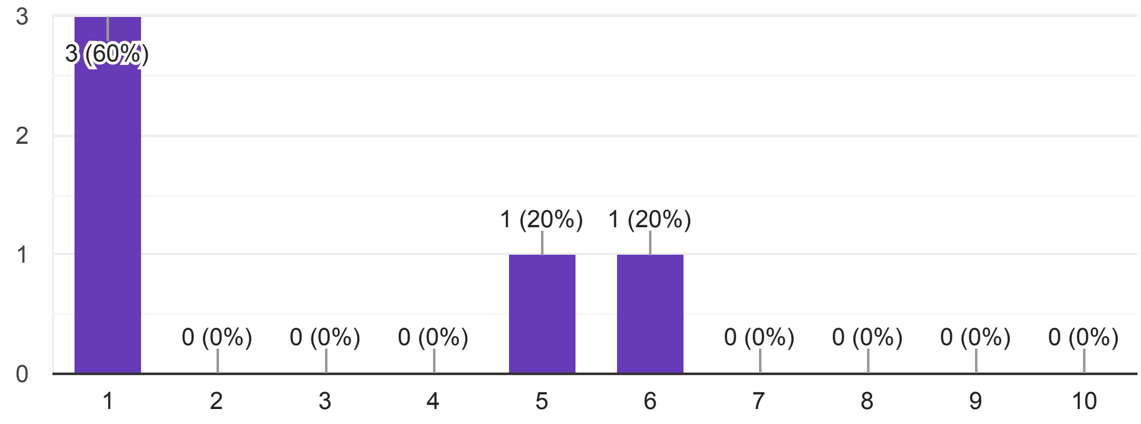
Not enough, as indicated by the vertical separation mistake at the end of the exercise.

Did not use it all, due to how cluttered the display is. I used the labels in the plan view for vertical separation exclusively.

No I think that went well.

Q9: - Did the Vertical View help you understand the spatial position and orientation of each aircraft in the stack?

5 responses



Comments

4 responses

Only used it for FL info

Was not always looking at it, also often just looking at the EFL and FL in the lateral view its labels

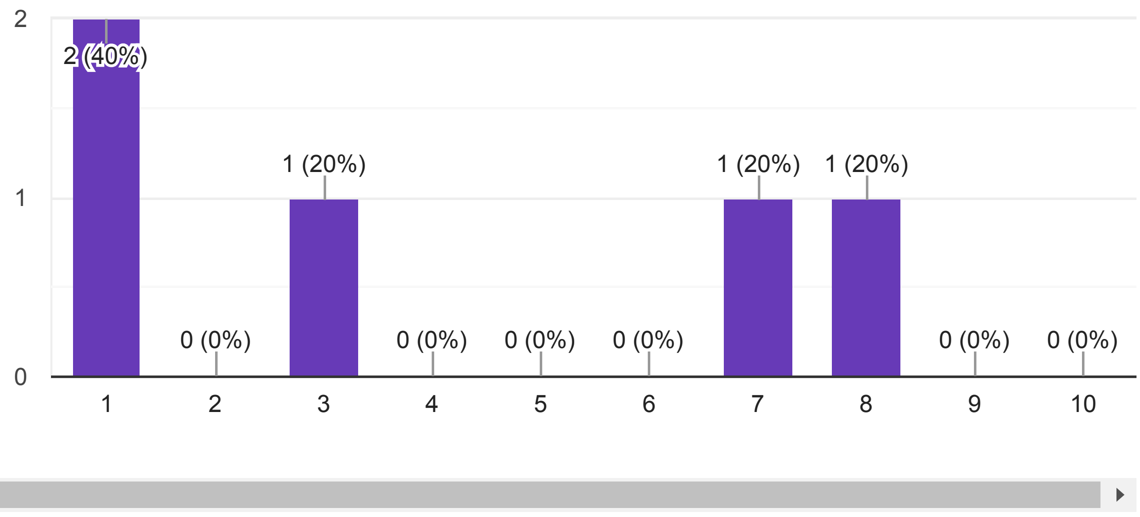
see previous answer

For altitude: YES, for position along the 'race track', seldom. I used the PVD for that as I could better 'imagine' the race track for the a/c I was working on (mostly the lowest a/c)

SASHA - Conclusion

Q10: - Was there difficulty linking the information between the radar display and the holding support tool?

5 responses



Comments

4 responses

Link is clear

I didn't really use the radar display much since I was not focused on spatial separation at all

Yes, because of the cluttering of the labels.

No not much.

Q11: - Are there any features that you would add to the display?

5 responses

Yes, see Lidis

Label decluttering as most important. Possibly vertical descent speeds and some kind of warning system in case of possible conflicts could be usefull.

Countdown timmer to let me know when I need to start paying attention to each aircraft, and when I can start descending the next aircraft

Possibility to move the labels, or reduce them in size. Also it might be useful to see inbound/outbound (left/right) indication or symbology.

You can think of the operator actively asking for an advisory regarding the HLT when the lowest a/c (the one you are working on) has passed the FIX and is turning to make its final round. I think then you could ask the computer for ' advised HLT' in 5 seconds resolution and work with that. To check your own prediction for instance. Would be helpful.

Q12: - Are there any features that you would remove from the display?

5 responses

Label information. The label is such that it is the same as the label on the RDS. This means copy of information, but also wasted space on the display which results in label overlap in the VRV.

Posssibly ground speed indicator seemed less important, as the holding stacks are time based. Same with A/C type, it did not seem like information i needed once the A/C were in the stack.

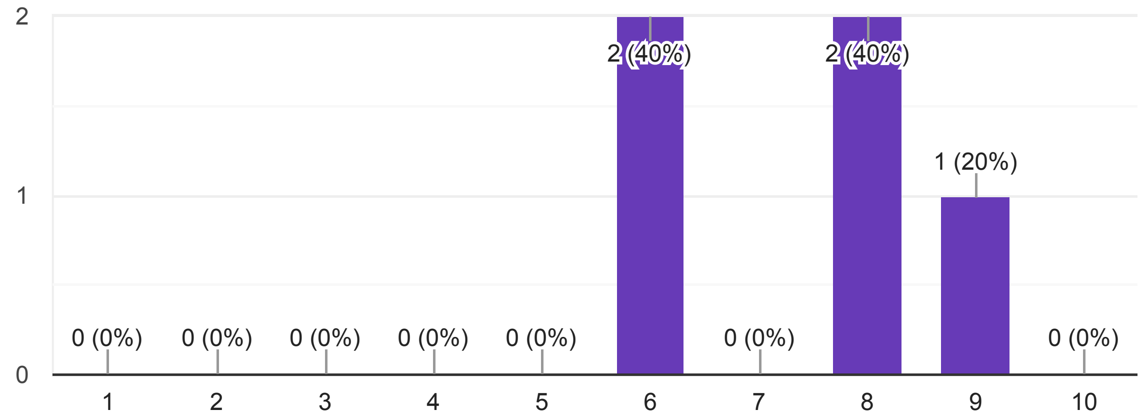
the label in the vertical view tool had too much info and was causing clutter

No.

I did not like the labels very much. You cannot do without but perhaps some ordering would help. HOWEVER, I learned to use the positioning of the labels myself to indicate 'how far I was with dealing with an aircraft'. That is, when an aircraft was 'done', I put the label at the '0 North position. A/c I was working on: South-East label position, All other a/c just descending and sufficient time for working on their EAT: position West. In that way the labels were useful. However, I did not like the clutter you got, especially in the Vertical view

Q13: - Finally how would you rate your overall situation awareness during the exercise?

5 responses



Comments

5 responses

(Manual) label decluttering introduced sometimes a (short) reduction in situational awareness (label swap)

Difficult to keep overview when many aircraft are in the stack.

I had to make a lot of paper notes to be able to keep track of what I needed to do next

Even though I did not use the vertical view, I felt I was able to keep a good overview of the situation and control the timing of the arrivals.

Pretty good. I would need much more training for further improving my skills but for the experiment scenarios I think my SA was just good.

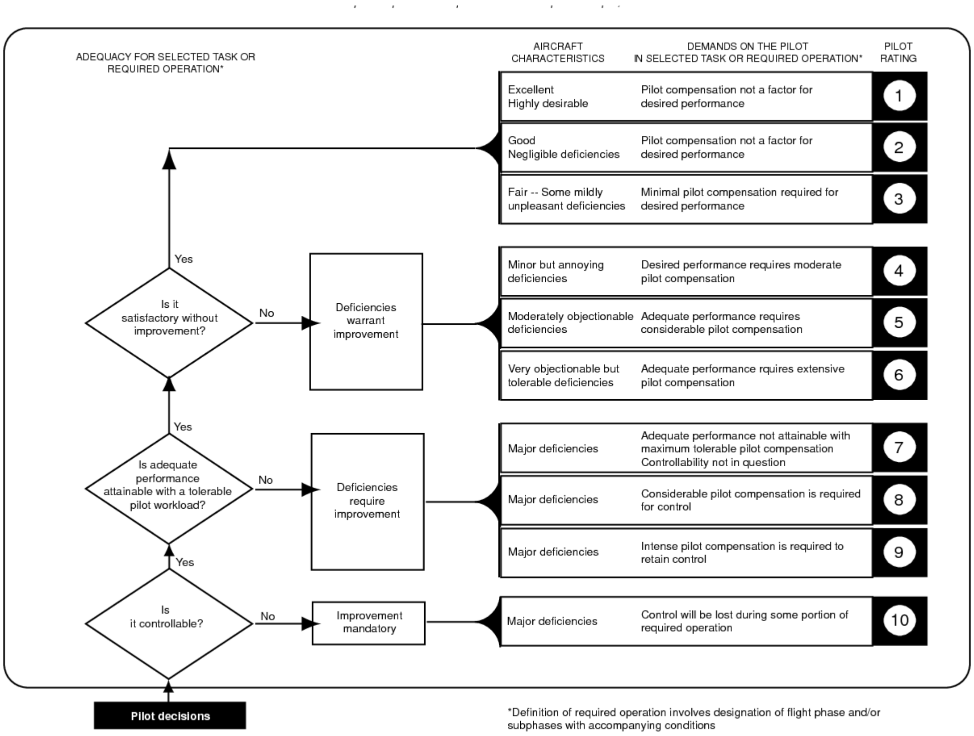


Figure B.2: Controller Acceptance Rating Scale (CARS)

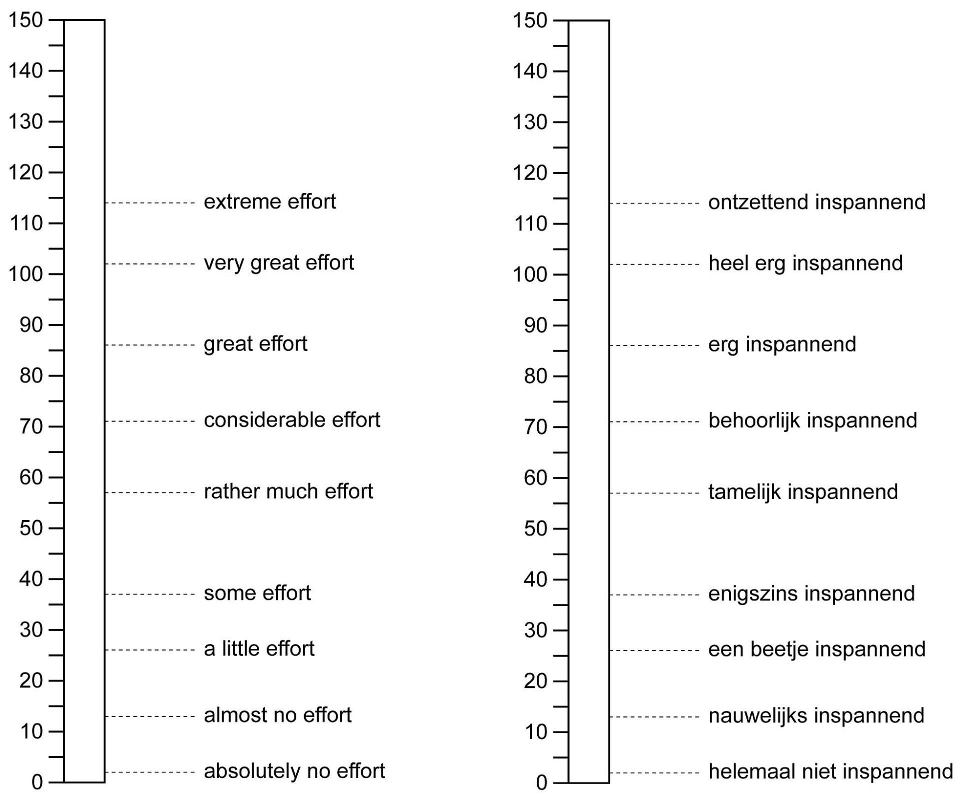


Figure B.3: Rating Scale Mental Effort (RSME) provided in both English and Dutch

C | Stack Planner results

The following pages will show a compilation of raw data gathered from the post-experiment google questionnaire. Each participant filled out a combination of mandatory questions with the option of adding comments for supplementary information. Figure C.1 is included in the SP questionnaire.

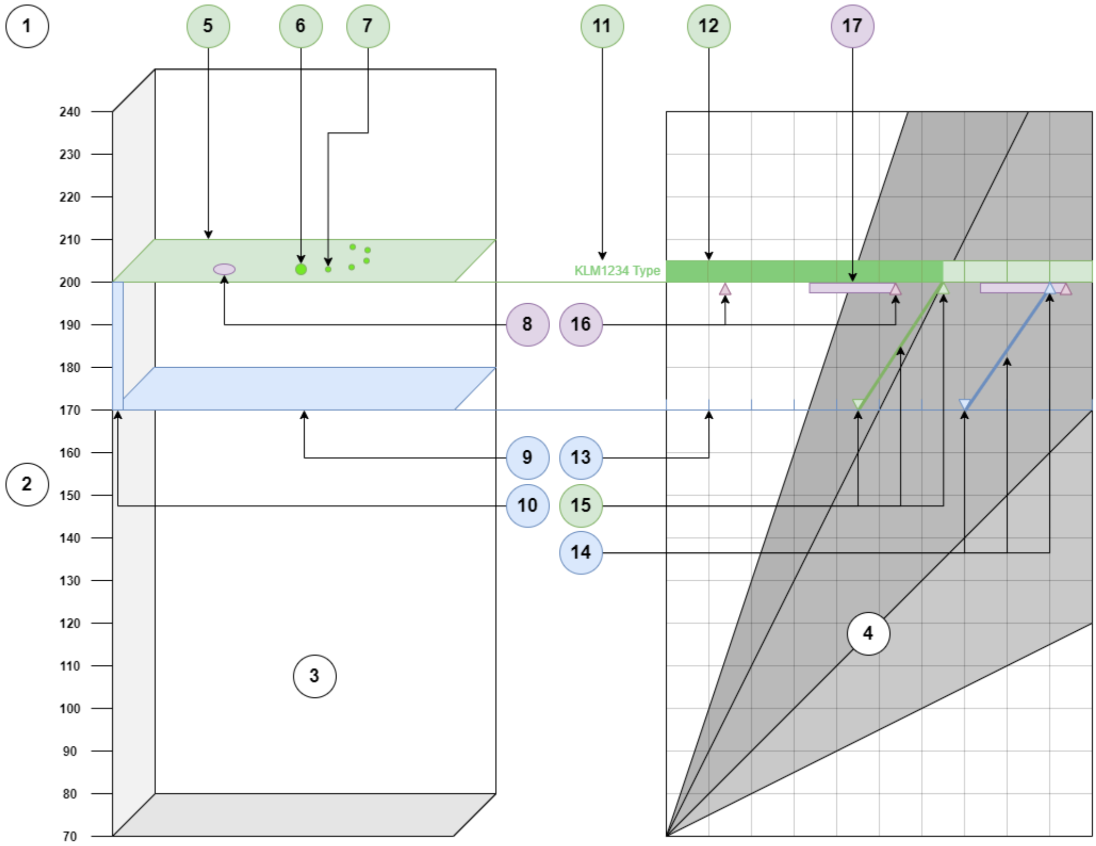


Figure C.1: Final display design with display element number references

Holding Procedure Support tool

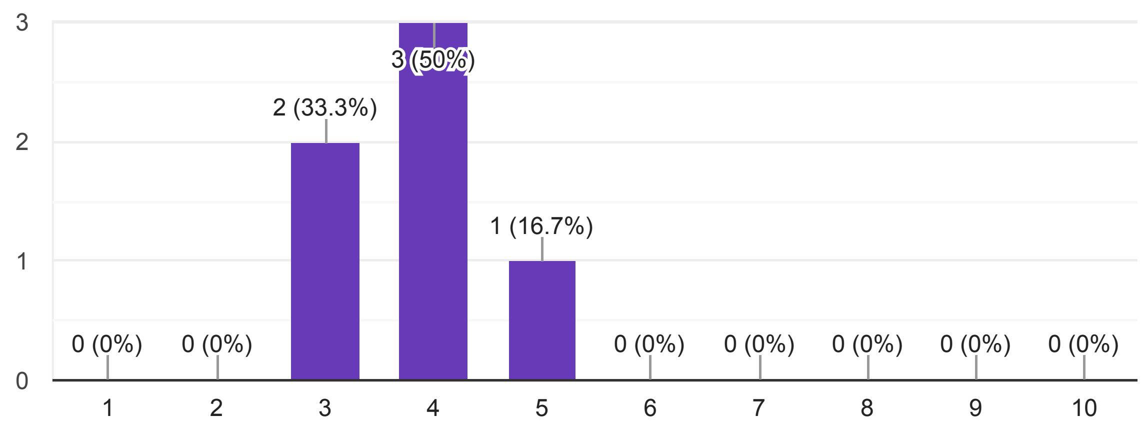
6 responses

Publish analytics

Controller Acceptance Rating Scale

Controller Acceptance Rating Scale

6 responses



Comments

6 responses

Under protest: Cooper-Harper scale needs specific scenarios, where adequate and desired performance levels are well-defined and observable by the evaluation pilot. The term compensation also has little relevance for this task, as no handling qualities deficiencies needed to be compensated for. I filled in the rating based on the term moderately objectionable deficiencies. This relates to the lack of feedback of the currently selected HLT for an aircraft. This made fine-tuning at a later time difficult, as the display shows relative HLT control actions, which must be translated to absolute control actions.

it would have been better to select aircraft on the holding support display instead of the radar screen / vertical display on NARSIM. Also, an indication of which aircraft has been selected would have been nice. Further, with the number of aircraft experienced, I was able to control the stack very nicely and safely. Without it (baseline), managing the stack as well as adhering to EAT would have been very difficult, I supect, and may require many hours of training.

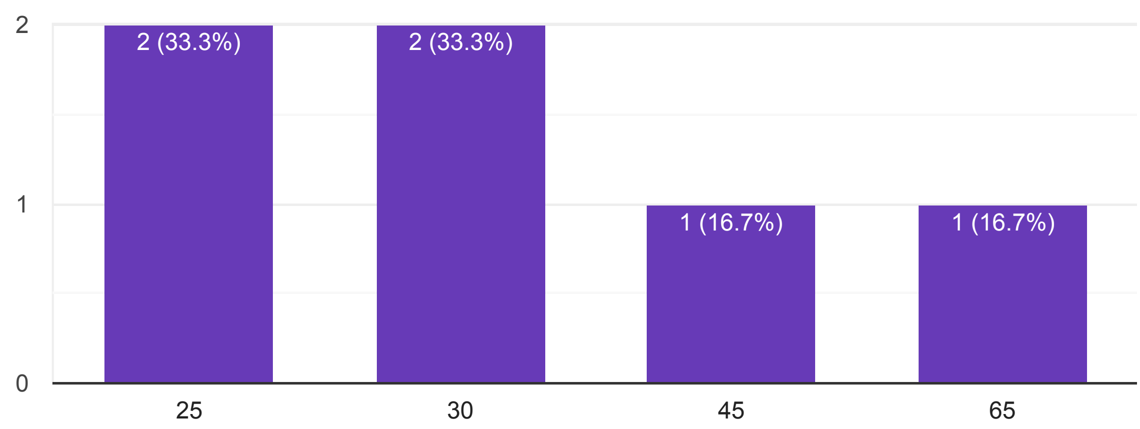
No deficiencies as such, but more suggestions for improvement. See later remarks.

I find the system very promising in this simulated set-up. I am interested to see how

Rating Scale Mental Effort

Please indicate, by entering a number below how much effort it took for you to complete the task you've just finished. Choose between 0 and 150

6 responses



Comments

6 responses

workload was divided over allowing a continuous descent profile for each aircraft, managing the HLT if needed, and releasing aircraft to approach control

workload was acceptable, not too high, not too low.

Once you're used to the information on the display and how to 'control' the information on the display (Holding Leg Time!) it is fairly easy.
However, focus is very much on timing only and you only use the radar display to see which aircraft you will have to take UCO.

The system requires a little effort, but that is partly because it is new to me. I don't find the task demanding.

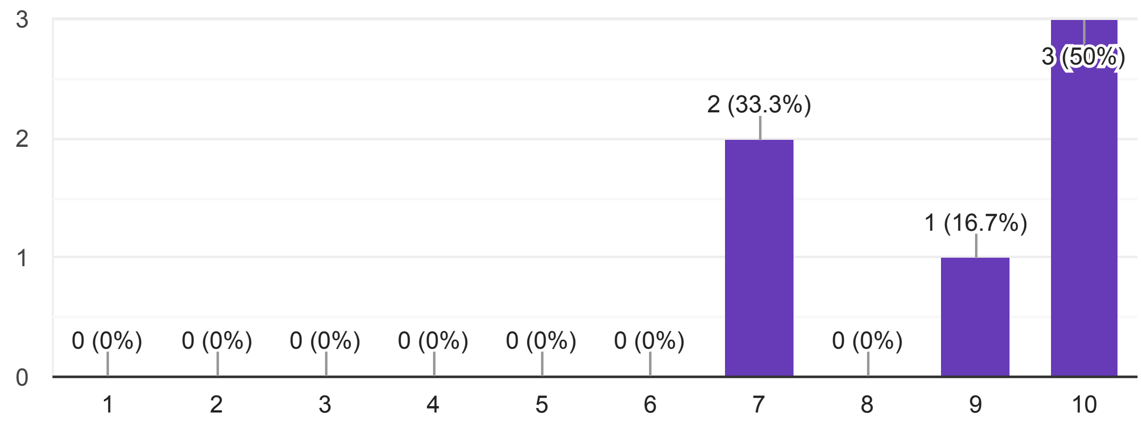
am not too experienced, but workload acceptable most of the times.

easy to use, never was in a hurry to give instructions, traffic sample without major complications

SASHA - General

Q1: - Did you have the feeling that you were ahead of the traffic, able to predict the evolution of the traffic?

6 responses



Comments

5 responses

I could clearly see how the aircraft were moving down the stack and where they were in the holding by focusing on the stack volume. The timings were more difficult to estimate, so with ROD fan and triangles, I was more trying to overlay magenta with green EAT markings (trial and error).

Yes, but only when you're sufficiently familiar with the tool. This will improve with experience.

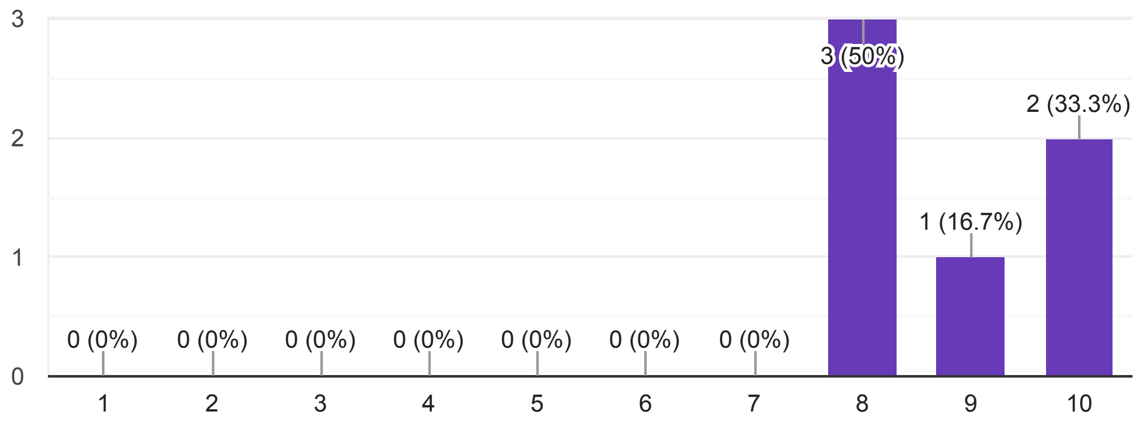
It is possible to make an early planning, so you don't get behind on traffic.

at some points too busy, but with experience expect very good performance

never was in a hurry to give instructions, always knew what I needed to do

Q2: - Did you have the feeling that you were able to plan and organize your work as you wanted?

6 responses



Comments

5 responses

Having to specify an absolute HLT ahead of time, and not being able to issue last minute commands to extend the outbound leg (not sure if this is done in real life), posed some contraints

yes, was very useful to plan and organize the aircraft inside stack.

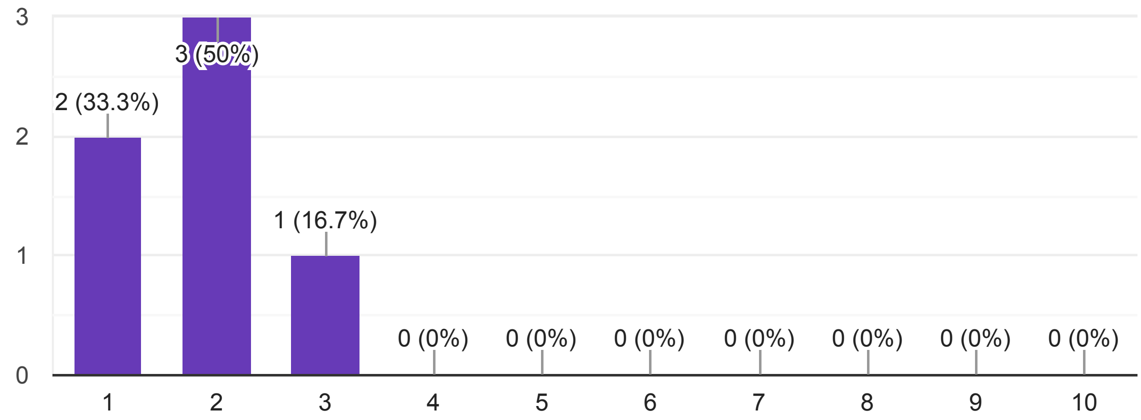
None.

was able to quickly develop work flow.

same as above

Q3: - Have you been surprised by aircraft behavior that you were not expecting?

6 responses



Comments

6 responses

Sometimes the vertical profile developed a little differently than expected. No ROD commands were given, though.

only one occasion where the aircraft EAT was not what I had planned. A glitch or perhaps a boo boo on my part, not sure.

Not applicable.

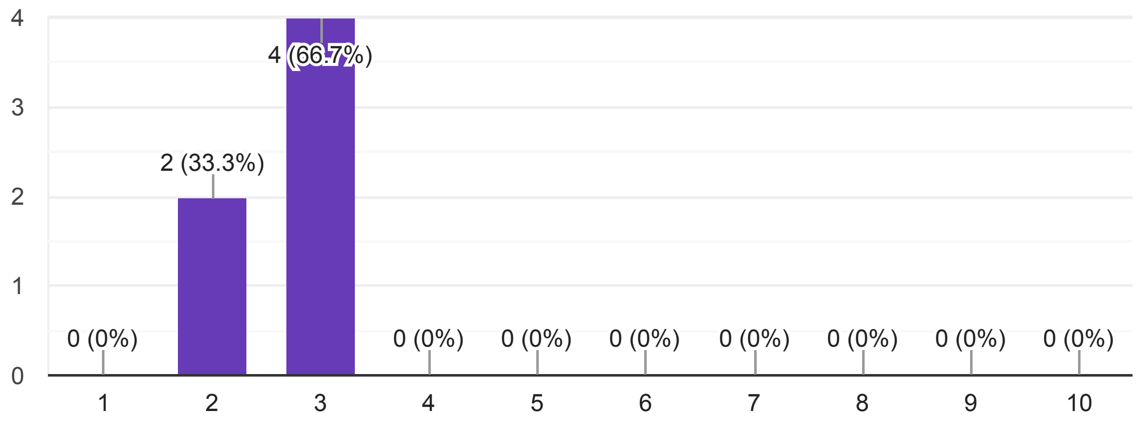
As this is a simulated environment, there is little uncertainty in aircraft behavior, this might be different in real life.

have to be careful to select right aircraft; visual momentum issue

with the exception of the aircraft coming in at 200

Q4: - Did you have the feeling of starting to focus too much on a single problem and/or aircraft?

6 responses



Comments

4 responses

the focus eventually was more on the bottom end of the stack volume and ROD fan. with more a/c in the stack between FL70 - FL100, it became a bit of an attention grabber.

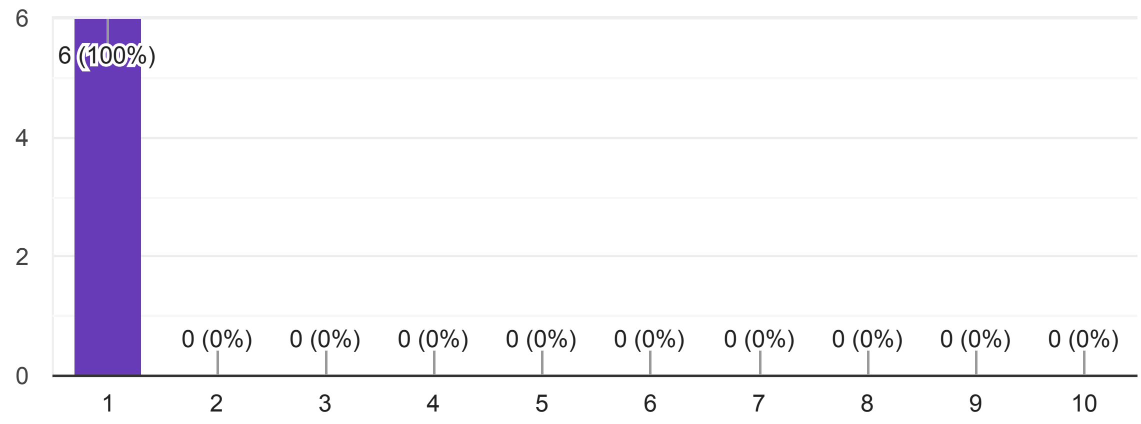
The focus (and goal of course) is very much on timing ('getting the green arrow on the purple arrow'). Initially this requires some 'trial and error', but once you're more familiar with the 'behaviour' of the tool, you do this very quickly and you have sufficient time left to monitor all aircraft.
So in the initial situation the answer would be around 6, but with some experience the answer to this question is 2 (value indicated).

Only during the last holding of the bottom aircraft, I started to focus on one aircraft. This is also (probably even to a higher degree) the case in normal real life situations, though.

eventually you need to clear the a/c to SPL in time, however the traffic sample never forced me to focus on other situations instead

Q5: - Did you forget to transfer any aircraft?

6 responses



Comments

4 responses

nope ;)

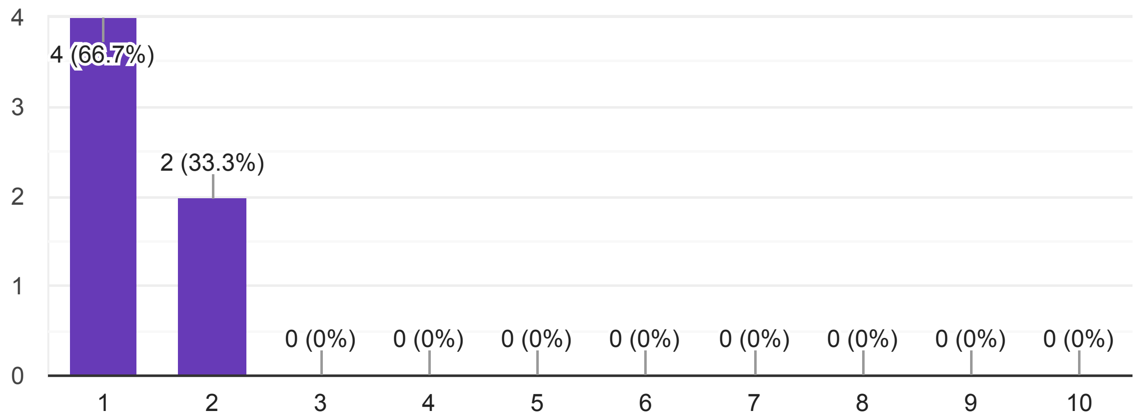
Having more and more experience with the tool, there is ample time to monitor for new aircraft.
Suggestion for improvement: change the appearance (e.g., colour) of the flight that has been released from the holding stack.

not that I know of

N/A

Q6: - Did you have any difficulty finding any static information? (information displayed in the background)

6 responses



Comments

3 responses

nope

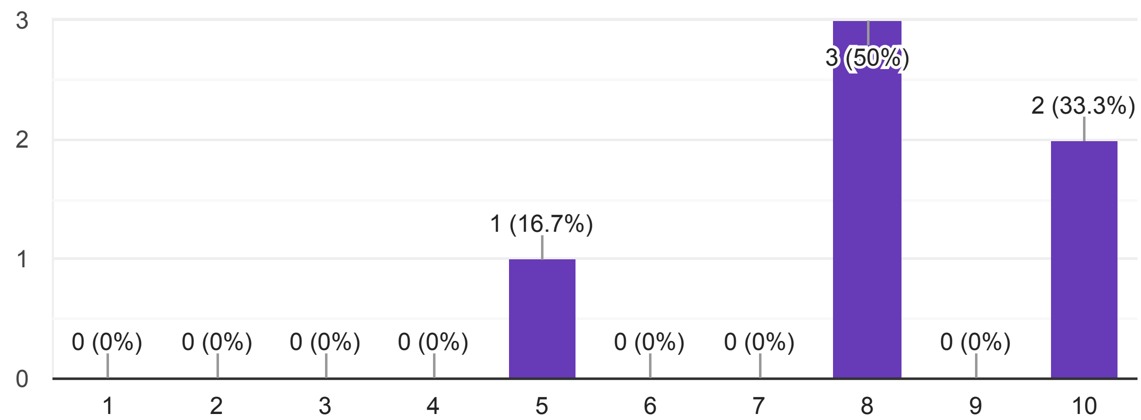
Initially you're wondering what the actual Holding Leg Time is that you have chosen for the individual flights. Later you 'discover' that the length of the purple bar provides that information (although not in exact seconds, but providing a fairly accurate estimate).

N/A

SASHA - Stack Volume (#2 & 3)

Q7: - Do you think the stack volume provided you with useful information?

6 responses



Comments

6 responses

Mostly used for vertical information, and very occasionally for an idea of position within the race track

this was most helpful!

Most used information is on the right-hand side of the display, with the required and estimated times.
Personally I did hardly or not use the Rate Of Descent information, only one initial glance verifying that the aircraft 'will manage'.

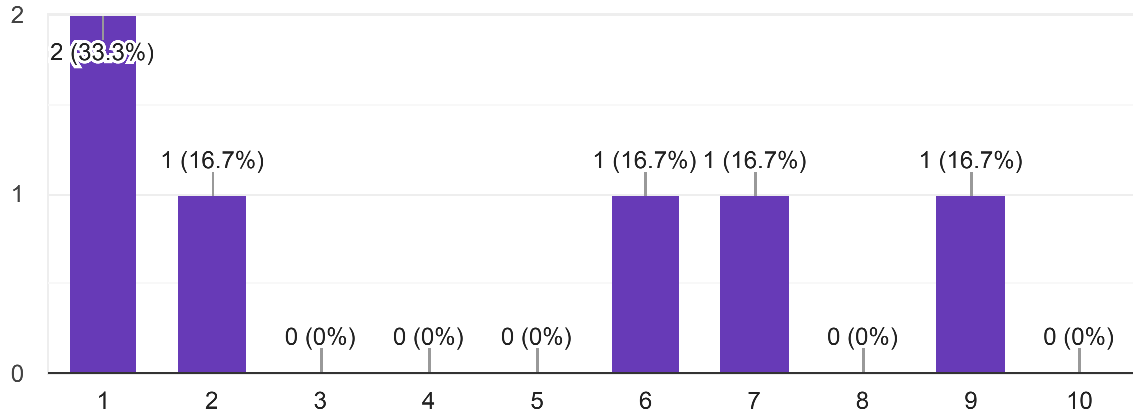
I'm used to working from a radar screen, so that's what I used most of the times. I find the stack volume useful as a replacement of the regular vertical view, but I have my doubts about the usability of the display of the lateral position, as this is already shown on the radar.

would have liked a reminder of issued HLT.

easy to clear FLs, position of IAF and a/c useful

Q8: - Were you paying too much attention to the stack volume?

6 responses



Comments

3 responses

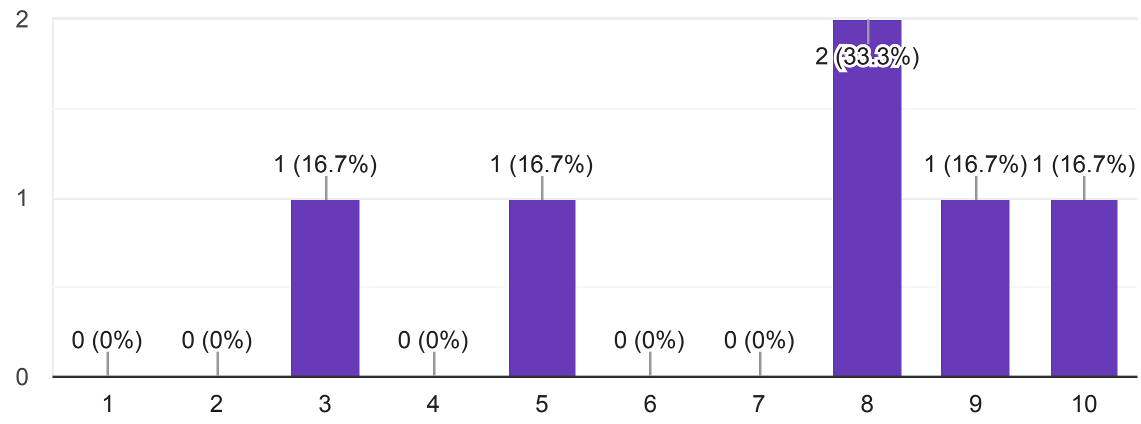
almost grabbed my full attentional, except at occasions where I needed to change holding leg time and/or clear aircraft to SPL

This part of the display used:
1) for vertical separation of aircraft (for EFL instructions)
2) To verify whether or not the aircraft had started its last turn in the holding stack, in order to 'release' the aircraft.

it's one part of the job, but you never focus too much on it, there's a balance between safety (stack volume) and timeliness (right display)

Q9: - Did the stack volume help you understand the spatial position and orientation of each aircraft in the stack?

6 responses



Comments

6 responses

I was not focused on the spatial position or orientation of the aircraft

sometimes it was a bit difficult to very clearly see where the aircraft was in the holding. A more slanted viewing angle would have helped. A top-down would have been better for estimating position in the holding race track, but then you loose the vertical view. So, the balance that was chosen was surely acceptable, but not 100% perfect.

Basically this stack volume was used:
1) for vertical separation in order to give EFL instructions
2) to identify the position of the aircraft in the holding stack, but only for aircraft at the bottom of the stack, waiting to be released.

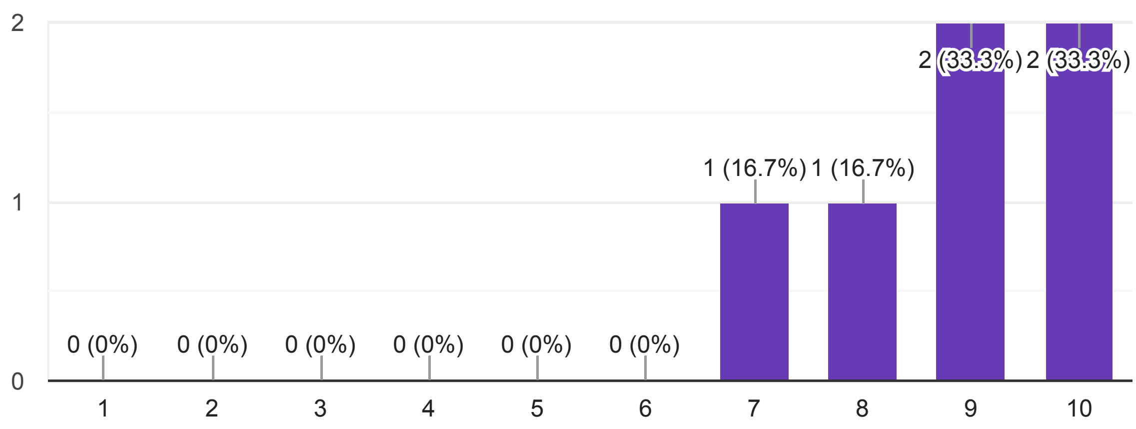
The radar screen in combination with a growing understanding of the timeline already gave me a rather complete picture of the spatial position and orientation of aircraft.

once halfway the experiment, had more time to look & correlate

SASHA - Timeline (#9, 10 & 11)

Q7: - Do you think the Timeline provided you with useful information?

6 responses



Comments

5 responses

This was my main point of focus

was useful mainly as a feedback to check if current ROD allows the a/c to reach the target FL on time (blue ROD should be in front of green ROD) and to match fix with EAT.

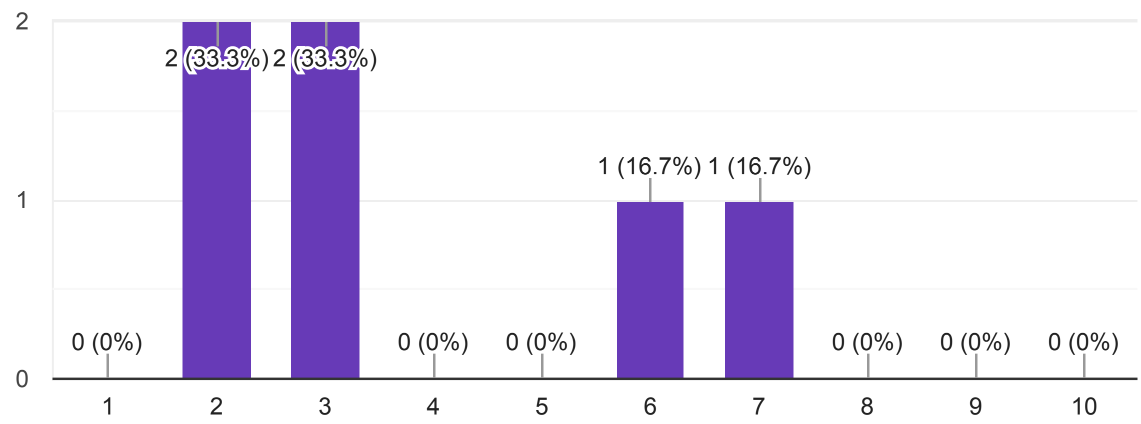
Very useful: basically this feels as the goal/purpose of the exercise: to get the green time arrow on top of the purple time arrow.

Once getting the hang of it, I think the timeline provides very intuitive information. There might be some things missing, such as selected HLT and possibly some other extras.

it's clear what to do with the information, planned stack levels are shown, ROT is clear, it's clear when you're behind or ahead of the planned exit time, just need more information about the current HLT and perhaps the current a/c selected (the first for planning, the second for SA/WL)

Q8: - Were you paying too much attention to the Timeline?

6 responses



Comments

5 responses

What is too much? My focus on it did not seem to cause any problems.

focus was more on stack volume, as it was more intuitive.

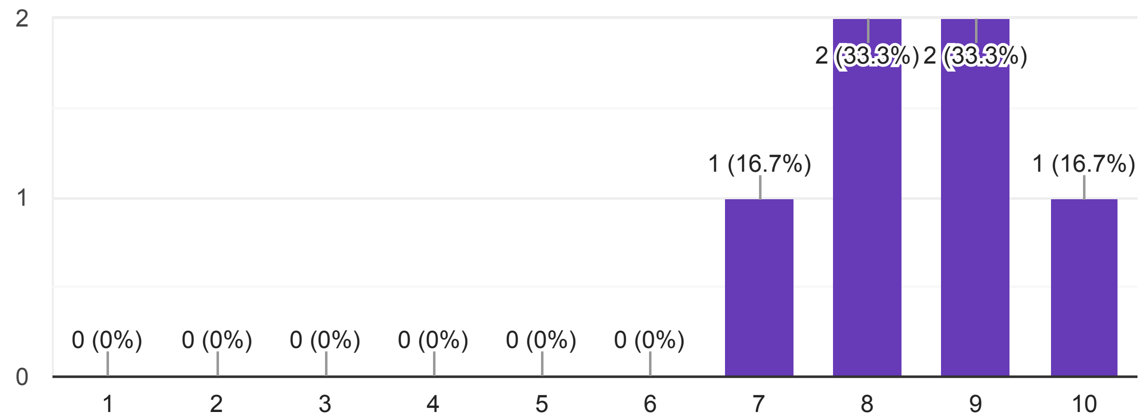
Spent possible some more time on Timeline than on Stack Volume.

I don't think I payed too much attention to the timeline, but I did notice how very quickly you look at the radar screen less than I'm used to.

there's a good balance between stack and timeline, showing which a/c is selected would improve the WL effort spent to sort out what command is given to what a/c in both displays

Q9: - Did the Timeline help you understand future events for each aircraft?

6 responses



Comments

4 responses

yes, but was more tricky to interpret. I used it as a simple checking tool (like "blue should be in front of green ROD line). I would have needed more training time to become fully comfortable with it.

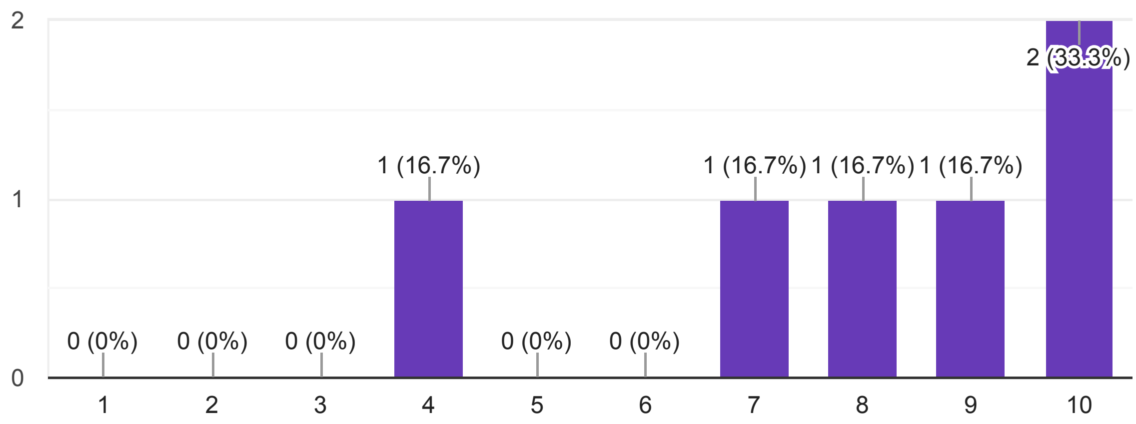
With respect to planning of activities: yes.

The timeline gives a clear indication of future events.

you first check if ROD is sufficient (never had to do anything about it, traffic sample with that task would have been interesting), then you plan your exit strategy and try to set an accurate HLT, I just checked once for accuracy of that planned time below FL110 but never really had to adjust

Q9: - Did the Timeline help you organize future events for each aircraft?

6 responses



Comments

4 responses

helped as a checking tool and fiddling with HLT, but as I mentioned before, was trial and error (not always a purposeful strategy)

Particularly for planning/estimating the Holding Leg Time required.

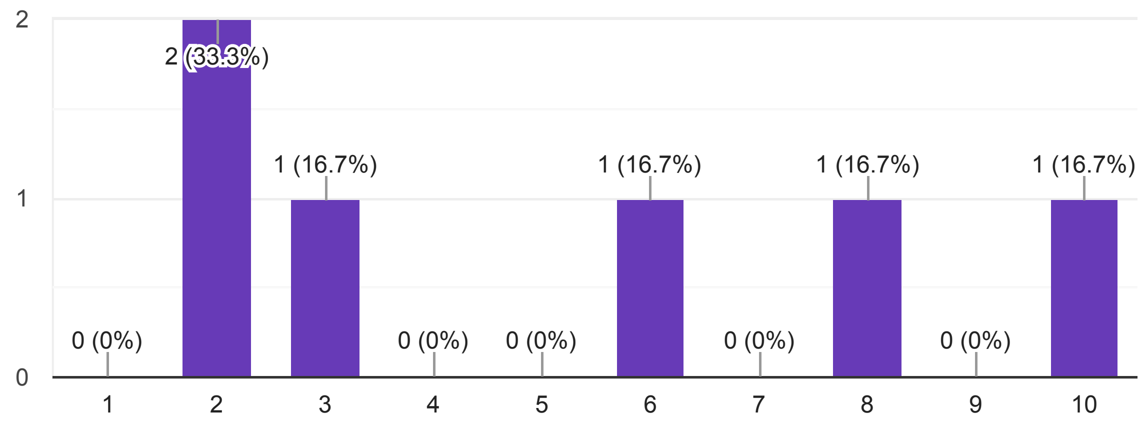
Yes, the timeline helped me plan my next decisions for aircraft

yes, as explained above

SASHA - RoCD fan (#4)

Q10: - Do you think the RoCD fan provided you with useful information?

6 responses



Comments

6 responses

RoCD was never an issue. The fan just served as an indicator that no problems existed, and was not used in control.

for the control task, it contained all information that I needed. Maybe only information on what HLT was inputted would have been better.

Almost never used the ROD information, except for an initial check that the aircraft 'will manage'.

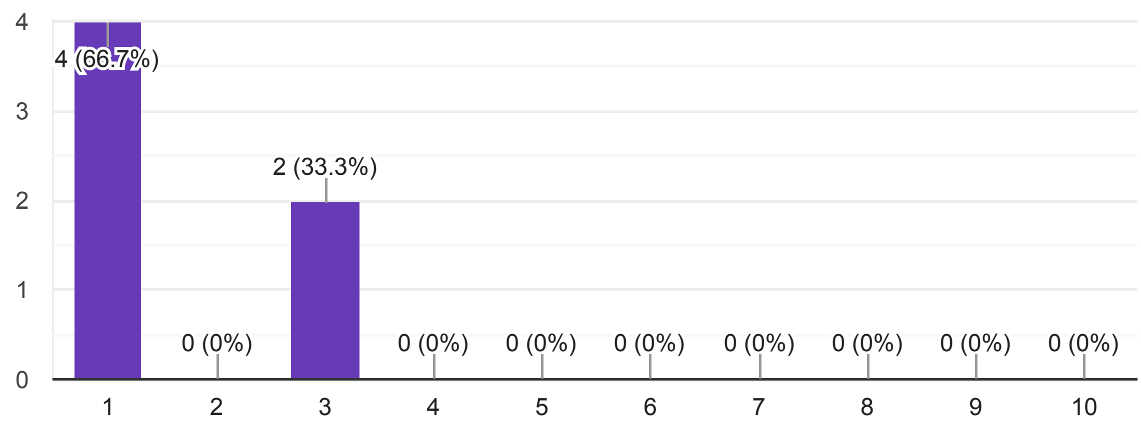
I noticed from my ATCo perspective that RoCD is usually not an issue in the holding, apart from pushing traffic down to fill up a hold. In the simulation I noticed that there was never the real need to instruct rates, but that might depend on the traffic sample.

Could let all aircraft use preferred/default descent, no need in the scenario to force this.

yes, together with the current and required ROD it is extremely useful (just didn't have to do too much about it in this traffic scenario)

Q11: - Were you paying too much attention to the function of RoCD fan?

6 responses



Comments

3 responses

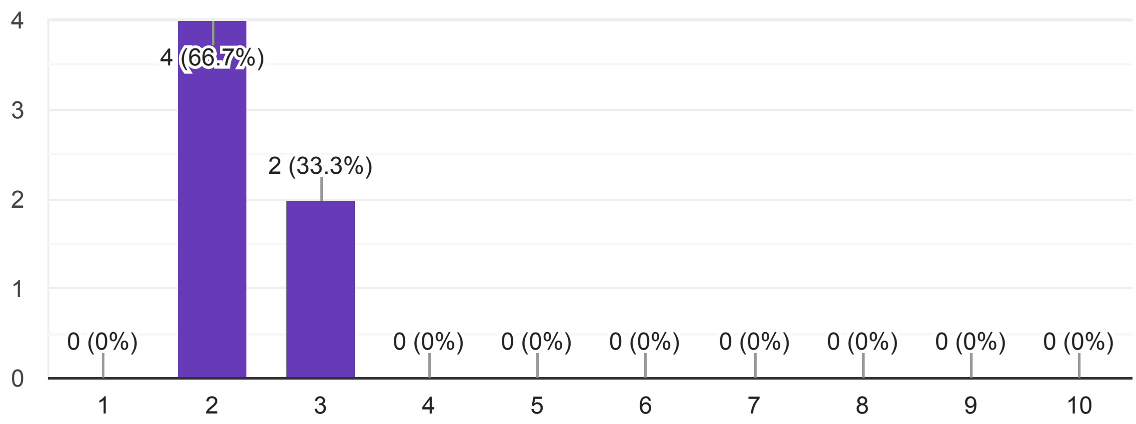
not really, once I understood the basiscs and how to use it, I focussed more on stack volume.

Spent hardly any time on ROD info.

no, it's not distracting at all

Q12: - Did the RoCD fan help you plan vertical transition of aircraft?

6 responses



Comments

5 responses

RoCD was never an issue, so no planning was necessary

not really, only use stack volume for that.

See previous explanation.

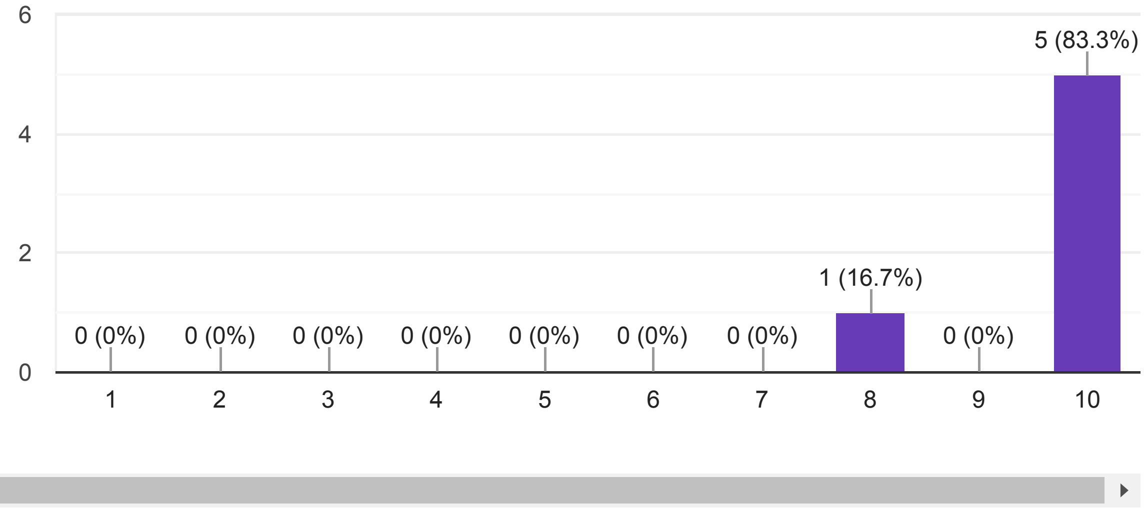
I saw no need for vertical planning apart from level separation, which is accomplished by looking at the vertical situation, not at the RoCD fan.

would have, if the traffic scenario had required it, but never had to do anything about it

SASHA - Cleared Flight level (#12, 13, 14)

Q13: - Do you think the cleared flight level provided you with useful information?

6 responses



Comments

3 responses

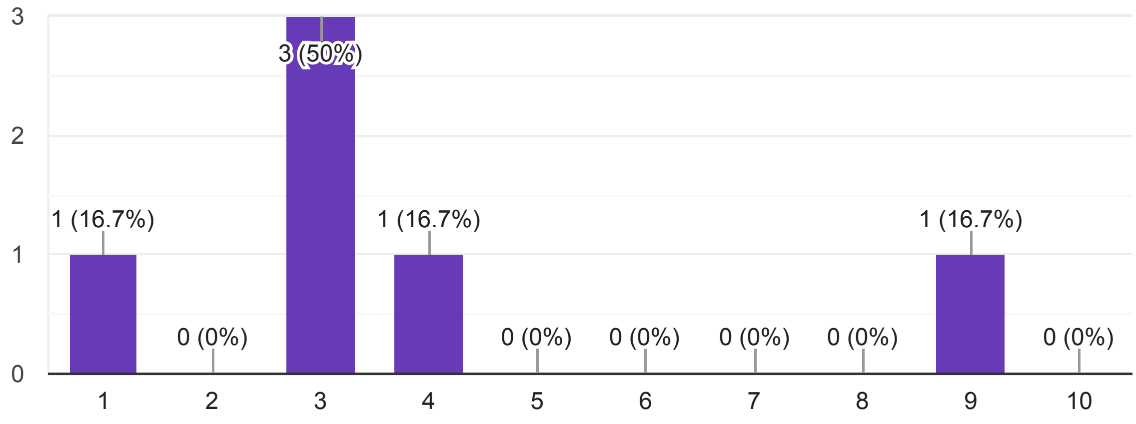
extremely helpful in managing the stack and time when I could give EFL commands

The cleared flight level gives a good extra indication of the way you're stacking a hold.

very useful because main concern of safety is the cleared FL, it also shows you when to do something about your stack, helps you with the flow of work

Q14: - Were you paying too much attention to the function of cleared flight level?

6 responses



Comments

3 responses

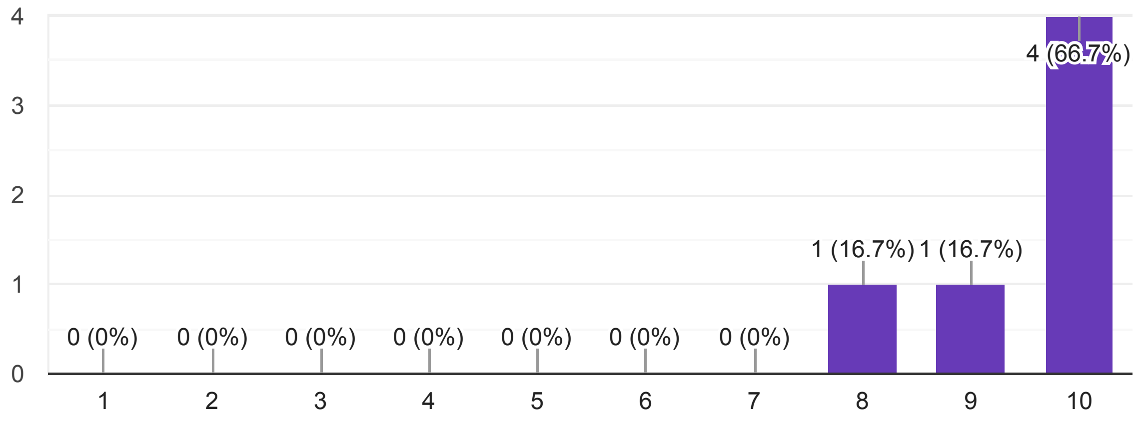
It was one of the focus points, but I was not fixated on it

yes, used it to time when I needed to provide next EFL command.

not "too" much, but still a lot of attention because it allows you to work efficiently and with higher capacity

Q15: - Did the cleared flight level help you to understand the aircraft's target flight level?

6 responses



Comments

2 responses

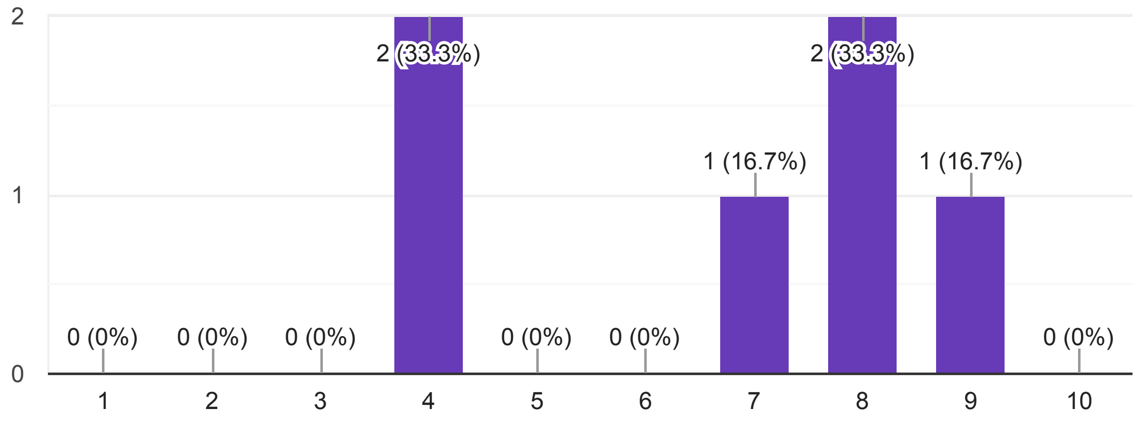
me liky a lot ;)

Even though you can also find the cleared level in the label of aircraft, I think the visualization makes it more intuitive.

SASHA - Connection between timelines (#15 & 19)

Q16: - Do you think the connection between timelines provided you with useful information?

6 responses



Comments

6 responses

It was a bit confusing, as it might be upside-down. Especially the bottom point of (19) was confusing.

was useful

Yes, but only for the initial check that the aircraft 'will manage'. Ignored during the progress of the flight.

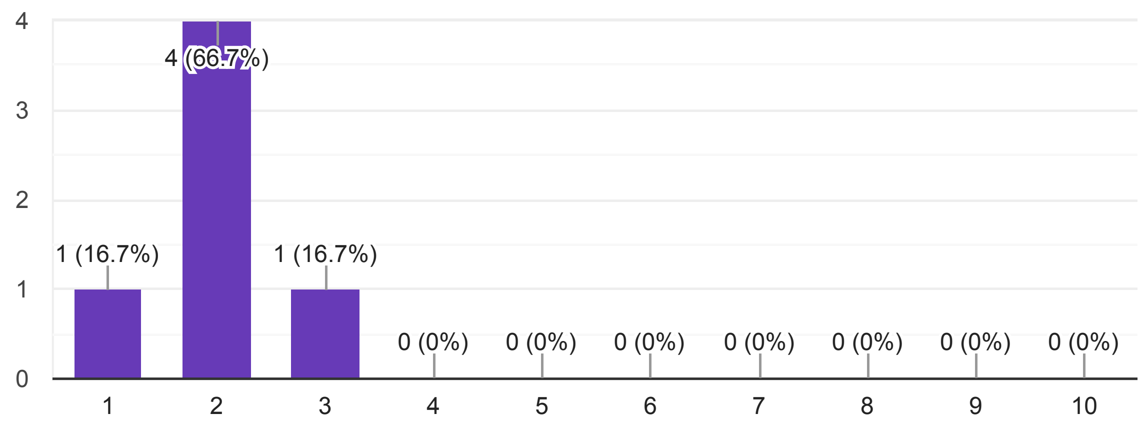
The connection shows when to turn traffic inbound, which I found useful.

it was possible to manipulate without considering the connection. Helps to find ac in pvd.

not always, as the information is not accurate in the beginning... once the first pattern is flown the information stabilizes and is very useful of course

Q17: - Were you paying too much attention to the connection between timelines?

6 responses



Comments

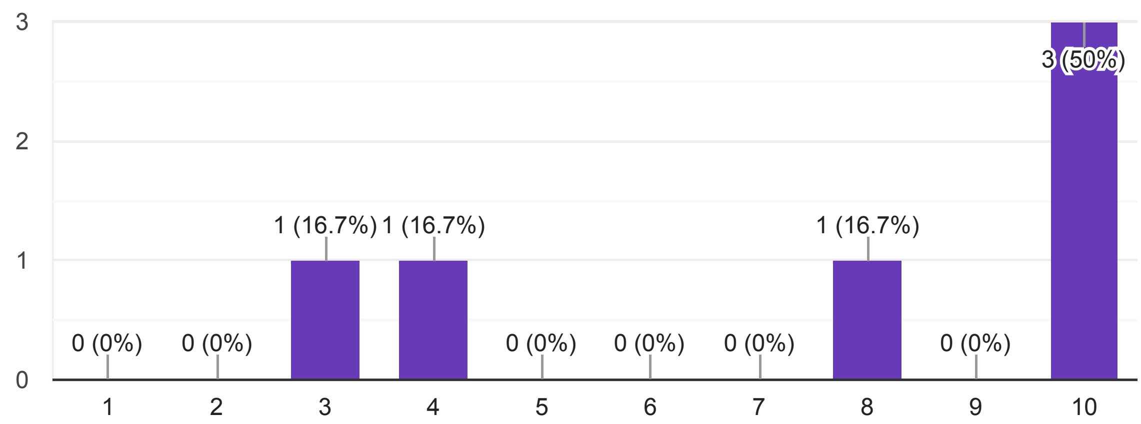
2 responses

not really

Not too much since RODs were always more or less in the expected range

Q18: - Did the connection between timelines help you to understand if the aircraft would reach FL 70 on time?

6 responses



Comments

4 responses

Although this was never an issue, the display served as a quick check that no problem existed.

yes, was an easy to perceive visual check.

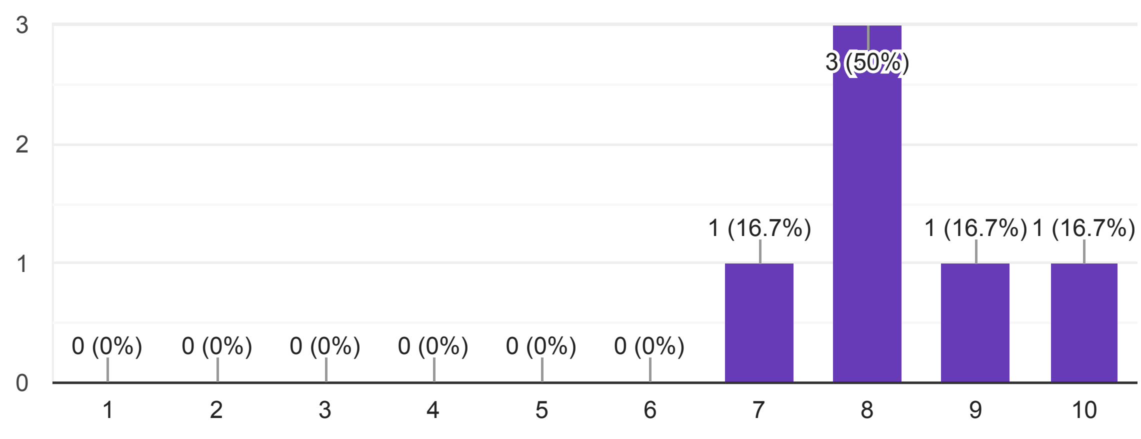
The connection does show if traffic would reach FL 70 on time, but that was never really an issue, so it was a little abundant.

yes, that was the case always, but I was clearing pro-actively, perhaps a different traffic sample would have caused more trouble

SASHA - IAF flyover frequency (#16, 17 & 18)

Q19: - Do you think the IAF flyover frequency provided you with useful information?

6 responses



Comments

4 responses

Only the one in the timeline was used (17). The one in the volume was not understood or used well.

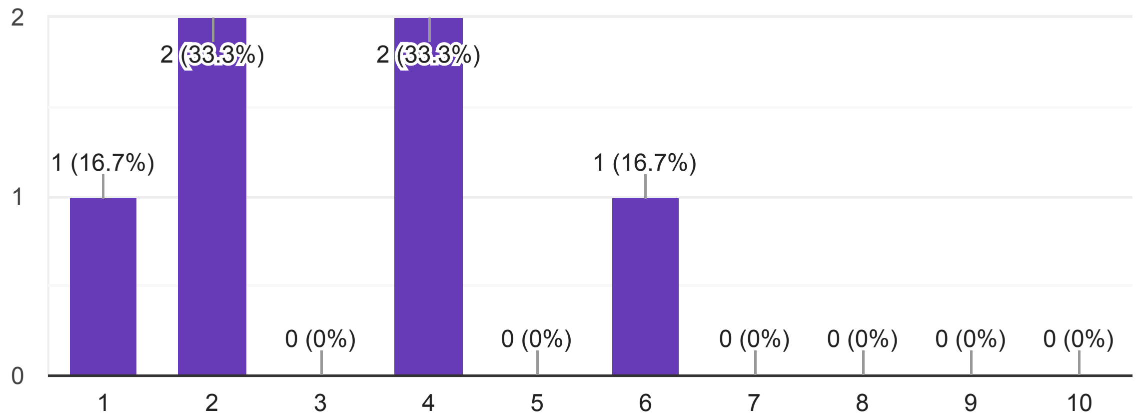
yes, but I feel I would have needed more training ti fully use it to my advantage.

The flyover frequency gives a good indication of the effects of HLT inputs and helps form a good mental picture of overall timing and spacing in the hold.

you use it for assessing how many holdings are left to fly and with what accuracy you can make them - absolutely necessary here

Q20: - Were you paying too much attention to the function of IAF flyover frequency?

6 responses



Comments

3 responses

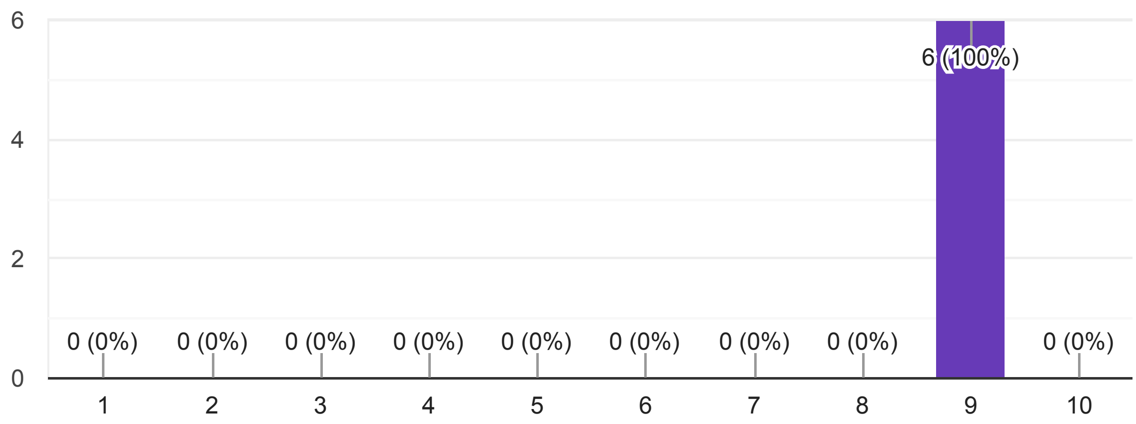
It was one of the focus points, but not so much that it posed a problem.

nope

No, not too much, it was always manageable, even when there was a lot of traffic in the stack that had to be separated

Q21: - Did the IAF flyover frequency help you with a more precise exit?

6 responses



Comments

5 responses

The drift of the prediction during the descent required some compensation, which was performed towards the end of the scenario. Instead of aiming right for the exit point, some initial offset into the magenta was accepted and even encouraged.

yes, but only focussed on matching the green and magenta triangles

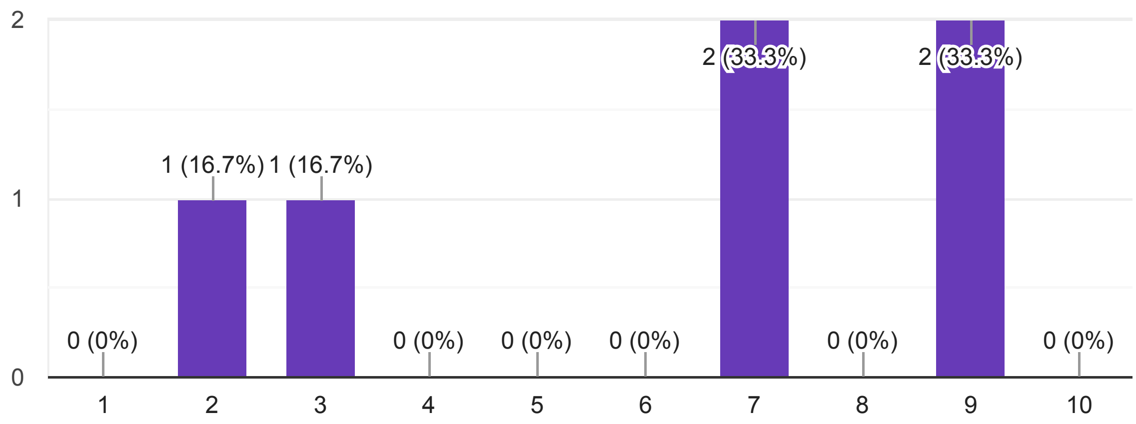
Yes: it's like a computer game with the goal to get the green and purple arrows on top of each other.

The flyover frequence most definitely helped me with a more precise exit. It works intuitive and I achieved rather precises exit without much effort.

as an indication in the beginning, and with one check later when the aircraft was getting closer to the stack exit

Q22: - Did the IAF flyover frequency help you understand future holding procedure timings?

6 responses



Comments

4 responses

As mentioned in Q21, the drift complicated things a bit.

this was more difficult and required more training

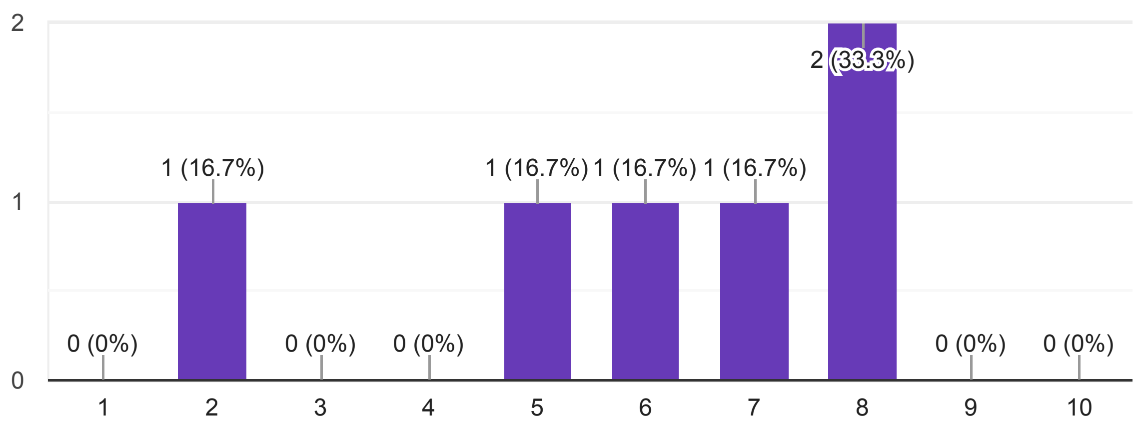
Yes, however it might look a bit far too head for my taste. This results in a bit more uncertainty and I question the need to look too far ahead. Apart from that, no issues.

yes, although I still had to force myself into a pattern to recognize that right of means to early (= longer HLT) and left of is a bit too late but with room to exit early (or shorter HLT)

SASHA - Conclusion

Q23: - Was there difficulty linking the information between the radar display and the holding support tool?

6 responses



Comments

6 responses

The radar display was almost only used to select aircraft for giving commands and as a rudimentary cross check. Sometimes the position within the race track of an aircraft was deduced from the radar display, instead of from the volume display.

difficult to answer, because on the radar display I also saw the vertical view. I used the vertical view to connect between the two screens, not the topdown radar view (because it would become cluttered)

It would be nice to see in the tool the aircraft that you have selected (e.g. colour).

In general, no, however, there are a few extras that might help such as highlighting selected aircraft and ability to select or input on the holding support tool too.

ended up linking a/c through their flight levels in both tools

yes, I didn't use the radar anymore once the aircraft were in the stack, only to check if new aircraft were coming, and of course to select aircraft; the latter was a bit of a hassle as there is no connection between the a/c you select on the radar and input

Q24: - Are there any features that you would add to the display?

6 responses

Definitely the currently selected HLT for each aircraft.

indicate what aircraft was selected and feedback on what holding leg time was inputted. Also making the holding display interactive, so select a/c on this display and make EFL changes "click & drag" (for future work). For now, I think it works nicely as a standalone aux display that LVNL can already add to their current operations, because it takes info that is already there and simply displays it.

1) Identify the aircraft currently selected.
2) Identify the aircraft that has been released from the holding stack.

As stated above, probably a better visible link between traffic selection on the radar screen and display.

selection information. SPL clearance information.

definitely a highlight of the selected aircraft (e.g. label colour of the label between stack and timeline display); even more so, for planning efficiency, an indication of the

Q25: - Are there any features that you would remove from the display?

6 responses

Numbers (16), bottom parts of (15) and (19)

not really, everything seems useful.

None.

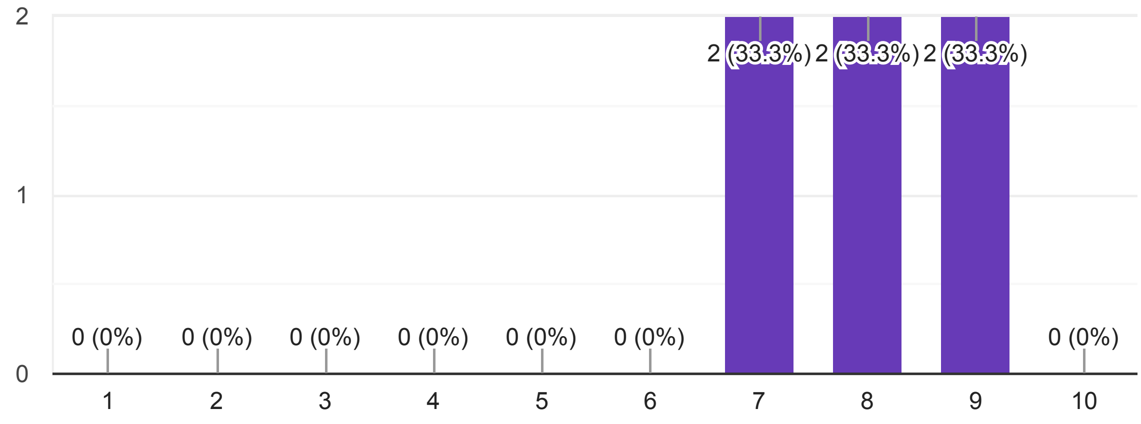
I'd consider removing the RoCDfan and maybe parts of the situational display

NA

no

Q26: - Finally how would you rate your overall situation awareness during the exercise?

6 responses



Comments

5 responses

As with all advanced displays, the situational awareness shifted from raw data (position of aircraft) to a higher abstraction level (state of altitude profile, number of holds left and precision of hold exit). I would be quite lost if this display would fail halfway a scenario, so if that signifies situational awareness, then it decreased. If the awareness includes the future development of the scenario, then the awareness increased and comes directly from the display.

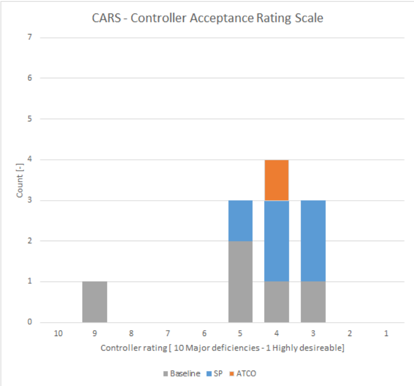
good, but only related to managing the stack and whereabouts of aircraft in the stack. connection between stack and radar display (spatial position in the world) was lost, because it captured my full attention.

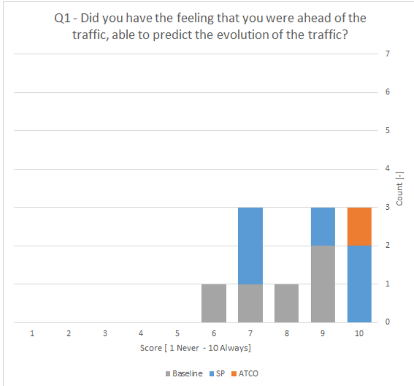
Answer relates to the 'vertical separation' situation awareness.
Focus on lateral separation / radar display was less.

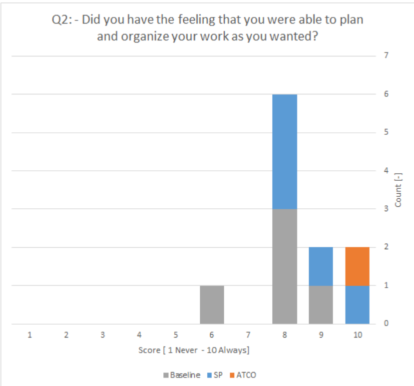
Nice and really useful display.

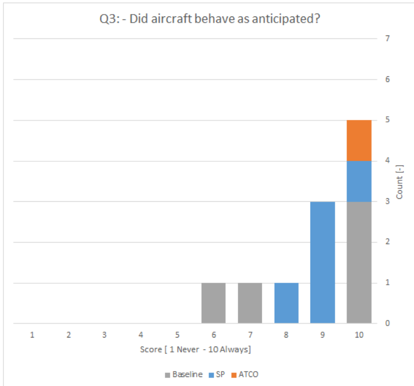
takes a while to clearly understand what the tool does, but once you know it, it is very easy to use and can lead to a very accurate planning

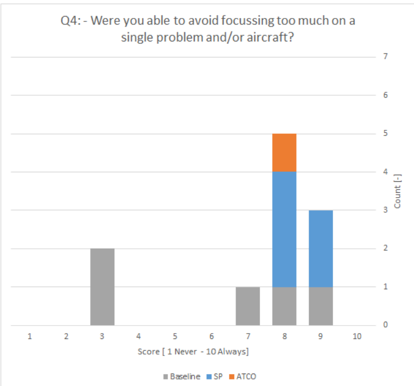
D | Questionnaire data compared

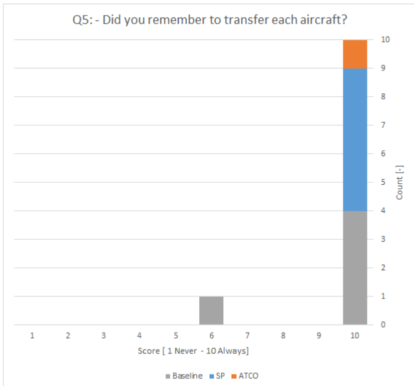


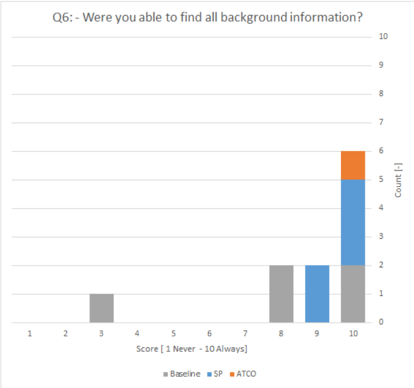


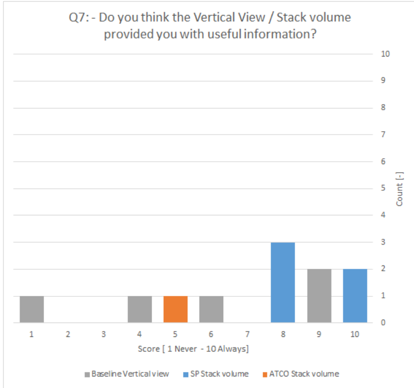


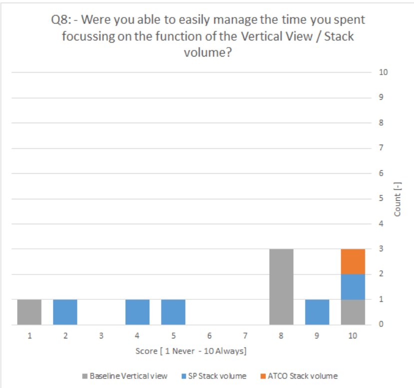


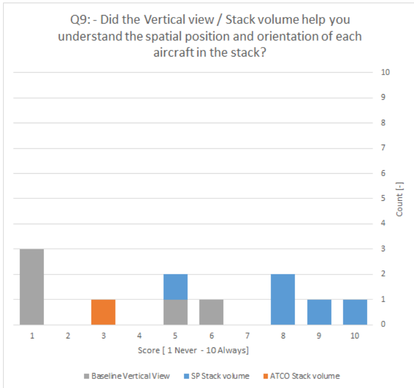


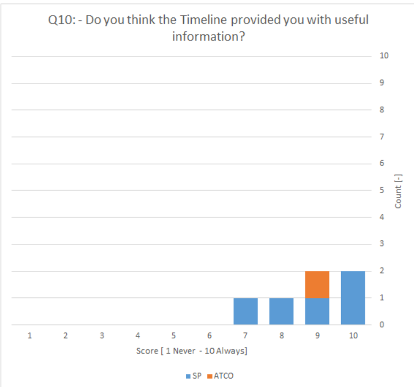


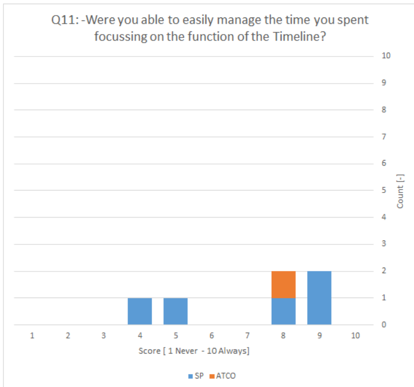

Q6: - Were you able to find all background information?
Count [-]
Score [1 Never - 10 Always]
Baseline
SP
ATCO

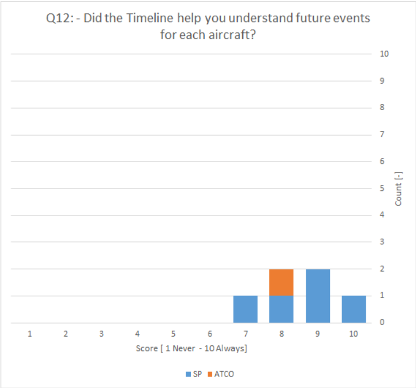

Q7: - Do you think the Vertical View / Stack volume provided you with useful information?
Count [-]
Score [1 Never - 10 Always]
Baseline Vertical view
SP Stack volume
ATCO Stack volume

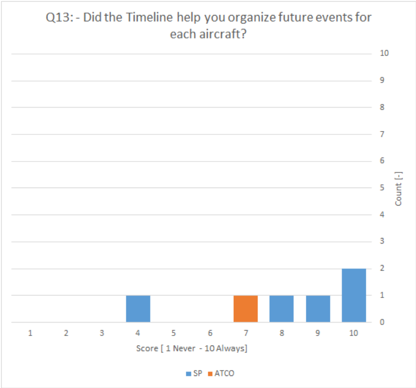

Q8: - Were you able to easily manage the time you spent focussing on the function of the Vertical View / Stack volume?
Count [-]
Score [1 Never - 10 Always]
Baseline Vertical view
SP Stack volume
ATCO Stack volume

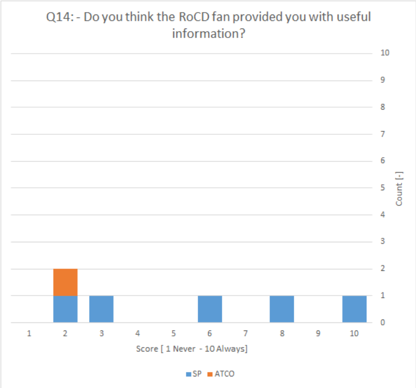

Q9: - Did the Vertical view / Stack volume help you understand the spatial position and orientation of each aircraft in the stack?
Count [-]
Score [1 Never - 10 Always]
Baseline Vertical View
SP Stack volume
ATCO Stack volume

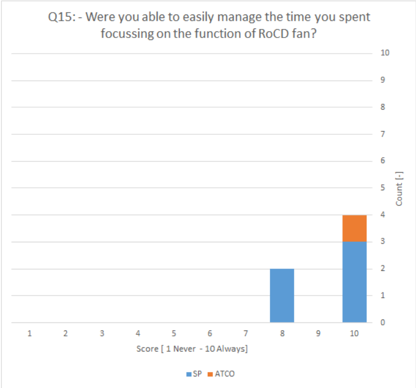

Q10: - Do you think the Timeline provided you with useful information?
Count [-]
Score [1 Never - 10 Always]
SP
ATCO

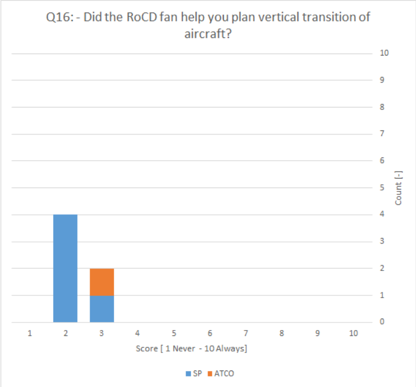

Q11: -Were you able to easily manage the time you spent focussing on the function of the Timeline?
Count [-]
Score [1 Never - 10 Always]
SP
ATCO

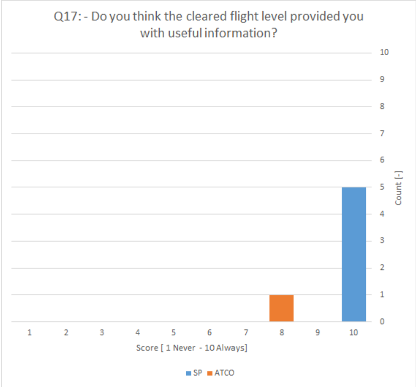

Q12: - Did the Timeline help you understand future events for each aircraft?
Count [-]
Score [1 Never - 10 Always]
SP
ATCO

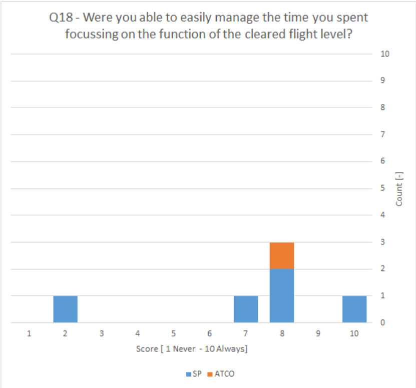

Q13: - Did the Timeline help you organize future events for each aircraft?
Count [-]
Score [1 Never - 10 Always]
SP
ATCO

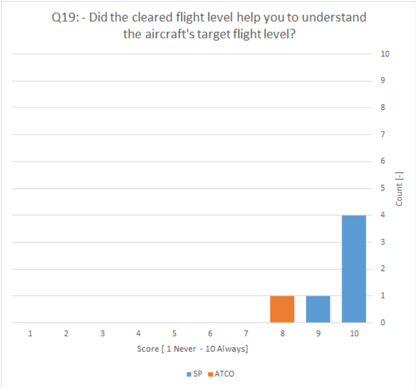

Q14: - Do you think the RoCD fan provided you with useful information?
Count [-]
Score [1 Never - 10 Always]
SP
ATCO

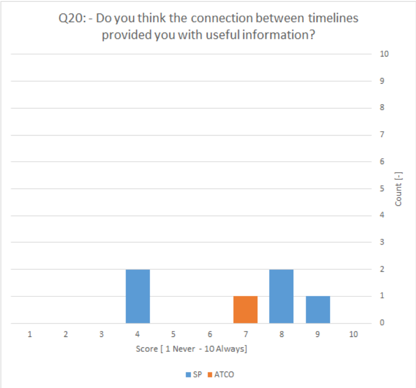

Q15: - Were you able to easily manage the time you spent focussing on the function of RoCD fan?
Count [-]
Score [1 Never - 10 Always]
SP
ATCO

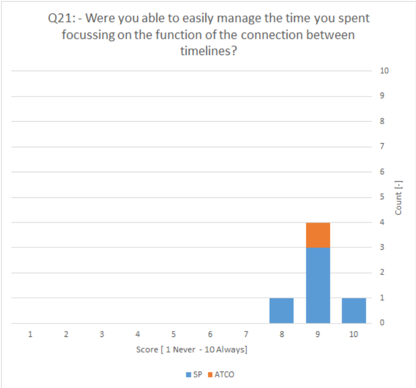

Q16: - Did the RoCD fan help you plan vertical transition of aircraft?
Count [-]
Score [1 Never - 10 Always]
SP
ATCO

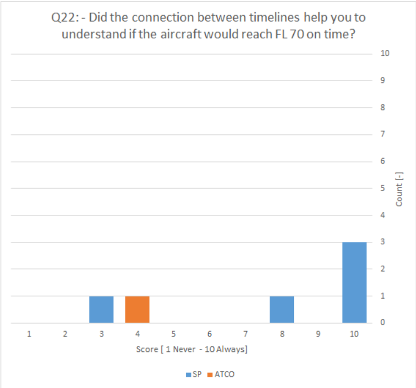

Q17: - Do you think the cleared flight level provided you with useful information?
Count [-]
Score [1 Never - 10 Always]
SP
ATCO

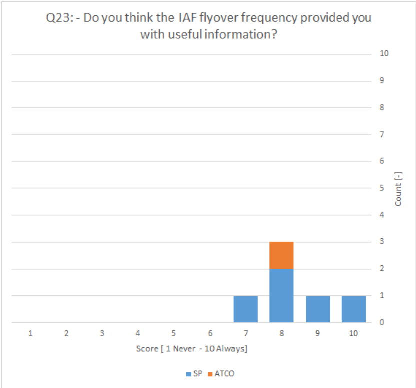

Q18 - Were you able to easily manage the time you spent focussing on the function of the cleared flight level?
Count [-]
Score [1 Never - 10 Always]
SP
ATCO

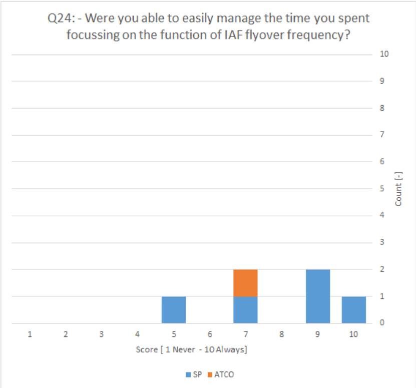

Q19: - Did the cleared flight level help you to understand the aircraft's target flight level?
Count [-]
Score [1 Never - 10 Always]
SP
ATCO

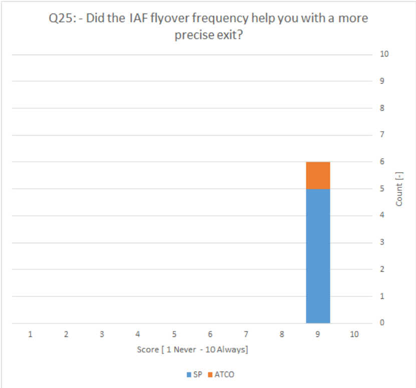

Q20: - Do you think the connection between timelines provided you with useful information?
Count [-]
Score [1 Never - 10 Always]
SP
ATCO

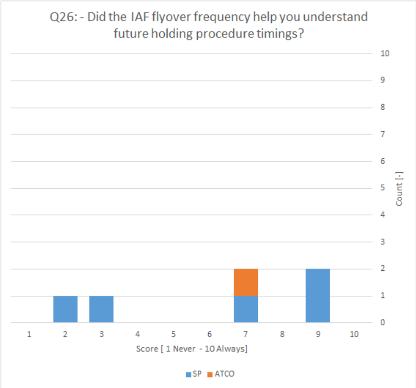

Q21: - Were you able to easily manage the time you spent focussing on the function of the connection between timelines?
Count [-]
Score [1 Never - 10 Always]
SP
ATCO

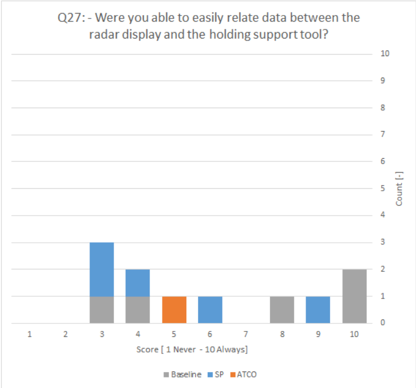

Q22: - Did the connection between timelines help you to understand if the aircraft would reach FL 70 on time?
Count [-]
Score [1 Never - 10 Always]
SP
ATCO

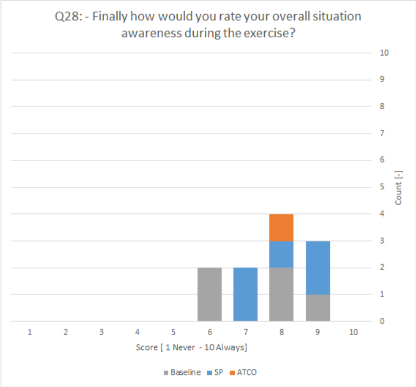

Q23: - Do you think the IAF flyover frequency provided you with useful information?
Count [-]
Score [1 Never - 10 Always]
SP
ATCO


Q24: - Were you able to easily manage the time you spent focussing on the function of IAF flyover frequency?
Score [1 Never - 10 Always]
Count [-]
SP
ATCO


Q25: - Did the IAF flyover frequency help you with a more precise exit?
Score [1 Never - 10 Always]
Count [-]
SP
ATCO


Q26: - Did the IAF flyover frequency help you understand future holding procedure timings?
Score [1 Never - 10 Always]
Count [-]
SP
ATCO


Q27: - Were you able to easily relate data between the radar display and the holding support tool?
Score [1 Never - 10 Always]
Count [-]
Baseline
SP
ATCO


Q28: - Finally how would you rate your overall situation awareness during the exercise?
Score [1 Never - 10 Always]
Count [-]
Baseline
SP
ATCO

E | Display project overview - Unity setup and code

This display is developed in Unity3D environment and as such must be build around the Update functions and the gameobjects present in the Unity scene. Attaching a script component (derived from monobehaviour) to a gameobject in the scene will result in the script running any `Start()`, `Awake()`, `Update()` or `FixedUpdate()` methods present in the script. `Start()` and `awake()` are run once while `Update()` and `FixedUpdate()` are run continuously. Examples of this are Application Manager and Display Update Manager which all will show up in the hierarchy as a GameObject which will in turn hold their respective component script. Furthermore code is stored in the Assets/Code folder and classes need to be named after their file name.

This display uses the Model View Controller design pattern where the display's sole responsibility is to View the Model. The Model is the NARSIM simulation environment which this display connects to. NARSIM also handles all Control inputs to the system.

E.1 Data flow

Because this display is to display information on a screen from a separate source an information flow must be established. This is done in the form of an XML data stream. Information that this display is interested in is the information of each aircraft near the holding area as well as simulation information such as current time. Information of each aircraft comes in various forms. All information received from NARSIM relevant to a single aircraft will be stored as a "track". Information can come in such as planner information in the form of an SPLplan message, clearance information in the form of an SPLclr message or positional information in the form of a track message.

Regardless of the type of incoming information, if it holds the id of a single aircraft, it will be added to the track list stored in `LiDisTrackManager` as a `LiDisTrack`. Figure E.1 shows how information coming from NARSIM is collected, parsed and stored in the track list. The flow of information to the display is handled by the following classes:

- **Connection** - Responsible for connecting to the external NARSIM server passing NARSIM messages to the decoder

- **Decoder** - Responsible for deserializing the data stream and passing this information to prepdata.

- **PrepData** - Responsible for filtering for relevant data as well as performing some operations on the data such as offsetting, scaling and rotating position data. After the data has been handled by `PrepData` it is passed to the `LiDisTrackManager`.

- **LiDisTrackManager** - Responsible for managing the TrackDict, a dictionary containing all relevant tracks. Incoming data must be added to the TrackDict. If there is no track with a given id, a new track must be created. If a track already exists in the track list, this track's information must be updated.

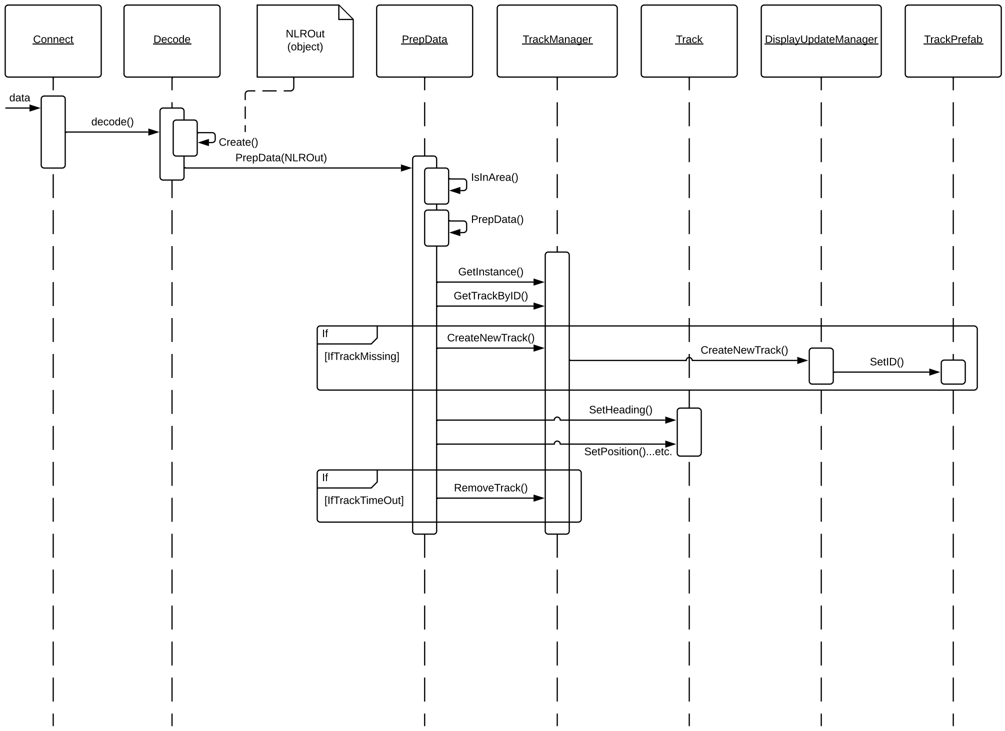


Figure E.1: Sequence diagram of NARSIM event sequencing

- **LiDisTrack** - A structure to hold an aircraft's information. Each track has a distinguishable id which is used as a dictionary key.

- **DisplayUpdateManager** - Once a track is created by the `LiDisTrackManager`, the `DisplayUpdateManager` will search for an available `TrackPrefab` to assign an id to.

- **TrackPrefab** - Will check each frame if an id is assigned to it. If there is no id assigned to it, it will not show on the display. If the `TrackPrefab` has an id, it will get information from the `LiDisTrackManager` using the id as a key. This event sequence is visualised in Figure E.2. The `TrackPrefab` is also responsible for updating all dynamic elements on the display. This is done with transformations and color alterations.

E.1.1 Application Manager Class

The Application Manager is responsible for starting the connection between NARSIM and the display. It holds the information of the port and IP Address which can be changed in the editor. When the application is booted up it will call `Connection.Set()` to set the port and IP information and then it calls `Connection.Start()` to initialize a connection with an agreed upon IP and port. Figure E.3 shows an overview of the entire display's data flow by means of a UML diagram.

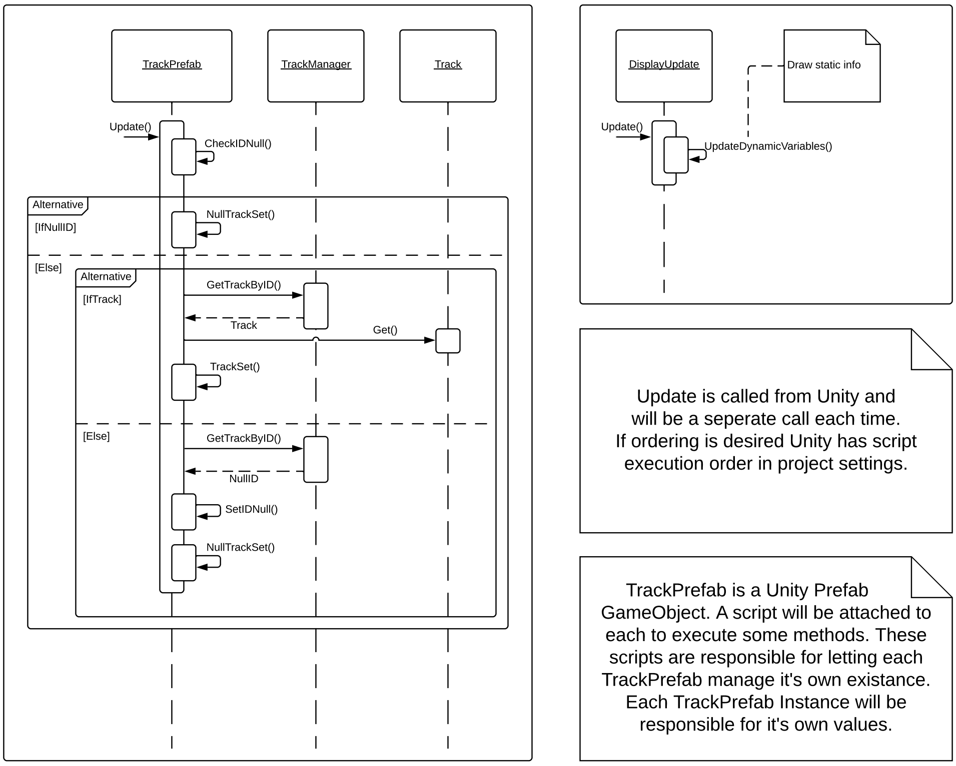


Figure E.2: Sequence diagram of Unity event sequencing

E.1.2 Stack Volume Class

The Stack Volume class controls how the volume of the stack volume is shown in 3D space by shaping the quads. Transformations can be done in play mode for editing purposes if the updateDisplay boolean is turned true in the inspector.

E.1.3 NLR_XML messages

This folder includes files with expressions required for decoding the data stream from NLR from a data stream to XML format. The naming and code setup in each file is determined by the incoming NLR XML message type and format.

E.1.4 Flight level Indicator Class

This class is responsible for drawing the FL indicator lines and numbers.

E.1.5 IafTimings Class

This class will have an instance per aircraft. It will be responsible for knowing when the last IAF flyover was, what the aircraft's current holding leg time is and what the simulation time is. It is also responsible for using this information to calculate the minimum time to exit, the predicted time to next exit using the known holding leg time and perform and operations on the child game objects necessary. This technology effectively uses dead reckoning after each IAF pass to predict future events and display them under the aircraft timeline.

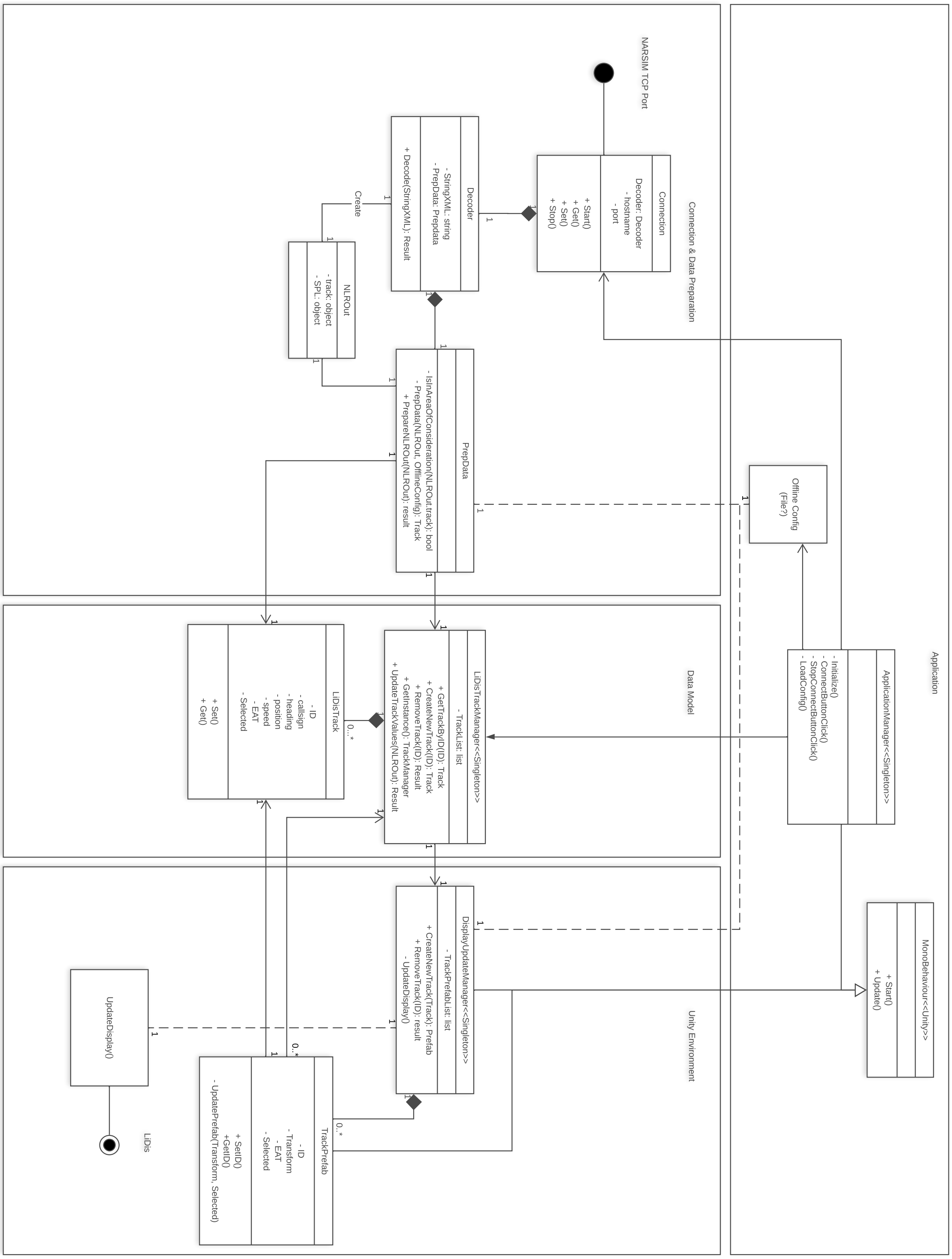


Figure E.3: UML diagram of code architecture

E.1.6 TrackPrefab Class

This class is responsible for moving all dynamic elements connected to a single aircraft. In the `Update()` method a check is done to see if this prefab has an ID and if it is within the scope of the holding stack. If there is no ID assigned to it, it will move all elements off screen with the method `SetNullTrack()`. If it has an ID then it will get all information related to this aircraft from `LiDisTrackManager`.

The `SetPrefabUpdates()` method will call all the main methods required to change the dynamic display elements. These main methods include:

- `UpdateInfo()` - A method to update the information text displayed between the stack volume and the RoCD fan
- `UpdateTimeline()` - A method which will use the current event timings to predict what a future timelinw will look like given current RoCD.
- `UpdateTransform()` - A large method which calculates what transformations are required to display the dynamic elements correctly. This includes resizing, repositioning and rotating most elements that the TrackPrefab is responsible for.
- `UpdateColors()` - A method which will take care of all dynamic colour update requirements.

Furthermore the `TrackPrefab` class will also reference renderer components to the child GameObjects so that their materials and colours can be changed with code. This is done with the `ReferenceMaterials()` method and the `InitializeColours()` method.

E.2 Unity Scene

When editing the display in the Unity3D editor, the scene view will show shapes in 3D space, The hierarchy will show all GameObjects in the scene and the inspector will help view components attached to these GameObjects. Code derived from MonoBehaviour can be attached to GameObjects.

E.2.1 Stack Planner hierarchy

In the Stack Planner hierarchy all GameObjects in the scene are found. The Stack Planner hierarchy is shown in Figure E.4. The hierarchy consists of:

- **Four different Cameras** - Different cameras can be used for different projections or angles but the main camera used for the display is the "Main Camera 3D Orthographic" which uses an orthographic projection. A noteworthy camera is the "Video Recording Camera" which uses code from RockVR to record a video of what the camera captures.
- **Directional Light** - shows a lightsource which helps controllers distinguish the 3D aspect of the volume.
- **ServerDummy** - This GameObject holds the `LiamTCPDummyServer` class which is able to simulate some test XML messages and send them through an IP and port. This can be used to test some of the functionality of the display.

- **ApplicationManager** - This GameObject holds the **ApplicationManager** script.
- **PrefabPool** - This holds all Prefab GameObjects. This is the GameObject parent with all the child prefabs. The number of prefab children under this parent is the maximum amount of aircraft that the display can handle. This number can be increased or decreased.
- **DisplayUpdateManager** - This parent GameObject will hold the DisplayUpdateManager script component. It will also parent many static background elements with the option to update them in play mode using the updateDisplay boolean.
- **Flight level indicator** - This GameObject holds the FlightLevelIndicator script component as well as a LineRenderer component to draw the flight levels.
- **StackVolume** - This parent GameObject holds 11 child GameObjects. Six of these GameObjects are Quads which are displayed as squares in 3D space. The roof quad is disabled as it does not need to be displayed. The size and orientation of these quads is controlled by the StackVolume script attached to the StackVolume GameObject. This script uses CornerFBL, CornerBTR, Start Time Axis and End Time Axis GameObject Transforms as references on how to size and orient the quads. The most noteworthy quad of the seven child quads is the QuadEATRight Fan. This quad holds the RoCD fan by means of a material which uses the RoCD Fan shader. Gradients and colours can be adjusted using this shader. The gradient uses the vertical axis with a ratio of 1 Unity unit = 10 FLs. It also uses the horizontal axis with a ratio of 1 Unity unit = 1 minute.
- **RoCD Grid** - This GameObject holds two Grid Drawer script components. One draws the grid for every minute and the other draws a slightly thicker grid for every 5 minutes. This GameObject also holds many child text GameObjects containing text information for the controller.

E.2.2 PrefabTrack hierarchy

The PrefabTrack is responsible for each dynamic display element of a single aircraft. As such there are many moving parts in this GameObject and some extra attention is required. The prefab hierarchy can be seen in Figure E.5. The prefab hierarchy consists of:

- **PrefabTrack** - The parent GameObject which is turned into a Unity Prefab. This is a type of file that can be dragged into the scene from a project explorer and the Unity editor will know exactly how to construct it in the scene. This GameObject is also responsible for holding the `TrackPrefab` script component. This script holds references to nearly all child GameObjects that are changed dynamically.
- **AC, CFL and IAF Position GameObjects** - These GameObjects are all visual elements which are controlled by the `TrackPrefab` script.
- **Grid GameObjects** - The Grid GameObject holds a `GridDrawer` script component which draws a grid around the EAT timer bar. number of columns should be equal to the minutes.
- **LineEAT and Line RoCD GameObjects** - These GameObjects are responsible for drawing the connecting line between the two timelines. This is done with the `LineConnector` script.

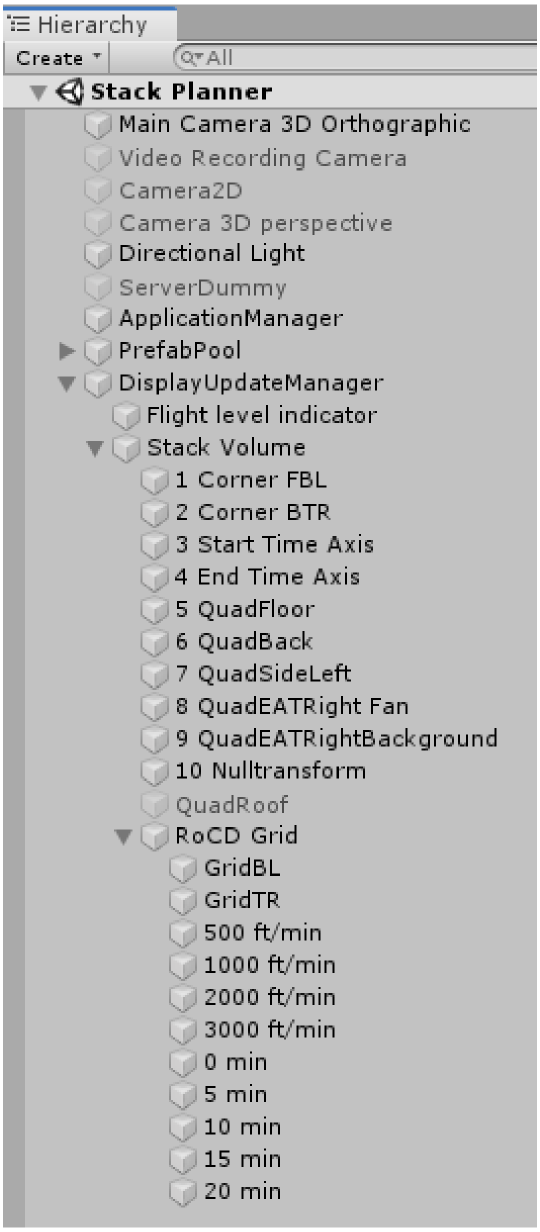


Figure E.4: Main scene hierarchy in Unity3D editor

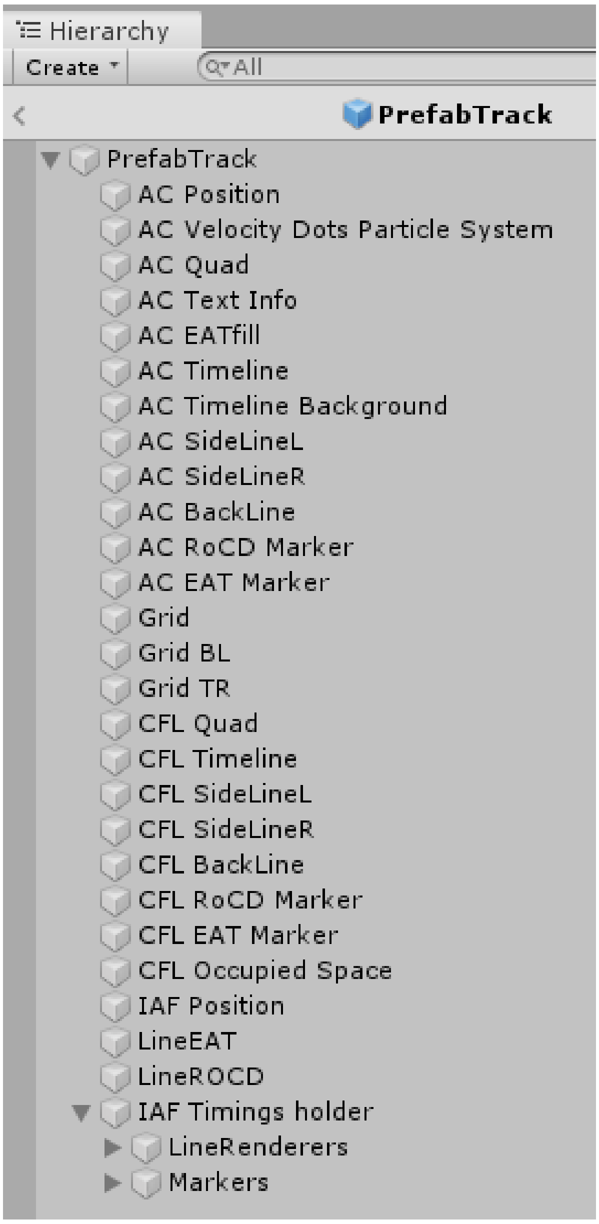


Figure E.5: PrefabTrack hierarchy in Unity3D editor

- **IAF timings holder** - The IAF timings holder holds the IAFTimings script component which references the LineRenderers and Markers child GameObjects which are also parents of LineRenderers and triangle marker sprites respectively.

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