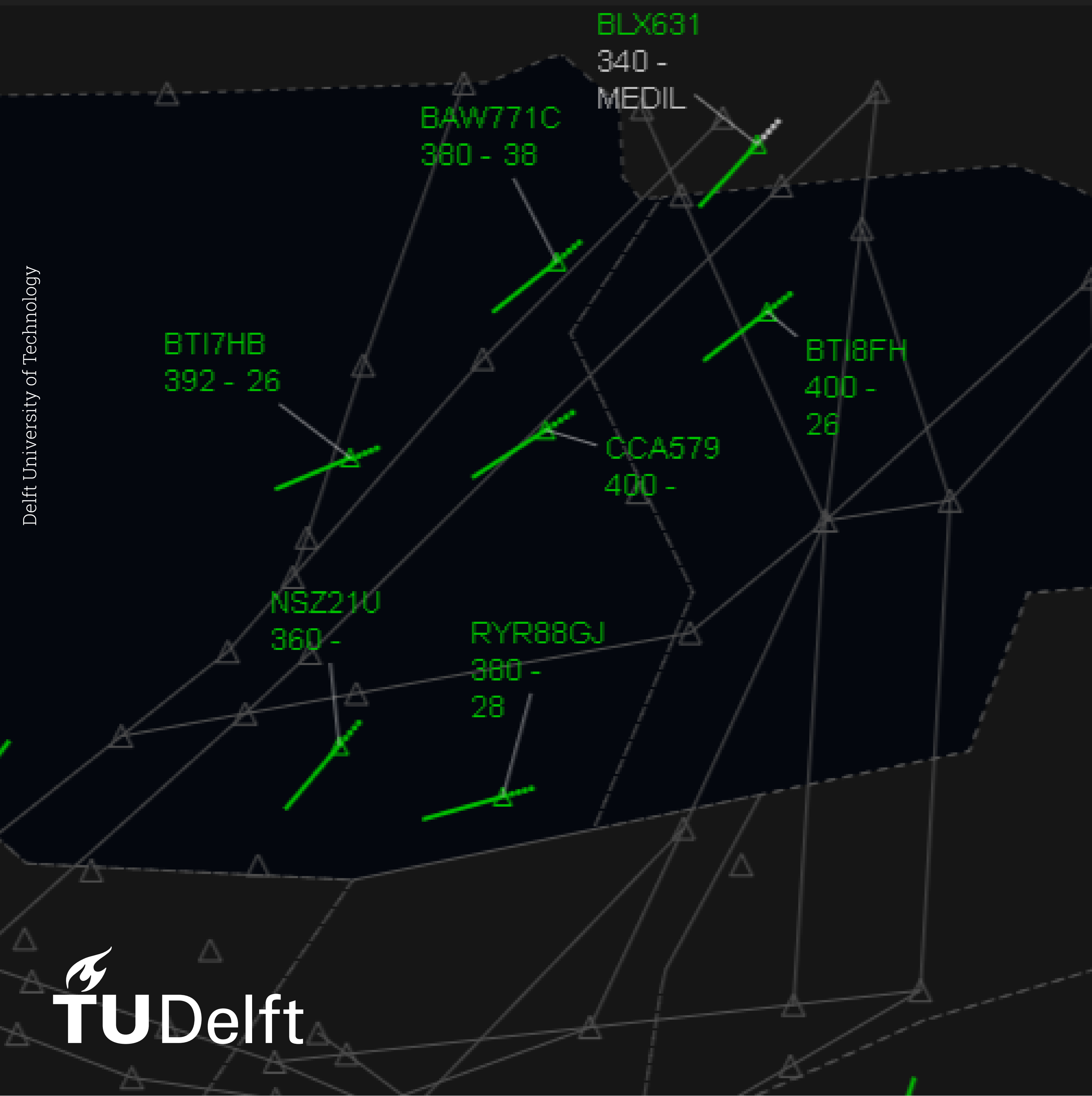
Guiding Visual Attention to Relevant Flights in Supporting Air Traffic Controller Decision Making

Final Thesis Report

Ajay Kumbhar Vijay Kumbhar

Delft University of Technology



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by

Ajay Kumbhar Vijay Kumbhar

Student Number:	5316529		
Thesis Committee:	Dr. Ir. C. Borst	TU Delft	Daily Supervisor
	Prof. Dr. Ir. M. Mulder	TU Delft	Committee Chair
	Dr. Ir. M.M. van Paassen	TU Delft	Committee Member
	Dr. Ir. A. Bombelli	TU Delft	External Examiner
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Cover: Jever airspace as displayed in the SectorX ATC Simulator

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Preface

This thesis marks the culmination of my master's in pursuing the Control and Simulation Profile in the Faculty of Aerospace Engineering at TU Delft. The journey has been arduous yet rewarding, and I express my heartfelt gratitude to lecturers, fellow students, and family for their invaluable support.

I am deeply grateful to Dr. Clark Borst, my daily supervisor, for his invaluable guidance, unwavering support, and exceptional technical expertise throughout this thesis. Your mentorship has not only influenced the direction of my research but has also inspired me to pursue excellence in my professional endeavors. I feel privileged to have Prof. Max Mulder and Dr. Rene van Paassen as my co-supervisors, and I am grateful for their feedback and encouragement during the initial stages of the thesis. I extend my gratitude to the Ph.D. Candidates Gijs de Rooij and Wenying Lyu for the frequent brainstorming meetings during the documentation and scenario design for the experiment. I am thankful to the participants for voluntarily participating in the experiment and providing their valuable insights into the proposed work.

The journey would not have been as smooth without the support of my friends in Delft, who kept me motivated, provided comfort, and made my stay enjoyable. I'm grateful to my housemates at Cesar 71+108 and HDK 117 for their assistance with paperwork formalities and for sharing meals during super busy days. I always looked forward to the Stabilo events to catch up with Control and Simulation friends, and I extend my gratitude to them for their companionship during my time in the faculty. Lunch and coffee breaks wouldn't have been as enjoyable without my peers in the AE 2.44 master room, and I'm thankful to them as well. I wish nothing but good luck to all of you in achieving a happy and successful life.

Last but certainly not least, I extend my deepest gratitude to my family - parents, sisters, brother-in-law, and niece for their boundless love, encouragement, and unwavering belief in my abilities. Your unwavering support has been the foundation of my life goals, and I am profoundly grateful for the sacrifices you have made to see me thrive.

Ajay Kumbhar Vijay Kumbhar
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Nomenclature

Abbreviations

Abbreviation	Definition
ACAS	Aircraft Collision Avoidance Systems
ANSP	Air Navigation Service Providers
ATC	Air Traffic Control
ATCo	Air Traffic Controller
ATM	Air Traffic Management
CDR	Conflict Detection and Resolution
COCOM	Contextual Control Model
CPA	Closest Point of Approach
CPDLC	Controller Pilot Data Link Communications
CTA	Control Area
CTR	Control Zone
DST	Decision Support Tools
EAP	Extended ATC Planner
EID	Ecological Interface Design
FIR	Flight Information Region
FRA	Free Route Airspace
HCI	Human Computer Interaction
HMI	Human Machine Interface
LOS	Loss of Separation
MCD	Multi-Conflict Display
MoF1	Modell der Fluglotsenleistungen
MUAC	Maastricht Upper Area Control Centre
PVD	Plan View Display
RPV	Relative Position Vector
SESAR	Single European Sky ATM Research
SID	Standard Instrument Departure
SSD	Solution Space Diagram
STAR	Standard Terminal Arrival Route
STCA	Short-Term Conflict Alerts
SUA	Special Use Airspace
TBO	Trajectory Based Operations
TMA	Terminal Control Area
UI	User Interface
UTA	Upper Control Area
VERA	Verification and Resolution Advisory

Part I

Scientific Paper

Guiding Visual Attention to Relevant Flights in Supporting Air Traffic Controller Decision Making

Ajay Kumbhar Vijay Kumbhar
Supervisors: Dr. Ir. Clark Borst, Prof. Dr. Ir. Max Mulder, and Dr. Ir. Rene van Paassen
Faculty of Aerospace Engineering, Delft University of Technology

***Abstract*—Enroute Air Traffic Controllers (ATCOs) determine the appropriate course of action by scanning radar displays to identify and select a flight that requires clearances to ensure safe and efficient operations within their airspace sector. After selecting a flight of interest, ATCOs visually compare the flight parameter displayed in the flight labels to assess the impact of potential flight control actions on the sector safety. Expected surge in global air traffic will make it difficult for ATCOs to compare flight parameters, leading to delayed responses and increased workload. This research proposes a flight filtering mechanism based on interacting flight trajectories with spatio-temporal proximities to guide ATCO's attention toward potential interaction flights after selecting a flight of interest. ATCOs will find potential interaction flights more saliently as non-interacting flights fade once the flight of interest is selected. This approach targets ATCO's pre-attentive phase of visual processing, alleviating additional perceptual and cognitive efforts in finding and processing information during conflict detection and previewing clearances. Experiment results with eight subject matter experts as participants showed no significant differences in the safety, operator performance, and perceived workload while controlling traffic due to demanding task requirements and strategy variation among participants. Nonetheless, participants expressed positive feedback regarding the assistance offered by filtering in fading non-interacting flights. No significant differences in objective measures coupled with filtering's positive perceptions indicate filtering did not negatively affect the performance, suggesting further research with optimal balance between task requirements and participant expertise to evaluate the flight filtering concept.**

***Index Terms*—air traffic control, decision-making process, flight filtering, interacting flights, user strategies**

I. INTRODUCTION

The rise in global demand for air travel has made aviation operations more complex and has significantly increased the workload for human operators, posing a serious threat to safety standards [1]. The existing Air Traffic Management (ATM) system faces challenges, such as frequent delays and the need for flight reroutings, emphasizing a comprehensive reform in the Air Traffic Control (ATC) domain. Predictions indicate an upcoming shift towards collaboration between human operators and supportive tools to manage the growing demands effectively. An essential aspect of these tools is their active engagement with human input, promoting trust, reducing resistance to technology integration, and aligning with operational needs [2].

The Single European Sky ATM Research (SESAR) project is at the forefront of modernizing the ATM system in Europe, shifting the emphasis away from geographical borders to more effectively handle traffic demands [3]. Currently, flights follow structured routes through enroute airspace instead of choosing direct routes, resulting in suboptimal operations. Although tools like trajectory prediction and short-term conflict alerts (STCAs) have improved safety by addressing uncertainties, the decision-making process still heavily depends on the skills of human operators [4].

In managing the safe and efficient air traffic flow in their controlled upper airspace, enroute Air Traffic Controllers (ATCOs) are responsible for monitoring and managing traffic, addressing pilots' requests, and promptly identifying and resolving conflicts. The selection of a flight and the issuance of clearances involve considering various factors, including sector characteristics, traffic parameters, operational requirements, and human limitations. The clearances and issuing time are subjective among ATCOs, varying based on their strategies in perceiving information, comprehending its meaning, and implementing action. Previous research shows that conflict alerts generated in the upper airspace are not isolated but slightly interlinked, arising from the interconnected nature of conflicts, where ATCOs may inadvertently create secondary conflicts while attempting to resolve primary ones [5]. Additionally, generating efficient maneuvers, such as clearing flights directly to their sector exit, requires higher monitoring time and is usually avoided during higher workload [6]. Moreover, human operators have limited attention and face difficulties distributing attention toward flights and their parameters during increased traffic, potentially leading to errors in issuing safe clearances [7].

Research has shown redesigning visual elements of the radar display by providing visual cues or color coding related to the specific ATC events reduces cognitive efforts required to process information and increases acceptability among ATCOs [8-9]. PROSA project proposed that fading flights no longer threatening the sector due to maintaining sufficient separation from other flights enables ATCOs to allocate their focus to other flights [10]. Faded flights reappear on the screen if they no longer meet the spacing requirements while ATCOs provide clearances to them or other flights. Although the solution promises to increase the sector capacity with ATCO's acceptance, the algorithm is at the forefront of displaying the traffic situation to ATCOs. Collaboration between humans and machines in the ATC domain often leads to skill degradation of human operators [11]. Limited research has focused on capturing the decision-making process of ATCOs and enhancing their abilities to issue safe and efficient clearances.

This research proposes a flight filtering concept based on the flight trajectories with spatio-temporal proximities to identify the relevant flights potentially interacting with the selected flight of interest and ATCO's preferred clearance. By fading irrelevant flights, this approach enhances the salience of relevant flights, aiding ATCOs in conflict detection and clearance issuance. The thresholds for the spatio-temporal parameters and validity of the proposed filtering were evaluated through MUAC's research on flight allocation to automation, tasking professional ATCOs with identifying flights perceived to interact with the introduced automated flight [12]. The filtering aims to alleviate the cognitive load associated with comparing flight parameters during conflict detection and clearance issuance, contributing to enhanced safety, operational efficiency and reduced human workload in ATC operations. The proposed concept underwent experimental testing using eight subject matter experts as participants.

The article is structured as follows: Section 2 identifies the decision-making process of the enroute ATCOs and current trends in decision-aiding tools related to ATC tasks. Section 3 delves into the flight filtering concept, providing a detailed exploration of the filtering's inner workings, the definition of crucial parameters and thresholds, and an in-depth examination of its success rate. Sections 4 and 5 present the experiment setup and the obtained results. Section 6 discusses the findings obtained from data and recommendations for future research. Lastly, Section 7 concludes the article.

II. BACKGROUND

A. Decision-Making Process

Enroute ATCOs construct a mental picture of the airspace by integrating static information, such as sector boundaries and waypoint locations, with dynamically updated flight positions. This mental picture enables ATCOs to anticipate future flight positions and proactively prevent potential conflicts [13]. They employ a subjective look-ahead time strategy to predict future flight positions based on current flight parameters, assigned routes, and planned clearances. ATCOs assume control of incoming flights and issue clearances that maintain safe separation standards. They seamlessly transfer control of outgoing flights to adjacent ATCOs while maintaining an expansive view of the airspace to prevent conflicts in neighboring sectors. Figure 1 illustrates a flowchart detailing the conflict detection process and its critical role in anticipating and optimizing preferred clearances to meet operational demands.

Rantanen and Nunes [14] explored the flight characteristics that ATCOs prioritize for conflict detection in enroute airspace. Initially, ATCOs focus on verifying altitudes to guarantee adequate vertical separation between flights. Flights maintaining sufficient vertical separations necessitate minimal cognitive effort for safety evaluations. Subsequently, ATCOs carefully examine flight pairs operating at the same altitudes by assessing their positions and headings to determine their convergence and evaluate horizontal separations. Moreover, ATCOs also consider the speed of converging flights to determine which flight will reach the convergence point first by utilizing speed-distance computations. However, incorporating the speed parameter into the mental picture proves cognitively demanding and is therefore assigned a lower priority, contrary to altitudes and headings. The promptness of conflict detection is notably affected by both the conflict angle and its duration. Conflicts characterized by small conflict angles and short conflict times are detected more rapidly than conflicts with large conflict angles and extended conflict times [15].

The subjective look-ahead time, a crucial element in predicting future flight positions adopted by ATCOs, significantly influences conflict detection accuracy. The choice of resolution maneuvers varies among ATCOs and heavily depends on the spatial, temporal, and technical parameters of flights within the sector [16]. Typically, minimal heading changes are advised for flights separated by a considerable distance, indicating sufficient time for resolution. In contrast, closer flights, determined by positional proximity, often necessitate altitude changes, indicating the need for more immediate action to maintain separation standards.

Rantanen and Wickens [17] examined the cognitive factors influencing the selection of resolution maneuvers among ATCOs. Achieving sufficient vertical separation involves minimal mental effort, making altitude adjustments a popular conflict resolution strategy among ATCOs. However, it increases workload as ATCOs need to consider potential conflicts arising from overlapping altitudes during the transition, requiring additional monitoring and coordination. Conversely, a lateral maneuver via heading change is visually straightforward, maintaining a constant altitude without considering climb or descent rates. This maneuver diverts the flight from its intended route, necessitating rerouting unless cleared by ATCOs to skip intermediate waypoints. Speed adjustments are less favored than altitude and heading changes, especially at higher altitudes, due to their slower profiles and narrowness, primarily used for resolving overtaking conflicts [18]. The preferred resolution maneuver minimizes disruption in the sector, and ATCOs issue it accordingly.

Effectively resolving conflicts with minimal workload involves maneuvering a flight behind another or employing step climbs or descents to different flight levels (FLs) [19]. For efficiency, ATCOs may prioritize higher altitudes for extended periods or direct trajectories towards the sector exit (COPX), aiming to optimize traffic flow through the sector. They utilize a prospective memory approach, briefly storing critical flight information and issuing clearances at opportune moments to meet operational demands. However, this approach becomes vulnerable under high workload conditions due to its cognitive demands and the potential for overlooking conflicts [20]. Failure to resolve conflicts or missed alerts can limit available resolution maneuvers, leading to deviations from planned flight paths or altitudes and accumulations of errors [21]. Importantly, clearances issued by ATCOs to meet operational demands, such as clearing flights towards their transfer flight level or directly clearing towards sector exit, must always adhere to established separation standards between flight pairs within the sector.

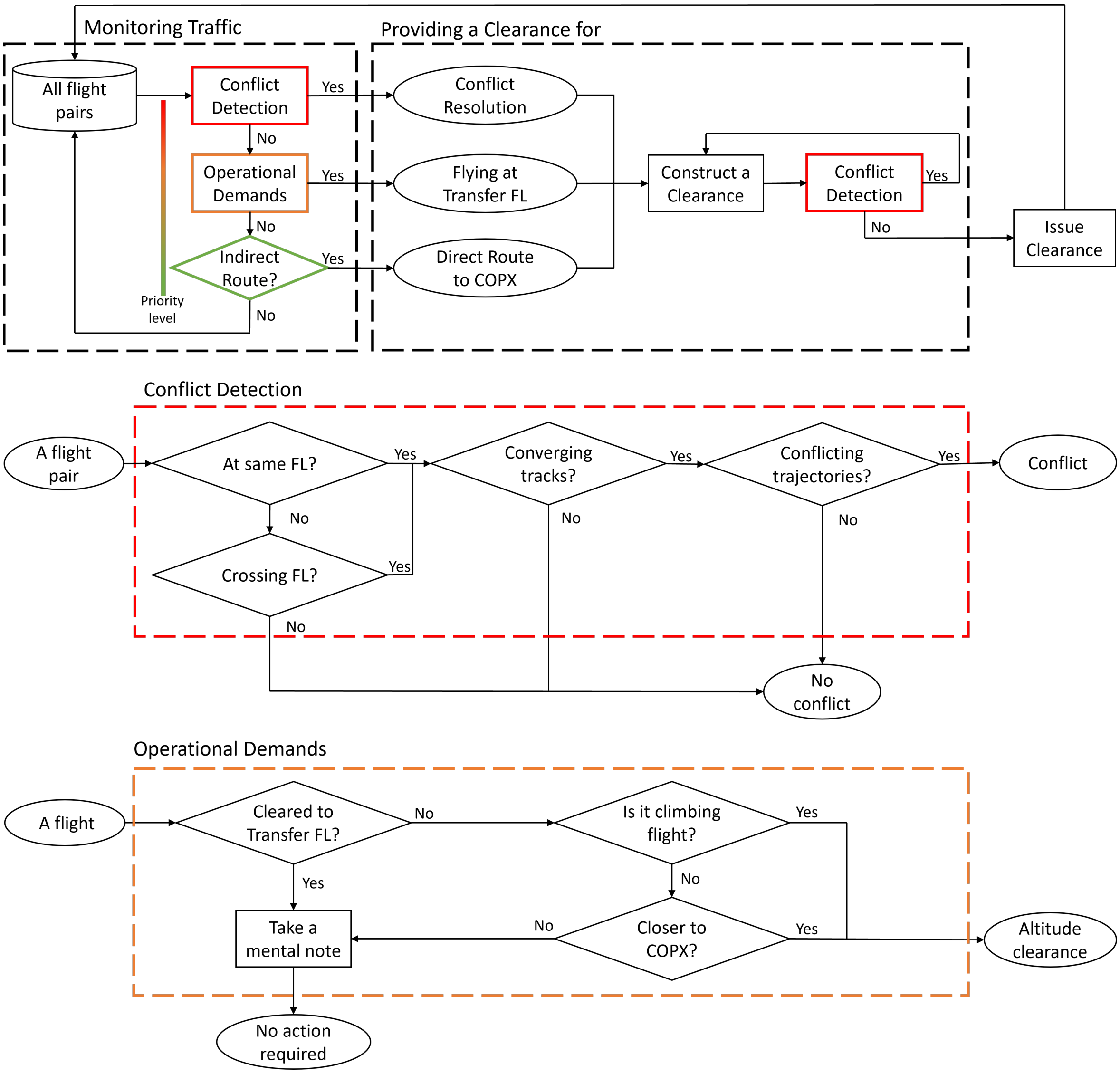


Fig. 1: Flowchart for issuing a clearance safely and efficiently while meeting operational demands

Having established the pivotal role of issuing clearances in enroute ATC, it is essential to delve into the multiple factors influencing the decision-making abilities of ATCOs, as shown in Figure 2. However, it is crucial to emphasize that these factors are interrelated and collectively contribute to the decision-making process. ATCOs operate efficiently within their workspace capacity, and the strategies they choose when issuing clearances aim to align the experienced workload with the desired workload [22-23]. Experienced ATCOs exhibit effectual situation awareness, swift response times, and superior scanning patterns, optimizing attention allocation compared to novices while expediting the flow [24]. The supporting tools designed for ATCOs strive to align with their work strategies while meeting operational demands.

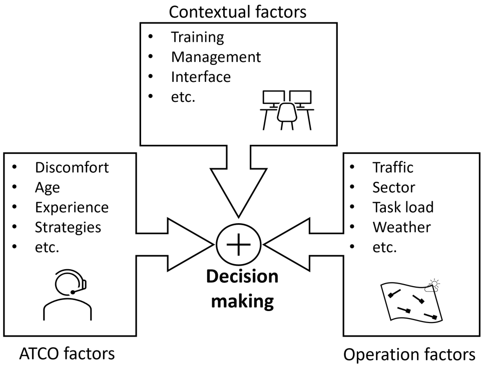


Fig. 2: Factors affecting decision-making process

B. Decision-Aiding Tools

Current tools integrated into ATC workspaces primarily operate at the lowest level of automation, assisting ATCOs in information acquisition and analysis [25]. These tools help ATCOs identify potential threats within their sector by examining current traffic. For instance, radar displays incorporate an STCA tool that warns ATCOs of imminent safety violations within a two-minute look-ahead time, assuming flights maintain ground tracks. To mitigate potential STCAs and minimize the need for last-minute maneuvers, ATCOs at MUAC utilize the Verification and Resolution Advisory (VERA) tool. VERA utilizes radar data to forecast future flight positions, distance at, and time to the closest point of approach (CPA) values for selected flight pairs by ATCOs [26]. This tool assists ATCOs in monitoring a flight pair over an extended period and assessing if current flight headings result in conflicts.

While current tools in enroute ATC are valuable for maintaining safety, research is lacking on developing tools to improve ATCOs' decision-making for efficient traffic flow within their sectors. Implementing interface designs presenting multiple feasible solutions could enhance ATCO's knowledge and encourage them to redefine their working strategies [27]. This shift could motivate ATCOs to develop better scanning patterns, enabling a broader understanding of traffic situations and issuing more efficient clearances.

Previous studies have shown that color-coding schemes on flight labels for ATC events can help ATCOs process information faster and improve their situation awareness while maintaining safety standards [8]. However, these schemes may lead to display clutter, legibility issues, and reduced salience of critical information among numerous display elements, questioning their reliability. Alternatively, luminance-based schemes that adjust brightness levels to differentiate crucial task-related elements from less critical ones might effectively capture ATCO's attention [10, 28-29]. While researchers have explored these schemes in other contexts, their potential to improve ATCO decision-making during clearance issuance in enroute airspace remains uninvestigated.

III. FLIGHT FILTERING CONCEPT

Enroute ATCOs scan radar displays to identify flights requiring clearances. Selecting a flight and providing a clearance can be motivated by multiple reasons, such as resolving conflicts, guiding them to their transfer flight levels, and optimizing their trajectories towards the sector exit to increase efficiency. To detect conflicts and ensure the chosen clearance does not disrupt traffic or create secondary ones, ATCOs preview parameters like flight level, heading, and speed. The proposed flight filtering model captures the pre-attentive phase of ATCOs while controlling a single flight. It identifies (relevant) flights with a higher potential for interaction with the selected flight, making them salient by fading away irrelevant flights (non-interacting) in the airspace. The proposed concept reduces ATCO's cognitive load required during conflict detection and previewing the impact of potential clearances.

A. Filtering Process

The filtering aims to reduce the cognitive effort required by ATCOs when comparing flight information, both for detecting potential conflicts and assessing the clearance's potential impact on surrounding traffic within the sector. It remains inactive during general traffic monitoring and activates only when the ATCO selects a flight for assuming/transferring its control, inspecting its route, or issuing a clearance. The filter identifies potentially interacting flights based on their flight characteristics rather than relying on sector-wide data. This approach seems practical because the effect of sector characteristics can vary for each flight, and creating separate sector-based filtering while controlling an individual flight would be infeasible. The structure of the filtering to capture relevant flights is as follows:

- **Altitude Overlap:** ATCOs initially focus on flight levels displayed on the radar because of their less demanding cognitive efforts to ensure safety. Ensuring sufficient vertical separations is essential, and once maintained, examining flight headings becomes unnecessary. Therefore, only flights whose flight levels overlap with the selected flight's current and transfer flight levels are considered relevant.
- **Spatial Overlap:** Flights having overlapping flight levels are further examined based on their heading to ensure horizontal separations. This step involves determining if their trajectories are parallel, converging, or diverging from the selected flight. Additionally, flights likely to share a common waypoint or cross paths with the selected flight are critical and require closer examination.
- **Temporal Overlap:** The subset of flights possessing overlapping flight levels and spatial proximity undergoes further refinement through additional temporal considerations. By utilizing speed-distance calculations, the filter pinpoints which flights will reach the potential interaction points, indicating their immediate threat level. Estimated arrival times at waypoints or intersections further assist ATCOs in focusing the most critical interacting flights to selected flight of interest.

Flights satisfying all three criteria are identified as potential interacting flights relative to the selected flight of interest, while the remaining flights are deemed irrelevant.

Altitude characteristics such as current, cleared, and transfer flight levels are identified using flight labels, while horizontal locations are represented as blips, accompanied by a speed vector. The look-ahead time, adjusted to predict future positions, is significantly influenced by the current traffic scenario and their preferred clearances to solve potential conflicts. For example, during heavy traffic, ATCOs may prefer safer solutions with a shorter look-ahead time, whereas during low-traffic conditions, a longer look-ahead time [30]. Since look-ahead time adapted by the ATCOs is highly subjective, the flight filtering concept proposes two filterings, state-based and intent-based, to determine relevant flights regarding space and time overlaps.

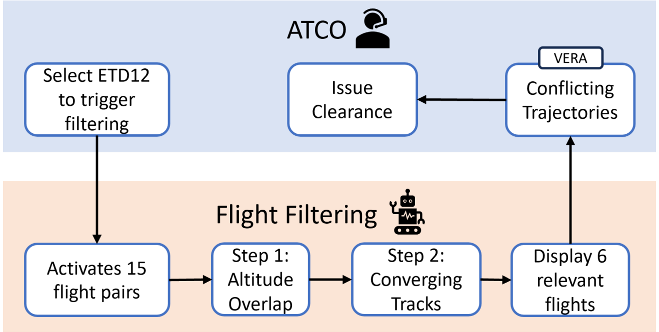
In a state-based filter, flights are projected forward from their current headings to determine the CPA position with other flights without considering their intended flight plan [12]. The state-based projection is a reactive approach signifying accuracy for a shorter time scale, issuing a locally optimal solution in the sector. However, introducing trajectory-based operations in future ATM systems will diminish uncertainties regarding future flight positions, resulting in enhanced ATCO decision-making by considering flight intent.

In an intent-based filter, flight positions are extrapolated along their intended trajectory and planned speed profile while using a geometrical approach to assess spatial and temporal overlaps. The path between two waypoints is considered a line segment for spatial overlaps and the estimated arrival time to the waypoints for the temporal overlaps. The intent-based projection is a proactive approach, motivating ATCOs to issue a global conflict-free trajectory solution for the selected flight of interest by considering the flight's entire trajectory.

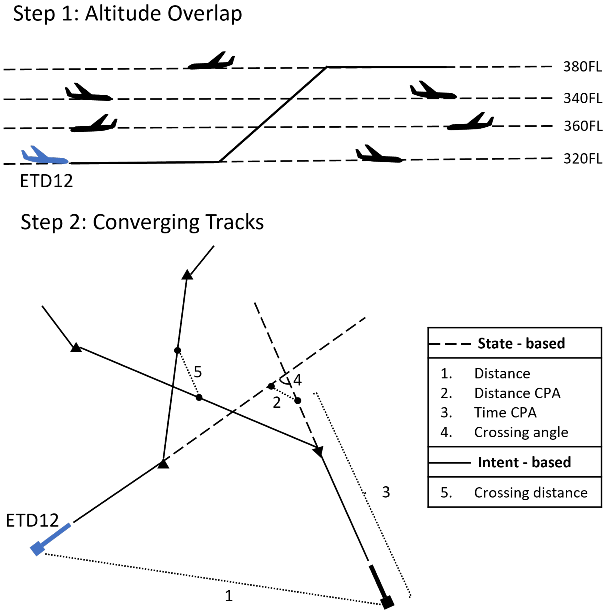
The proposed flight filtering concept combines state and intent-based filters to determine relevant flights to the selected flight of interest. The combined approach provides ATCOs the flexibility to examine various clearances and assess the impact of their preferred clearance, thereby enhancing their decision-making capabilities rather than merely suggesting a clearance. The filtering creates an artificial trajectory up to look-ahead time based on their current flight parameters for flights on a heading and not following the route. Table I summarizes the parameters used in state and intent-based filters, highlighting further refinement to determine relevant flights to the selected flight of interest.

The flight filtering concept aims to significantly reduce the cognitive efforts of ATCOs when comparing flight parameters to identify converging flights with overlapping altitudes along a selected flight's trajectory. For instance, consider a sector with 16 flights and Flight ETD12 cruising at FL320 requires a clearance to ascend to its transfer flight level of FL380, as shown in Figure 3. Traditionally, ATCOs would compare Flight ETD12's parameters with all 15 other flights to issue clearance while not violating safety standards. However, not all 15 flights pose potential interactions with Flight ETD12, making this exhaustive comparison unnecessary and time-consuming. With the proposed flight filtering concept, the filtering identifies overlapping altitude flights with high convergence potential, reducing the comparisons required from 15 flights to just six, as shown in Figure 3c. Nonetheless, it remains the responsibility of the ATCOs to ascertain whether the highlighted six relevant flights conflict with Flight ETD12, with the option to use the VERA tool to prevent safety violations while issuing a clearance.

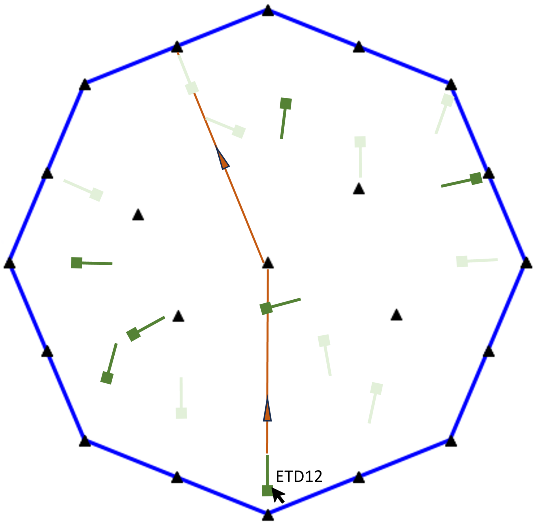
Figure 4 shows the process of inspecting relevant flights for Flight ZG04Z in the ATC Simulator. Flights DOT87 and YUT29 are faded on the radar display as their flight levels do not intersect with that of Flight ZG04Z while inspecting its route. In contrast, Flights NUZ73 and JT03N are at the same flight levels as Flight ZG04Z and have a converging path with the selected flight. The filtering dynamically updates



(a) Proposed work environment



(b) Filtering process - Altitude overlaps and Convergence criteria

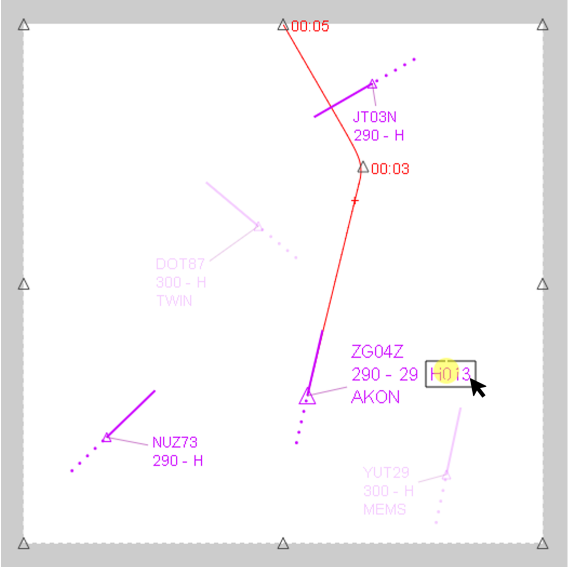


(c) Evaluating the filtered results depicting relevant flights

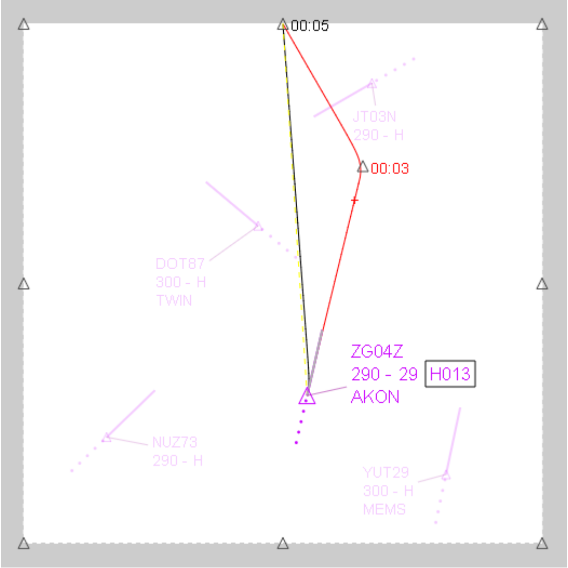
Fig. 3: Reduction in flight comparisons for clearing Flight ETD12 to meet its operational demand with proposed flight filtering concept

TABLE I: State and Intent based flight filtering parameters

State filter parameters [12]	
Distance	Current horizontal separation two flights.
Distance at CPA	Minimum distance calculated between two flights at their CPA along their current positions and headings.
Time to CPA	Time required for flights to reach their CPA from the current position update.
Crossing angle	The angle formed between the paths of two flights at their CPA.
Intent filter parameter	
Crossing distance	The CPA distance from the preceding waypoints between two flights crossing each other's paths. Alternatively, if flight paths are non-crossing, then the minimum distance between two flights along their flight paths.



(a) Determining relevant flights by inspecting the route



(b) Previewing impact of clearing flight towards COPX

Fig. 4: Activating flight filtering for Flight ZG04Z in the ATC Simulator - route inspection and previewing COPX clearance.

the relevant flights based on preferred flight level, heading, or sector exit clearance. When considering flights affected by flight level or heading clearances, ATCOs browse various options without selecting them. However, for intent-based impacts, ATCO selects the waypoint. While previewing the impact of clearing Flight ZG04Z towards its sector exit on surrounding traffic, Flights NUZ73 and JT03N are faded, indicating that they do not pose a potential interaction with Flight ZG04Z if cleared towards its exit.

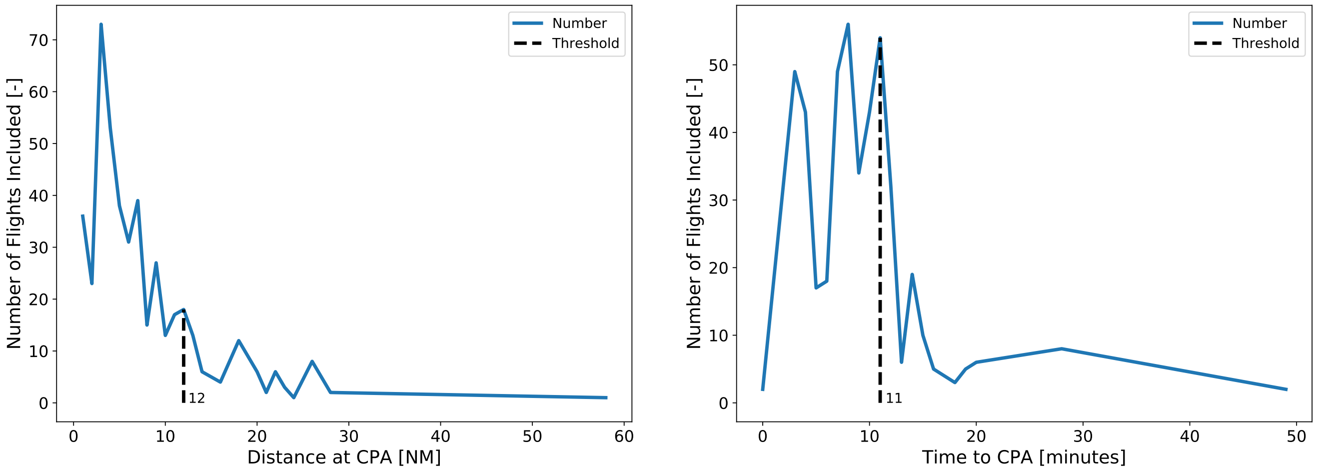
Through the integration of state and intent-based filters, the flight filtering concept enables ATCOs to evaluate the consequences of different clearances. The next step involves establishing thresholds for the parameters outlined in Table I. This strategic enhancement aims to improve the filtering's effectiveness in identifying potential interacting flights throughout flight trajectories and previewing preferred clearances.

B. *Deriving Thresholds*

The thresholds for the state-based filter parameters specified in Table I are established based on the MUAC study of allocating flights entering the sector between human operators and automation, considering individual flight complexities [12]. This research introduced a single flight into a static Brussels sector traffic scenario. Four ATCOs then included flights they perceived interacting with the introduced flight throughout its trajectory, from its current position to reaching the sector exit and transfer flight levels. Manipulating traffic factors and initial flight positions of the introduced flight created 36 distinct scenarios within the same traffic environment. For each scenario, the state parameter values of the flights included by ATCOs relative to the introduced flight, along with the number of ATCOs including them, were extracted. However, ATCOs' preferences for included flights varied based on experience and the specific traffic scenario, posing a challenge for developing a "one-size-fits-all" filtering model.

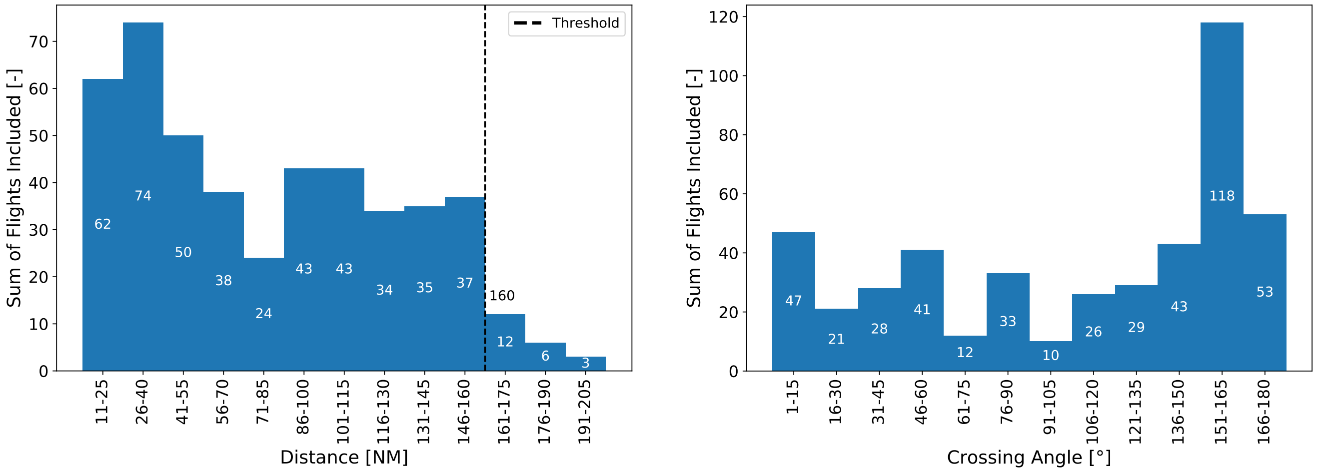
This paper proposes a unified method for setting state and intent parameter thresholds to identify relevant flights during individual flight control. The value at which the number of included flights relatively decreases can be set as a threshold to define a flight relevant for that particular parameter. As the parameter values increase, there is a natural decrease in the number of flights that appear to be relevant. Figure 5 shows the relationship, plotting the number of included flights against the parameter values used for threshold determination. Unlike distance at CPA and time to CPA, distance and crossing angle parameters exhibited an uneven distribution of included flights. To account for this unevenness and establish appropriate thresholds, the values for these parameters were grouped into ranges. The flights included by multiple ATCOs within each range were then summed to identify the range containing the most included flights and, with a sudden drop as a threshold for a flight to be relevant.

Figures 5a and 5b show multiple decreasing points, and the thresholds are set to appropriate values based on specific study needs and existing literature. Studies show that ATCOs prioritize flights with predicted distance at CPA under ten



(a) Distance at CPA Threshold

(b) Time to CPA Threshold



(c) Distance Threshold

(d) Crossing Angle Threshold

Fig. 5: The number of flights perceived to interact with the introduced flight against the state parameter values.

nautical miles (NM) [12] and aim to resolve conflicts 7 to 12 minutes before violating separation minima [16]. While the distance parameter had a decreasing trend for the sum of included flights after grouping the parameter values, no such trend was visible in the crossing angle parameter. However, state parameters often interact with each other while impacting a single flight's behavior. For example, considering CPA and current distance allows for anticipating the crossing angle between involved flights. This lack of a set threshold for crossing angle necessitates ATCO's vigilance across all conflict types during conflict detection and previewing clearance. The intent-based filter utilizes the same distance at CPA threshold as the state filter to identify relevant flights. For flights deviating from their route, an artificial trajectory is generated to project its flight path until the time to CPA threshold based on current flight parameters, accounting for flight intent.

Table II presents the final thresholds for state and intent-based filter parameters, determined through the MUAC study of allocating flights to automation and human operators. These thresholds intentionally exceed safety requirements to incorporate a safety margin, accommodate uncertainties, and align with ATCO's proactive approach of identifying interacting flights during individual flight control. The next step evaluates the filtering's performance in highlighting included flights for the introduced flight.

TABLE II: State and Intent based flight filtering thresholds

State filter parameters	
Distance	160 NM
Distance at CPA	12 NM
Time to CPA	11 min
Crossing angle	nil
Intent filter parameter	
Crossing distance	12 NM

C. *Filtering Performance*

Having established the thresholds for flight filtering parameters mentioned in Table II in determining relevant flights during individual flight control, this section delves into the performance of the proposed filters. This evaluation assesses the filter's ability to accurately highlight the included flights while selecting the introduced flight for the provided 36 scenarios, depicting the capture of the relevant flights during individual flight control.

Figure 6 shows confusion matrices, a tool to evaluate classification model performance by comparing predicted and actual classifications for the proposed flight filters. The actual label indicates whether the flight is included, along with its consensus, while predicted labels show if the filter highlights the flight when selecting the introduced flight. Using these matrices, several metrics are derived to evaluate the performance of filters, as shown in Table III. The primal metrics for inspecting the filter's performance in highlighting relevant flights during individual flight control are precision, recall, and F1-score. Precision measures the filter's accuracy in highlighting included flights, whereas recall measures the ability of the filter to highlight all included flights. Precision concerns reducing false positive alerts while recall to avoid potential misses. The F1-score calculates their harmonic mean to provide a balance, countering this trade-off.

State-based filter prioritizes highlighting flights included by multiple ATCOs within a shorter timeframe of 11 minutes. This approach emphasizes potentially critical interactions but risks overlooking later-stage interactions, leading to high precision but lower recall. Conversely, the intent-based filter highlights most interactions throughout the introduced flight's trajectory. This conservative approach ensures comprehensive coverage but may include nonessential flights, resulting in high recall but lower precision.

The state-based filter's limited timeframe contradicts a few ATCO's proactive approaches of considering flights throughout trajectories to plan conflict-free exits. This incompatibility raises concerns about solely relying on flight states in the flight filtering concept that aims to comply with each ATCO's judgment of identifying relevant flights during individual flight control. Hence, the combined filtering approach, merging state and intent-based filters, was proposed to determine the relevant flights. The combined approach also offers flexibility to preview flights impacted by preferred clearances and motivates them to issue direct-to-exit clearances.

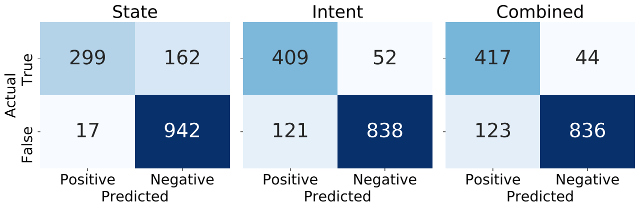


Fig. 6: Confusion matrix per flight filters

TABLE III: Flight filters - Performance

Filtering	Accuracy	Precision	Recall	F1
State	87.39	94.62	64.86	76.96
Intent	87.82	77.17	88.72	82.54
Combined	88.24	77.22	90.46	83.32

IV. EXPERIMENT METHOD

As ATCOs have not yet encountered a tool facilitating the comparison of flight parameters to identify potential interacting flights during clearance issuance, a within-participants experiment was devised to evaluate the effectiveness of the flight filtering concept in the enroute ATC domain. The experiment utilized SectorX, a Java-based simulator developed by TU Delft, mimicking the enroute radar display currently used at MUAC. This experiment aims to gather objective and subjective data to comprehensively assess filtering's effectiveness in meeting the operational demands of controlling traffic safely and efficiently.

A. *Participants and Tasks*

Novice participants are preferable for this experiment, as expert ATCOs skilled at managing complex traffic may not rely on the filtering for issuing clearances [31]. Eight participants (μ=43.75 years, σ=11.52 years) well-versed in ATC operations willingly joined the experiment by signing a consent form. Among them were six lecturers and two doctoral candidates from the Control and Simulation Department of the Faculty of Aerospace Engineering at TU Delft. Notably, seven participants had undergone a comprehensive five-day simulator training course in Area Control at the Netherlands Aerospace Centre (NLR), and the last participant had exposure to ATC-related concepts through university courses. While three participants had prior exposure to the SectorX ATC simulator, the remaining individuals were unfamiliar with this specific environment. Additionally, none of the participants had previous experience with the full complexity of managing air traffic flow in the upper airspace.

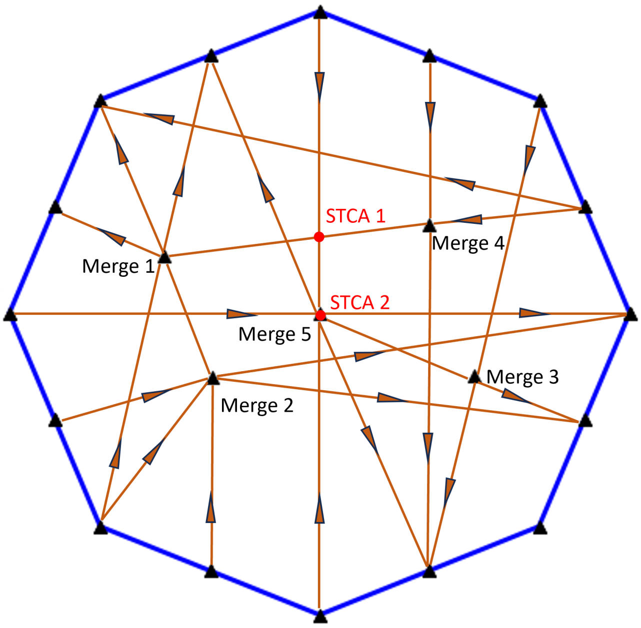
Participants performed the full range of enroute ATCO's duties of managing the traffic flow safely and efficiently within their assigned sector. The tasks involved were assuming control of incoming flights, issuing clearances to meet operational demands, and seamlessly transferring control of outgoing flights. Flight labels on the radar display update dynamically to highlight the current status and maintain participant focus on flight control and operational demands.

Participants received instructions to detect and resolve conflicts, promptly clear flights to their sector exit, and ensure that flights remain at higher flight levels for maximum time. The later instruction indicated clearing climbing flights to higher flight levels promptly and delaying descending flights to lower flight levels to expedite air traffic. While monitoring the traffic and issuing clearances, participants were required to ensure that STCA warnings did not arise within the sector. VERA tool was accessible, assisting participants in monitoring a flight pair over an extended period and assessing if current flight headings result in conflicts.

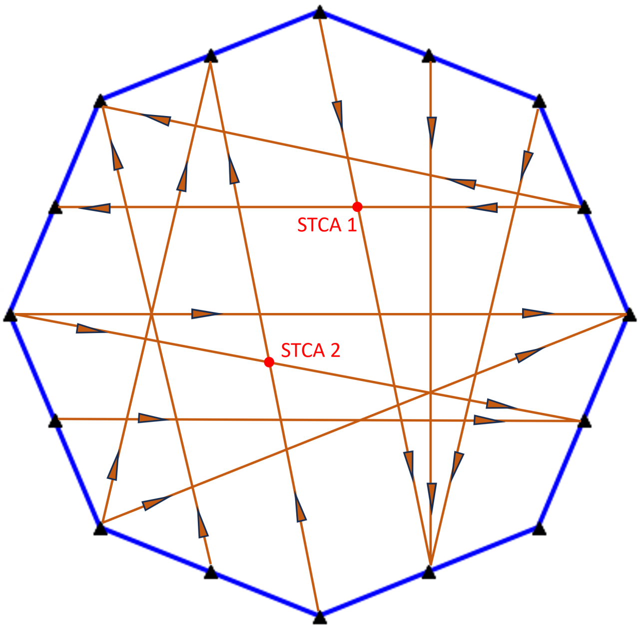
Throughout the experiment, participants provided Instantaneous Self Assessment (ISA) scores every four minutes. These scores indicated their perceived workload at that specific moment while managing the simulated air traffic. Additionally, after completing the simulation run, participants provided a Human-Machine Interface (HMI) difficulty score. This score reflected the participants' overall difficulty experienced in controlling air traffic throughout the simulated scenario.

B. Independent Variables

The experiment aimed to determine the effect of using the flight filtering concept to determine relevant flights during individual flight control. A within-participants experiment was designed to ensure all participants would control the sector, with and without filtering support. Thus, one independent within-participants variable was selected: the flight filtering mechanism, providing an objective comparison and excluding the personal differences between the experiment conditions. Scenario variants were created to prevent participants from recognizing the sector, and the order of conditions was randomized to account for order effects.



(a) Indirect routing structure through intermediate merging waypoints



(b) Direct routing structure

Fig. 7: Assigned sector in regular octagon shape used in experiment along with planned STCA crossings.

C. Traffic Scenario

Given the within-participant approach of the experiment, the sector shape must exhibit symmetry. This condition prevents participants from recognizing variations in scenarios if they were to be rotated or flipped across different experimental conditions while controlling the sector. The experiment utilized a regular octagon with each side approximately equal to 43 NM and a sector area of 8869 sq. NM, as shown in Figure 7. The sector was designed with nine entry points and six exit points, with five merging waypoints strategically positioned within its boundaries. Twelve routes were delineated to traverse through these waypoints, facilitating traffic within the sector. The sector designed for this experiment is exclusively a controlled sector, with no consideration given to the design of adjacent sectors. However, the experiment was designed such that issuing clearances within the controlled sector will not negatively affect the adjacent sector following the transfer of flight control, matching real-world operations.

The experiment utilized real-world radar data from the Brussels West sector to generate realistic "bunched traffic" scenarios – a common challenge in enroute ATC, where flights cluster together. This analysis informed the number of simulated flights and their temporal distribution, reflecting the traffic density and patterns observed in the real sector. While data limitations prevented replicating the specific flight level transition requirements of the Brussels West sector, the simulated flight levels were designed with general realism in mind, with flights requiring descent, generally moving east to west and south to north, and vice versa for climbing flights. This approach ensured that generated scenarios captured the core complexities of enroute ATC while acknowledging the limitations of the available data.

The flight characteristics in the research were employed to comply with real-world operations. The experiment classified the flights according to ICAO flight types, primarily consisting of the medium and heavy series of Boeing and Airbus aircraft. Flights exhibited speeds ranging from 235 kts to 297 kts, with an average speed of 268.5 kts. Participants had between 120 and 150 seconds to take control of incoming flights, with some flights having varied entry points due to advanced clearances, simulating coordination with adjacent ATCOs. The flight level transition requirements for climbing and descending flights varied and were limited to 70 FLs per individual flight. The flight level parameters range between FL300 to FL400 to align with the experiment's focus, omitting consideration for flights transferring via Area Control. Figure 8 shows a comprehensive overview of the traffic characteristics and operational demands for the bunched traffic scenarios employed in the experiment.

The traffic scenario included two deliberate safety violations designed to test the effectiveness of flight filtering in conflict detection. These violations involved flights cruising at assigned flight levels but following indirect routes, occurring at crossings shown in Figure 7. The planned safety violations were placed such that STCA warnings were neither triggered near sector entrances nor sector exits. This setup assesses the participant's ability to recognize potential conflicts promptly and provides sufficient space to solve them. While issuing direct-to-exit clearances to either flight would resolve conflict, providing such clearances to both simultaneously would violate safety standards. The pre-designed STCAs ideally occur at the 539th and 1140th seconds, lasting 154 seconds each. Figure 8 shows the traffic distribution within the sector and indicates the timestamps of the two planned STCAs if no clearances were issued.

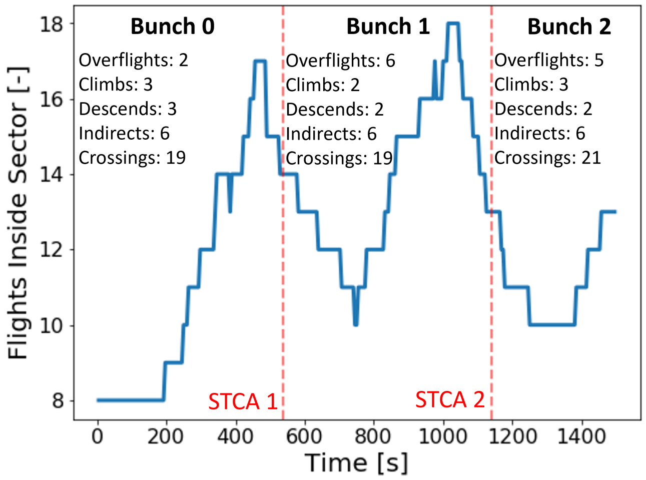


Fig. 8: Traffic characteristics of flights entering the sector. The red dashed line indicates the timestamps of planned STCAs if no clearances were issued.

D. Dependent Variables

The following measures were established to assess the sector safety, efficiency, and workload experienced by the participants while controlling the traffic with and without flight filtering:

- Response time for planned conflicts: The time taken to implement a resolution maneuver to address planned conflicts STCA1 and STCA2.
- STCA duration: The total duration during which the STCA tool remained active included both secondary conflicts generated during operations and planned conflicts.
- VERA Count: The count of flight pairs for which the VERA tool is activated to monitor and detect conflicts.
- Clearance time to meet operational demands: The average time taken to issue the first clearances for the climbing, descending, and indirect flights after they appear on the radar screen.
- Total clearances: The number of clearances issued by the participants while simulating air traffic.
- Flight route inspections: The total number of times and the duration participants inspected the flight routes.
- Clearance menu inspections: The total number of times and the duration participants opened the clearance menu to provide clearances.
- Average perceived workload: Workload scores provided by participants throughout the simulation were averaged. Additionally, the Z-score for each participant was computed to normalize differences in the provided scores.
- Overall difficulty rating: The overall difficulty experienced by participants in controlling the traffic simulation. Additionally, the Z-score for each participant was computed to normalize differences in the provided scores.
- Subjective responses: The responses to the questionnaire gained further insight into the flight filtering concept in controlling traffic. The questions encompassed participants' perceptions regarding the trust and reliability of the flight filtering concept, their agreement with the filtered results, and the usability of flight filtering in achieving enroute ATC tasks.
- Open feedback: The responses to the open feedback questions gained insights into participants' strategies for expediting air traffic safely and efficiently with the proposed flight filtering concept and suggestions to improve the filtering.

E. Control Variables

The following variables were controlled during the within-participants experiment to account for the variability in the enroute ATC domain with the introduction of the novel flight filtering concept:

- Sector characteristics: The sector shape was a regular octagon with nine entry points and six exit points, with five merging waypoints within the sector. The flight filtering scenario had distinct waypoint names and 90° view rotation to the no-filtering scenario.
- Traffic characteristics: The traffic density, flight characteristics, and operational demands were constant for all participants throughout both traffic scenarios with distinct flight callsigns.
- Degrees of Freedom: Participants can direct the flights in both traffic scenarios by providing heading, flight level, and direct-to-exit clearances.
- ISA scale update: Participants utilized the ISA scale to input their perceived workload at a given time, with updates occurring every 240 seconds for both traffic scenarios.
- Secondary tools: The VERA tool was available for monitoring simulated flight pairs and conflict detection, while

the STCA tool was employed to detect imminent safety violations.
- Radar update: The radar update frequency was set to every 5 seconds, accurately depicting the real-world radar installation at MUAC.
- Simulation speed: The simulation speed for both traffic scenarios was 1.25 times for all participants.
- Work environment: The workspace was oriented with no distracting elements nearby, and the simulator was operating in full-screen mode to hide the taskbar and clock of the operating system.

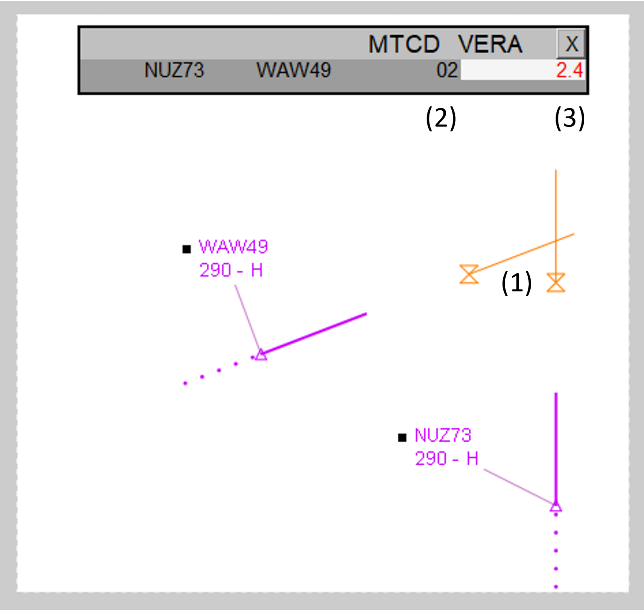
F. Apparatus

The experiment utilized a single computer paired with a multi-display setup, as shown in Figure 9. A central 26.5-inch EIZO monitor with a square aspect ratio and 1920 x 1920 resolution displayed the simulation, providing a suitable workspace. Additionally, two 24-inch displays with a 16:9 aspect ratio were employed during the experiment. The display on the right side served as a readily accessible cheat sheet for reference during the experiment, while the left display facilitated questionnaire completion at the experiment's conclusion. Throughout the experiment, participants engaged with the simulated flights by issuing clearances through data links and no radio communication. Participants directed the simulation interface using conventional computer input devices, specifically a standard mouse and keyboard.

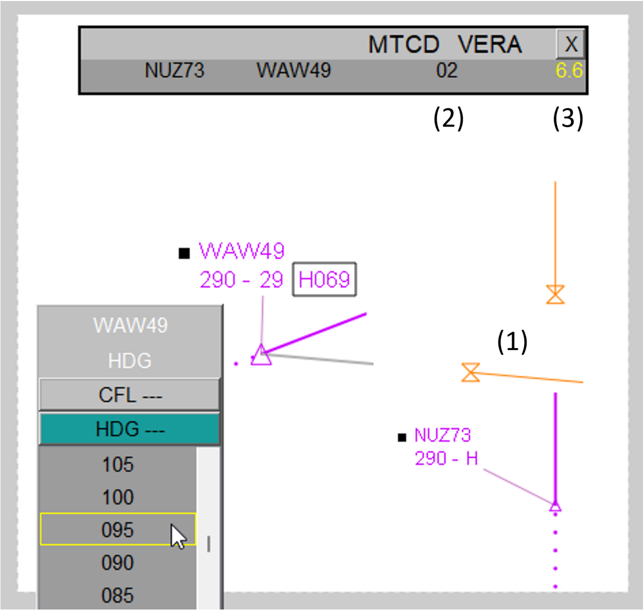
Minor adjustments were made to the simulator to maintain focus on the flight filtering concept and minimize the impact of extraneous variables. The STCA tool, designed to prevent safety violations, and the VERA tool, enabling potential conflict detection, remained operational within the simulator environment. However, the VERA tool underwent slight modifications to preview the separation characteristics during heading change, assisting participants in issuing minimal deviations during conflict resolutions. Figure 10 shows conflicting flights WAW49 and NUZ73 with the predicted horizontal separation of 2.4 NM, occurring within two minutes. Previewing the heading change for Flight WAW49 from 69° to 95° increases the separation to 6.6 NM, indicating the preferred clearance resolves the particular conflict.

Fig. 9: Hardware setup for the experiment

The flight information message tool, providing additional data like ground speed and flight type, was not concerning, could lead to potential distractions, and was disabled. Participants could issue flight level, heading, and direct-to-exit clearances to simulated flights but not alter speed or route. The speed parameter is cognitively demanding and is preferably less perceived or modified by ATCOs in the enroute airspace. The experiment occurred at the ATC Laboratory within the Faculty of Aerospace Engineering at TU Delft.



(a) Conflict detection using VERA



(b) Previewing impact of preferred clearance

Fig. 10: Modified VERA tool to preview separation characteristics between flight pairs based on preferred clearances: (1) predicted CPA positions, (2) time to CPA, (3) distance at CPA

G. Procedure

Several days before the experiment session, participants received a briefing manual describing the ATC simulator, experiment setup, tasks, and flight filtering concept. The manual also served as a script to train the participants through seven training scenarios. The initial two scenarios introduce flight label descriptions and their relevance in flight control and operational demands. Participants also underwent training to provide inputs concerning the control and clearances for flights under their supervision. Scenarios 3 to 5 introduce applications of the STCA tool to prevent safety violations and the VERA tool for conflict detection and resolution. Scenario 6 introduced the flight filtering concept of determining the relevant flights throughout the trajectory and previewing the impact of the issuing flight level and heading clearances. In the final scenario, participants previewed relevant flights through direct-to-exit clearances. Additionally, participants practiced providing perceived workload scores and overall difficulty ratings for a brief scenario run. The training phase ended with participants receiving tips and tricks for issuing safe and efficient clearances.

The one-hour training session ensured that all participants, regardless of prior experience, were comfortable operating the simulator. Following the training phase, the practice phase allowed participants to apply their acquired skills and knowledge to practical use, thereby building instinctive reflexes. The practice phase had two scenarios of 15 minutes each, where participants controlled the traffic and provided perceived workload scores without filtering, followed by filtering. The practice scenarios had relatively less complex traffic than the measurement scenarios to boost their confidence and prevent fatigue before the measurement phase. Following the practice phase, participants had a 15-minute break before the experiment session commenced.

In this within-participants experiment, the filtering mechanism serves as the sole independent variable, influencing the creation of scenario variants to prevent sector recognition. The filtering scenario had a 90° viewing rotation and varied callsigns and waypoint names compared to the no-filtering scenario. The measurement phase had two scenarios of 25 minutes each, where participants controlled the traffic with and without filtering while providing perceived workload scores every four minutes. However, the execution order varied to account for the order effects, and participants were informed about the order after their practice phase. Group A initially controlled traffic without filtering, followed by a scenario with filtering, whereas Group B underwent the reverse sequence by controlling the traffic with filtering and then without filtering. The experiment sessions were conducted individually, with the researcher present during the measurement phase to ensure a smooth simulation run and collect notes. Following the measurement phase, participants were required to complete a questionnaire, offering valuable feedback on the flight filtering concept. The experiment procedure spanned approximately three hours for each participant, as shown in Figure 11.

Figure 12 shows the comprehensive simulator interface consisting of the proposed flight filtering concept and the secondary tools used during the experiment. The relevant flights to the selected flight of interest can be determined by inspecting its current route (holding the heading), assuming/transferring the control (clicking callsign), and providing the clearance (clicking the associated clearance item). The filtering gets dynamically updated while previewing the impact of preferred clearances on the surrounding traffic before the participant executes it, as shown in Figure 4.

H. Hypotheses

The hypotheses regarding the experiment primarily centered on reducing the cognitive efforts required to compare flight parameters while controlling a single flight. Based on the dependent variables, the following hypotheses are formulated and tested:

HP1 **Safety** - Flight filtering assists participants in determining relevant flights, motivating them to detect potential conflicts and provide a resolution maneuver sooner than the no-filtering scenario. The preview feature highlights flights affected by preferred clearance, mitigating potential risks of creating secondary conflicts. Thus, implementing flight filtering in enroute ATC improves safety within the sector.

HP2 **Performance** - By determining the relevant flights throughout the trajectory, participants can compare flight levels displayed on labels and implement efficient maneuvers for climbing, descending, and indirect flights. Participants can clear climbing flights sooner and delay clearance to descending flights to maintain flights at higher flight levels. The preview feature highlighting flights affected by preferred clearances assists participants in issuing direct-to-exit clearances sooner for indirect flights. Thus, implementing flight filtering in enroute ATC improves the operator's performance to provide efficient clearances.

HP3 **Control Activity** - Flight filtering assists participants in determining the relevant flights throughout the trajectory, reducing the number of VERA checks compared to the no-filtering scenario. Flight filtering provides participants the opportunity to reduce the clearance count while clearing flights to their transfer states. Thus, implementing flight filtering in enroute ATC decreases the operator's control activity in achieving operational demands.

HP4 **Workload** - The filtering reduces the participant's cognitive efforts by guiding their attention to relevant flights through route inspection or previewing preferred clearances for the selected flight of interest. The decision selection and action implementation still rely on the human operator, providing participants the freedom to execute strategies matching their work capacity. Thus, implementing flight filtering in enroute ATC decreases the perceived workload of the participants while controlling the sector.

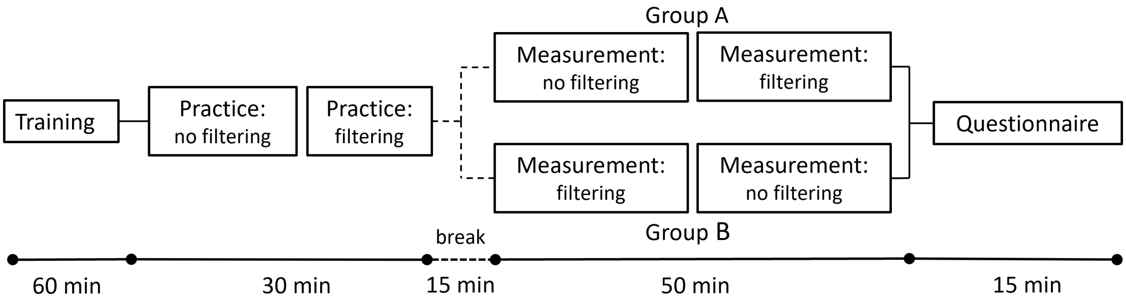


Fig. 11: Experiment session timeline for an individual participant

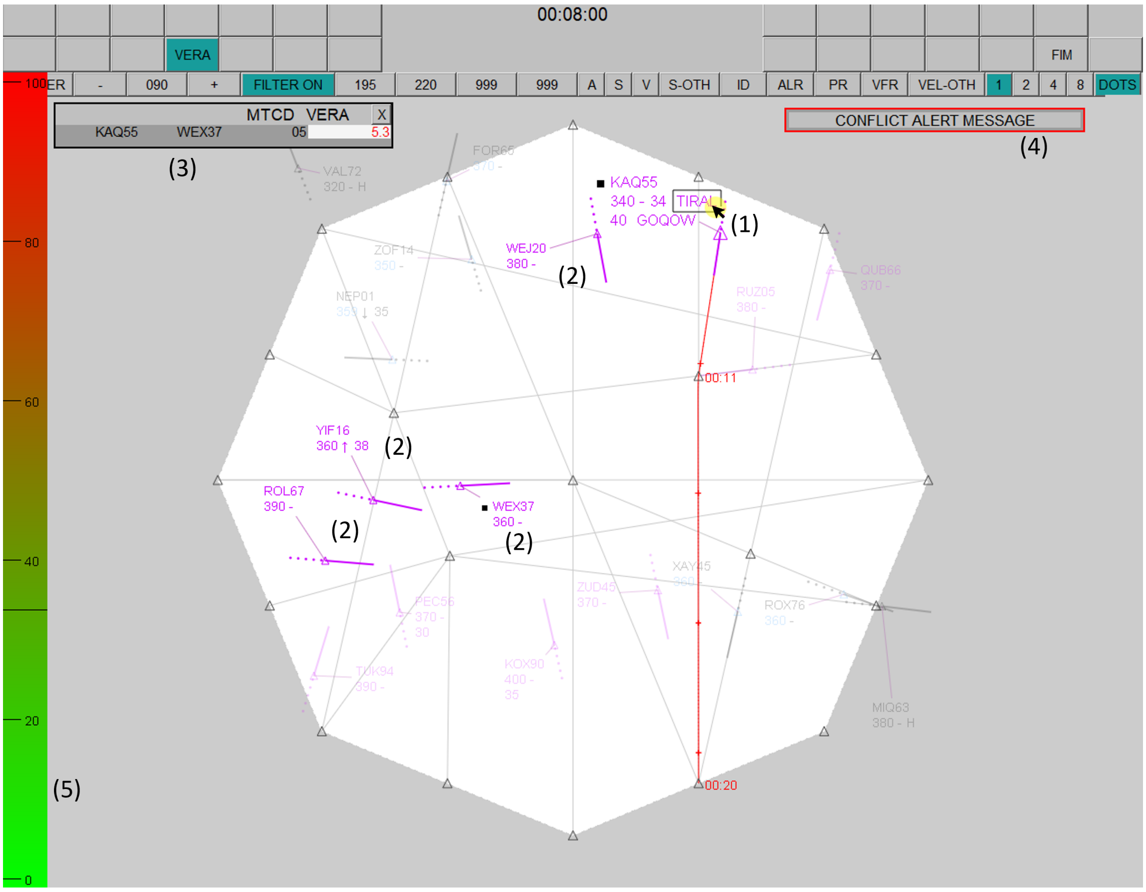


Fig. 12: Screenshot of flight filtering experiment setup with inverted colors for clarity: (1) inspecting the route of selected flight of interest, (2) highlighting relevant flights to the selected flight of interest, (3) VERA tool for monitoring flight pairs, (4) STCA tool to detect imminent safety violations, (5) ISA scale to input perceived workload at a given time

V. RESULTS

This section presents the findings from the experiment's measurement phase. The section begins with analyzing objective measures results, followed by subjective responses analysis to the flight filtering concept. Lastly, the section concludes how flight filtering influenced participants' control strategies for ensuring safe and efficient traffic flow and suggestions to improve the filtering. Moreover, due to the small sample size of eight participants, non-parametric tests are used to analyze the objective measures.

Due to the within-participants design, the Wilcoxon signed-rank test assessed the impact of flight filtering on response time for planned STCAs, total STCA duration, clearance time to meet operational demands, VERA checks, and perceived workload. This analysis aims to determine the effect of flight filtering on these dependent measures and reach conclusions regarding the experiment's hypotheses.

A. Safety

Figure 13 shows the clearance issuance time to resolve planned safety violations. Negative data points indicate proactive conflict resolution before STCA warnings. The Wilcoxon signed-rank test revealed no significant difference in response time for planned conflicts between conditions with and without filtering. In both scenarios, there were 11 planned STCA warnings, with eight arising due to participants clearing both conflicting flights to their designated exits before potential crossing points. The data distribution in Figure 13 reveals a preference for proactive conflict resolutions where participants primarily issued direct-to-exit clearances for one conflicting flight, allowing the other to follow its planned route. In the no-filtering condition, participants collectively issued eight flight levels, five headings, and three direct-to-exit clearances addressing the planned conflicts. Under the filtering condition, participants issued eight flight level clearances, three heading clearances, and five direct-to-exits clearances. Both scenarios indicated a preference for participants to solve conflicts by altitude clearances after STCA warnings for planned conflicts.

While resolving primary conflicts or clearing flights for operational efficiency, participants occasionally activated secondary conflicts. Figure 14a shows a surprising finding that the no-filtering condition resulted in fewer secondary conflicts than the filtering condition. Interestingly, the distribution of secondary conflicts within the filtering condition was uneven, ranging from zero to four instances per participant. The primary contributors to the maximum secondary STCAs, irrespective of the experiment conditions, were conflicts between a descending flight and an overflight sharing the same sector exit during the flight level transition and a climbing flight encountering multiple STCAs due to its steeper rate of climb.

Figure 14b shows the total duration the STCA tool was warning, incorporating primary and secondary conflicts. Although medians and means were similar between conditions with and without filtering, the filtering condition displayed a wider data spread. The Wilcoxon signed-rank test revealed no significant difference in overall STCA duration between experiment conditions. The outliers in both conditions involved the same participant descending a flight near the sector exit, triggering an STCA with an overflight sharing the same exit. The limited resolution space due to the smaller convergence angle near the exit resulted in longer STCA durations and safety violations between flights.

The no-filtering condition witnessed six safety violations, one involving a planned conflict, compared to four violations with filtering. The significant number of planned STCA warnings in both scenarios arose from participants issuing direct-to-exit clearances to both conflicting flights, raising questions about their perception of safety when evaluating filtered results. Furthermore, proactive conflict resolution by directing a single flight to the exit, while efficient, might not always indicate a clear intention to resolve the conflict. Additionally, the uneven distribution of secondary conflicts and total STCA duration within the filtering condition further suggests potential differences in participants' adoption of filtered results while issuing clearances. By analyzing the data related to the response time for the planned STCAs, generated secondary conflicts, and total STCA duration, Hypothesis 1, stating that flight filtering improves safety within the enroute ATC domain, cannot be confirmed.

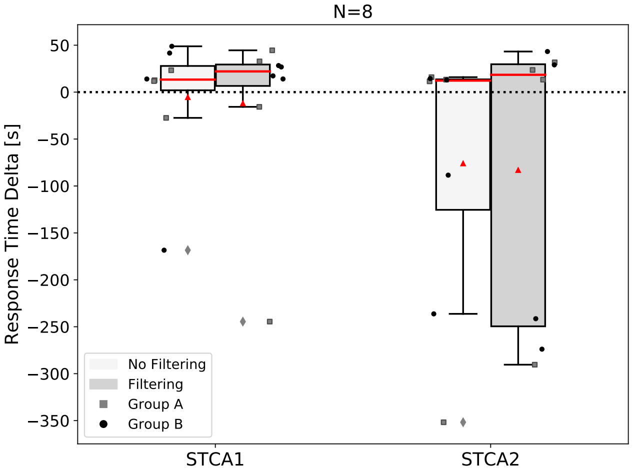
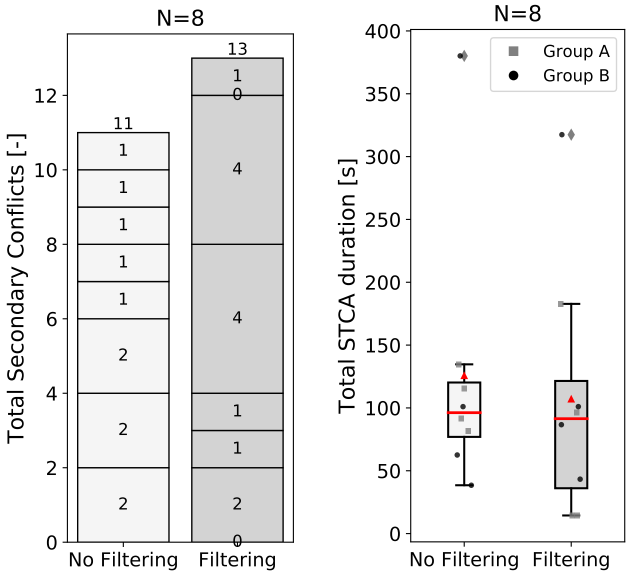


Fig. 13: The time a resolution clearance was issued for planned conflicts. Data points below zero indicate that the participant solved the conflict without triggering STCA warning for that conflicting pair.



(a)

(b)

Fig. 14: Conflict measures through the experiment: (a) total secondary STCAs triggered while providing clearances, (b) total duration the STCA tool was warning encompassing both planned and secondary conflicts.

B. *Control Performance*

Analysis of the average initial clearance issuance time assessed the impact of flight filtering on the operator's performance to issue efficient clearances. Bunch 0 traffic was excluded from this analysis because these flights were already present in the sector at the start of the simulation, and their clearance times can affect the overall average due to their varying clearance time. Participants actively controlled traffic flow by prioritizing flights to maintain higher flight levels and expediting indirect flights to their sector exits. Participants employed varied clearance strategies to attain the transfer flight level, encompassing stepwise and direct approaches. Nonetheless, the initial clearance time is an essential indicator, signifying the acknowledgment of a flight and initiating the first step toward fulfilling its operational demand.

Figure 15 shows the average time taken by participants to issue the first clearance for climbing, descending, and indirect flights to meet operational demands for filtering and no-filtering conditions. Unexpectedly, the filtering condition's medians and means for climbing flights were substantial, with an extensive data spread compared to the no-filtering. However, the Wilcoxon signed-rank test revealed no statistically significant difference in issuing first clearances between experiment conditions for climbing flights. The participant with the longest clearance time in the filtering condition complained that the filtering still considered transfer flight levels while browsing flight levels between cleared and transfer levels. Consequently, manual flight level comparison was required, resulting in an extended time to issue climbing clearances.

While the median clearance time for descending flights was higher in the filtering condition than no-filtering, the Wilcoxon signed-rank test revealed no statistically significant difference between experiment conditions. For indirect flights, the filtering condition displayed a lower median clearance time for issuing direct-to-exit clearance compared to the no-filtering condition. However, again, the statistical test did not show a significant difference. The outliers in the direct-to-exit clearances for both conditions represent the same participant preferring vertical separations between flights and hesitating toward issuing direct-to-exit clearances, leading to delayed responses.

Similar to the safety-related measures, the flight clearance time to meet operational demands, accounting for efficiency, also demonstrated extensive spread in the filtering condition, although not as pronounced. Additionally, participants reported difficulty in using filtering for flight level clearances due to unavailable information like climb/descent rates. This limitation may have contributed to delayed responses for climbing flights and secondary conflicts generated during flight level transitions while using filtering. Conversely, participants found sector exit clearances easier to evaluate with filtering, potentially explaining the prompt issuance of direct-to-exit clearances. Therefore, by analyzing the average first clearance issuance time to climbing, descending, and indirect flights, Hypothesis 2, stating that filtering improves the operator's performance to issue efficient clearances within the enroute ATC domain, cannot be confirmed.

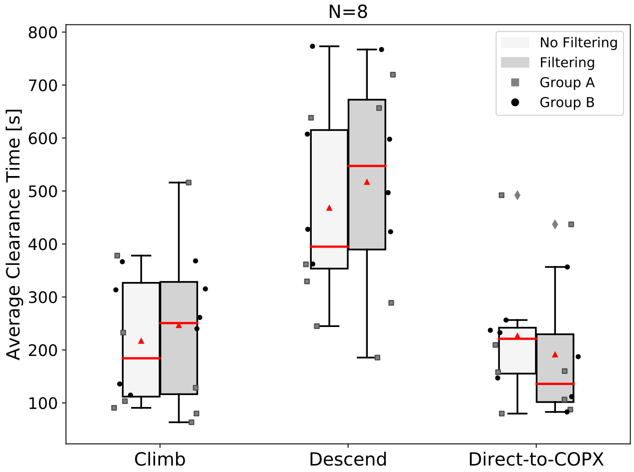


Fig. 15: The average time participants took to issue the first clearance for climbing, descending, and indirect flights depicting operational efficiency.

Upon evaluating the participant's performance in executing efficient clearances, the subsequent stage entails examining the follow-up measures taken by the participants to meet operational demands. This stage includes assessing supplementary aspects like the number of clearances issued and deviations from task specifications.

Figure 16c shows the total number of clearances participants issued, with black dotted lines indicating the minimum clearances required to meet operational demands within a simulation trial. The aim was to evaluate whether filtering resulted in fewer clearances while maintaining efficiency. The filtering condition had slightly more climbing clearances and fewer descending clearances than the no-filtering. However, the differences were deemed insignificant, with a narrower data spread observed in the filtering condition. Substantial data points for climbs and descends indicate that participants adopted step-wise clearances to meet operational demands or issued flight level clearances for conflict resolution. The outliers in climbing and descending clearances for the filtering condition were associated with the same participant who triggered two planned and four secondary STCAs. His resolution strategy primarily involved issuing step climb/descend, potentially explaining the higher number of flight level clearances.

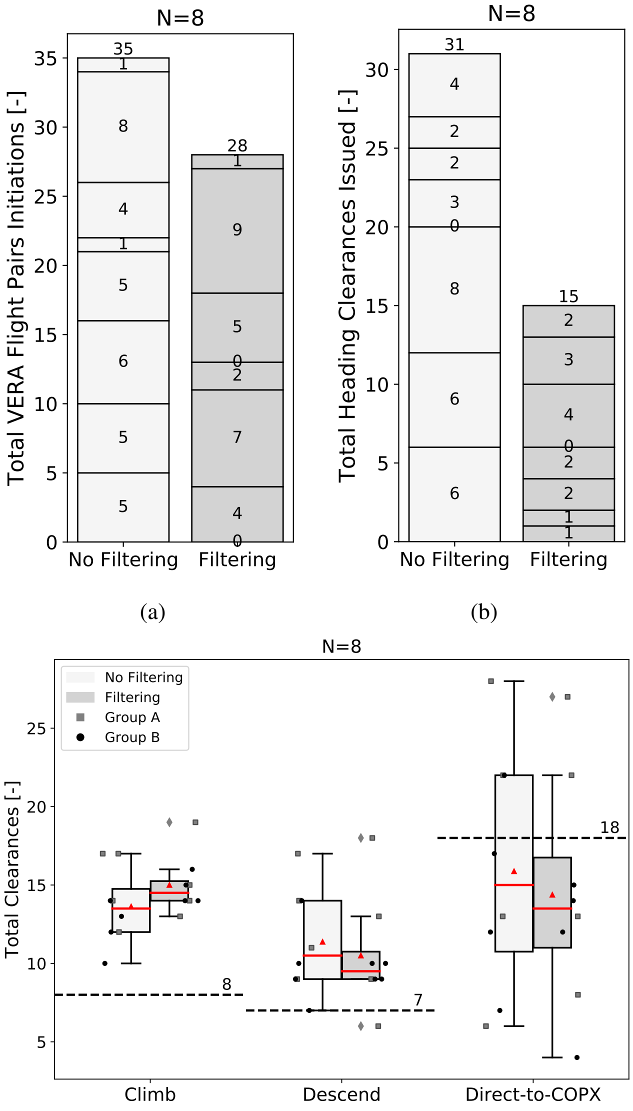
Participants in the no-filtering condition issued more direct-to-exit clearances than the filtering, which contradicts initial expectations. Figure 16b shows that the no-filtering condition had more heading clearances, explaining the observed difference. These heading adjustments might have temporarily steered flights away from their exit paths, necessitating subsequent direct-to-exit clearances to get them back on the assigned flight path. Similar to flight level clearances, the filtering condition displayed less variation in the number of direct-to-exit clearances than the no-filtering. Interestingly, the participant who issued the most direct-to-exit clearances in the no-filtering condition was also the outlier with the highest number in the filtering condition. The participant tended to issue direct-to-exit clearances to all flights while controlling the traffic.

After evaluating the total count of clearances passed, as shown in Figure 16c, the subsequent phase involves analyzing particular occurrences where participants diverged from task specifications across both experimental conditions.

Analyzing deviations from task requirements revealed discrepancies in achieving the designated transfer flight levels for climbing flights. In the no-filtering conditions, two participants fell short of the transfer flight levels by a combined 50 FLs, while under filtering conditions, three participants underachieved for a total deviation of 70 FLs. Analysis of deviations for descending flights uncovered a more concerning trend regarding discrepancies from task requirements. In the no-filtering condition, only one participant fell short of the transfer flight levels by 20 FLs. However, under filtering conditions, a significantly immense total shortage of 380 FLs was observed across four participants. Two participants in the filtering group underachieved by 120 FLs individually, while another two fell short by 70 FLs each. For overflights, there was just one instance in the filtering condition where a participant descended the flight by 10 FLs to resolve a conflict but did not ascend back toward the assigned flight level. This substantial discrepancy suggests potential issues with the filtering's ability to support requirements related to flight level transitions.

Flights typically exited through their sector exit unless instructed to follow a specific heading, bypassing their assigned flight plan and not redirecting it. During the no-filtering condition, two separate incidents occurred where participants issued instructions that diverted flights from their flight plans, and these flights were not redirected back to their sector exits. In these cases, one participant issued a 13° deviation, and another issued a -25.0° deviation. Similarly, under the filtering condition, four participants issued one heading deviation, individually, ranging from -11.0° to 41°, with flights not redirected towards their planned exit paths. These incidents typically occurred near the exit points, where the sector becomes more congested and maneuvering options are limited to resolve potential conflicts. With speed clearance disabled in the simulation, participants controlled traffic flow primarily by issuing large heading deviations near the exit. The goal was to temporarily divert flights and then realign them towards the exit when safe. This strategy proved largely successful, although, in some instances, participants failed to achieve realignment before the flights departed the sector.

The control activity analysis indicated a narrower data spread under the filtering condition than no-filtering. This result contrasts with other dependent measure outcomes. Heading deviations were more prevalent in the no-filtering condition, resulting in more direct-to-exit clearances than filtering. These findings suggest that filtering may facilitate a smoother horizontal maneuver approach than the no-filtering condition,



(a)

(b)

(c)

Fig. 16: Control activity measures through the experiment: (a) total activations of unique flight pairs in VERA, (b) total heading clearances issued, (c) total flight level and direct-to-exit clearances issued with black dotted lines indicating the minimum clearances required to meet operational demands within a simulation trial.

although no significant differences were observed using the Wilcoxon-signed rank test.

Both conditions yielded a similar clearance count during flight level transitions, but filtering exhibited suboptimal performance in meeting operational demands for descending flights. This difference might be explained by participants in the filtering condition delaying clearances for descending flights for efficiency, potentially leading to incomplete tasks. In contrast, participants in the no-filtering condition promptly descended flights, even if it resulted in inefficiencies.

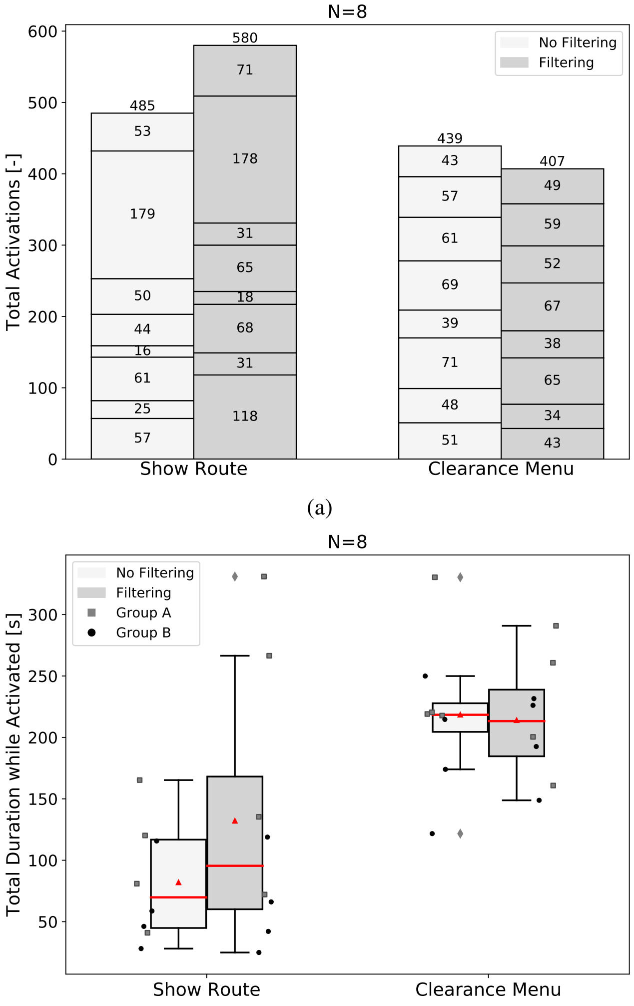
Therefore, by analyzing the total clearances passed to meet operational demands and deviations from the task requirements, Hypothesis 3, stating that flight filtering decreases the operator's control activity in achieving operational demands within the enroute ATC domain, cannot be confirmed.

C. Control Effort and Perceived Workload

Figure 16a shows the total number of VERA checks performed by participants in both filtering and no-filtering conditions. Interestingly, the no-filtering condition initiated more VERAs than the filtering condition, aligning with our initial expectations. However, the Wilcoxon signed-rank test revealed no statistically significant difference in VERA usage between conditions. It is important to note that VERA primarily serves as a confirmation tool for identifying potential conflicts and determining minimum horizontal adjustments. While valuable for ensuring separations, it does not directly affect the safe and efficient traffic flow management. For instance, participants can sometimes predict future flight positions based on trajectories and identify conflicts without relying on VERA. This claim is evident from the distribution of the VERA activations among all participants for both experiment conditions.

Participant triggers filtering by inspecting their route or during clearance issuance to highlight relevant flights. Figure 17 shows the comparisons between conditions with and without filtering among participants relying on these activities. Participants during the filtering condition inspected flight routes more frequently and for a longer duration than no-filtering to make the best use of the flight filtering concept to meet operational demands. The more substantial data points during route inspection also might indicate the participant's curiosity about the filtering mechanism and its inner workings. However, the difference between the experiment conditions was insignificant for route inspection characteristics. While issuing clearances, no significant differences were observed between conditions with and without filtering. The data points recorded during clearance issuance take into account the duration the clearance menu remained open and the participants' browsing through different clearances. Hence, the diminutive data points might indicate participants who had finalized the clearance during traffic monitoring and directly executed it.

While controlling the traffic, participants indicated the perceived workload at a given time by providing input on the ISA scale. The scores were recorded every 240 seconds through the simulation run, making it up to six recordings. The Z-scores of perceived workload were calculated for both experiment conditions at every time step to normalize the differences. Figure 18 shows the distribution of Z-scores of workload over time for filtering and no-filtering conditions. The distribution of Z-score values for workload measures over time between conditions with and without filtering appears similar. However, it is noteworthy that filtering exhibited a slightly more extensive data spread than the no-filtering condition. At the end of the scenario, participants also provided an overall difficulty rating experienced controlling the simulation and later converted to the corresponding Z-scores.



(a)

(b)

Fig. 17: Control activity measures through the experiment: (a) total activations for inspecting the route and opening clearance menu, (b) total duration while inspecting the route and browsing through clearance menu.

The mean workload was calculated by averaging the perceived workload obtained from the ISA scale between the second and fifth-time stamps, excluding the initial and final stamps due to lower traffic complexity. Figure 19 shows the Z-scores for the average perceived workload and overall difficulty ratings provided by participants in both experiment conditions. A Wilcoxon signed-rank test revealed no statistically significant differences in workload between conditions with and without filtering. One possible explanation for this finding is that while filtering helps focus on relevant flights, participants still perform mental calculations to assess potential conflicts between the selected flight of interest and surrounding traffic. This cognitive process could potentially begin before triggering the filtering, thereby reducing the perceived benefit of the filtering in terms of workload reduction.

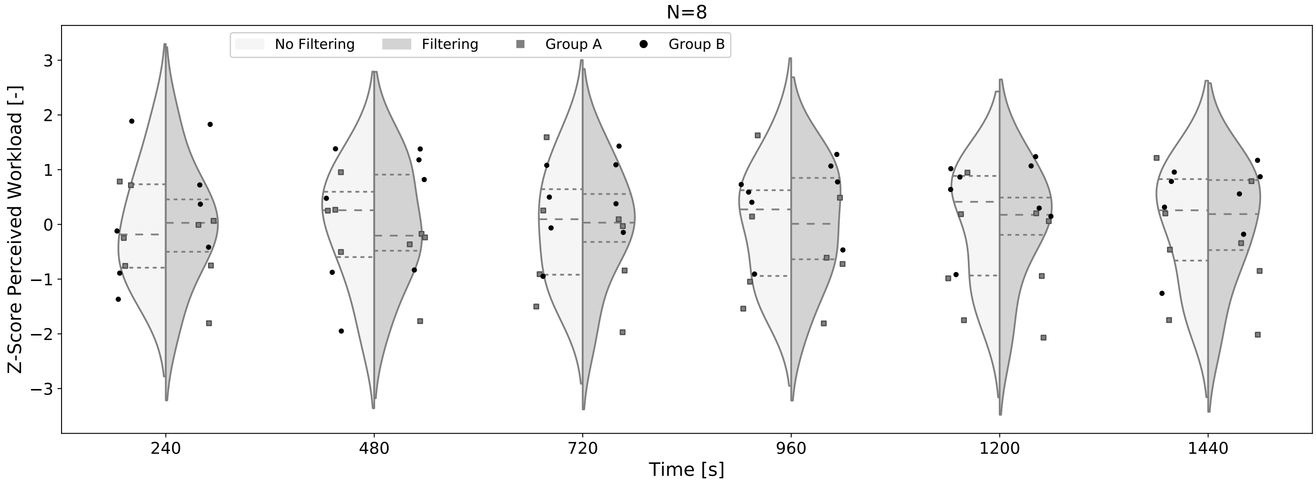


Fig. 18: Z-scores of perceived workload ratings over time provided by participants through ISA scale.

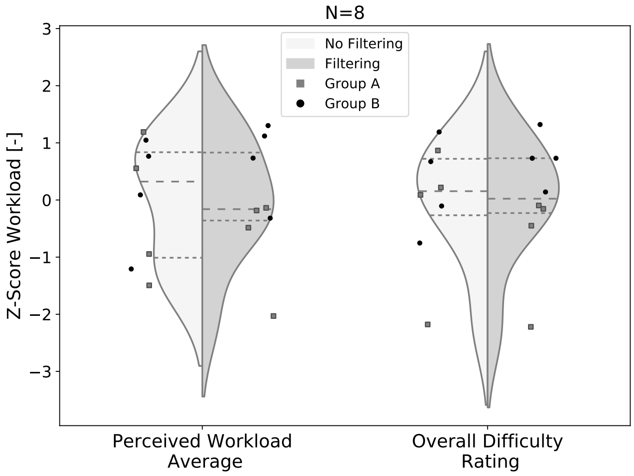


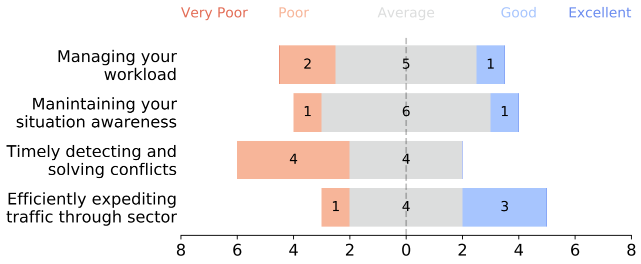
Fig. 19: Z-scores of workload measures through the experiment: average of perceived workload over time and overall difficulty experienced while controlling the scenario.

By fading irrelevant flights, filtering mitigates the necessity for additional comparisons to identify conflicts. While this was evident in total VERA initiations, the difference between experimental conditions was insignificant. Analyzing flight route inspections and previewing clearances revealed no significant differences between experiment conditions, signifying that participants did not abuse the filtering with unnecessary triggers and increasing workload. Based on the analysis of average perceived workload and overall difficulty ratings, Hypothesis 4, stating that flight filtering would decrease the operator's workload while controlling traffic in the enroute ATC domain, cannot be confirmed.

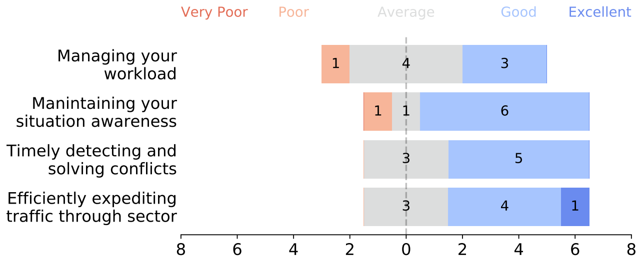
Objective measurement analysis focuses on how flight filtering affects managing traffic flow safely and efficiently without considering participants' efficiency in assuming or transferring flight control.

D. *Questionnaire*

The subjective responses from the participants display an optimistic perspective toward the filtering, not reflecting the objective results obtained. The participants either maintained their ratings or provided an improved rating for the filtering condition while controlling the traffic, as shown in Figure 20. However, some participants' subjective ratings of the filtering and no-filtering conditions may be biased due to their interpretation of the flight filtering during practice sessions, where the traffic was less complex.



(a) No-Filtering Condition



(b) Filtering Condition

Fig. 20: Participant ratings on controlling air traffic safely and efficiently: with and without filtering.

Figure 21 shows an overview of participants' perceptions of filtering while controlling air traffic. Two participants indicated that filtering helped them issue direct-to-exit clearances for indirect flights to increase efficiency. Three others found it handy to fade irrelevant flights, which they would have checked otherwise, without filtering support. However, one participant expressed being unaware of the rationale behind the filtered flights, and that was not part of his workflow/scanning pattern, leading to a reluctance to rely on filtering, resulting in the lowest rating. The participant further stated, "Once you get used to using it (filtering), I think it can be a practical addition to the HMI".

Figure 22 shows the agreement ratings with the highlighted relevant flights during individual flight control. Three participants felt filtering was reasonable and had no negative opinion about the highlighted relevant flights. Two participants indicated that flights expected to play no role concerning the selected flight of interest faded out, and the display of flights they would typically monitor helped them develop trust in the filtering. One participant reported that implementing a conservative approach by increasing safety margins for addressing uncertainties highlights additional flights deemed irrelevant by an individual, contributing to the trustworthiness of the flight filtering concept. Conversely, two participants reported that the filtering's conservative approach highlighted a few diverging flights while controlling the traffic, which they deemed unnecessary. The filtering was designed to prevent participants from issuing clearances that could lead to false STCAs, such as issuing flight level clearance just after divergence, which could trigger a false STCA due to overlapping flight levels.

Figure 23 shows how often participants utilized filtering for conflict detection and previewing clearances. Several participants expressed concerns that while filtering reduced the number of comparisons required, verifying whether the highlighted flights were conflicting maintained their workload and did not reduce it. This claim became evident when they previewed a direct-to-exit clearance and whether the new relevant flights were conflicting or highlighted due to an increased safety margin of up to 12 NM, making it less suitable for conflict detection. Participants noticed that for flights requiring significant flight level transitions, the filtering highlighted more flights, making it challenging to anticipate the consequences of a flight level clearance within their current and transfer flight levels. They expressed hope for fewer flights to concentrate on while issuing a flight level clearance.

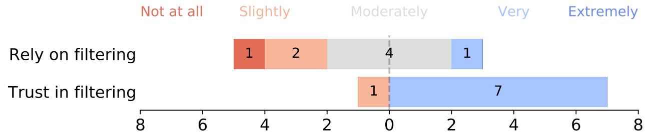


Fig. 21: Participant ratings on reliance and trust in filtering.

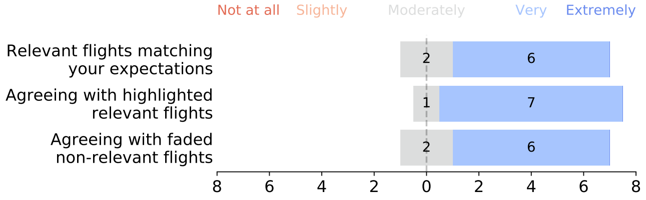


Fig. 22: Participant ratings on agreement with highlighted relevant flights during filtering.

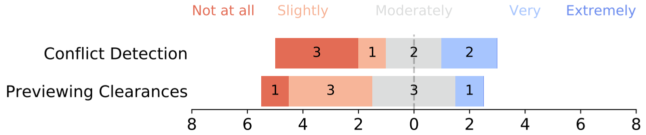


Fig. 23: Participant ratings on how often they used filtering.

Upon analyzing the results shown in Figure 23, an intriguing trend emerges regarding the ratings on the utilization of filtering among participants to meet operational demands are complementary. While one subset of participants provided higher ratings for filtering to narrow potential crossings along the flight route during conflict detection, others provided higher ratings on previewing clearances, highly influenced by direct-to-exit clearance. The subjective ratings on filtering utilization explain the variation observed in the objective data among participants in the filtering condition.

E. Open Feedback

The most common remark from participants centered on claiming that measurement runs were busier than the practice runs, hindering their ability to adapt to the filtered results, even though the filtering was activated with just a mouse click. With lower traffic conditions, they would have more time to evaluate the filtered flights and issue efficient clearances. A participant reported, "In the practice run, I used the filtering a couple of times, and it was useful. In the measurement run, I was often overwhelmed and did not have time to use the feature".

For expediting the traffic safely and efficiently through the sector, one participant mentioned "I used filtering most frequently for seeing if a DCT was safe and if it was safe to transfer an aircraft". Another participant reported, "I tried to vertically separate the flights as much as possible, based on the filtering, before fine-tuning the horizontal separation". Repeatedly issuing flight level clearances after STCA warnings indicates that participants strongly prefer vertical separations for safety. Few participants relied on the modified VERA tool to provide heading deviations for conflict resolutions, with one participant reporting, "I did use the VERA preview a couple of times when I wanted to give a heading clearance to see if it would provide sufficient separation". Interestingly, the participant with the lowest rating on flight filtering for previewing clearances reported, "I sometimes noticed it when selecting a command. In these cases, it served as a confirmation", expanding the further scope of flight filtering in the enroute ATC domain.

Three participants mentioned that while filtering seemed reasonable by highlighting relevant flights, the fading of irrelevant flights was perceived as excessive, almost causing them to disappear into the radar screen. One participant suggested, “Might be nice to still be able to see the faded flights a little bit better, to get a better overall overview of the airspace”.

VI. DISCUSSION

All eight participants completed the experiment successfully, with six reviewing the briefing manual before the experiment session. While participants found the measurement phase runs more complex than the practice runs, they acknowledged challenges in fully utilizing filtering during clearance issuance. Informal communication revealed that participants were unaware of the identical layout used in both measurement scenarios with varying view rotation, callsigns, and waypoint names. Additionally, participants noted a perceived increase in the simulation speed compared to standard conditions. The results of the practice phase are displayed in the Appendix.

A. Relevant Flights Analysis

The flight filtering concept introduced two filters to determine relevant flights while controlling a single flight. The state-based filter yielded higher precision in identifying urgent interacting flights, whereas, the intent-based filter complied with the requirements to direct conflict-free trajectories, resulting in higher recall values. The filtering adapted a combined approach, allowing participants to assess the impact of their preferred clearance and execute it accordingly. The highlighting of relevant flights while issuing clearances acquired positive responses from participants to narrow their focus by filtering out irrelevant flights.

While the experiment with professional ATCOs defined the thresholds for spatio-temporal parameters, few participants hesitated in accepting the filtered results for some flights. This hesitancy arose from the filtering’s conservative nature, which emphasizes recent diverging flights to minimize false STCAs and additional flights perceived as trivial by an individual. The mismatch between the human’s interpretation of the filtering and the actual filtering might make them rely less on the filtering mechanism to collaborate with in the workspace.

Previous research in the ATC domain suggests that personalizing decision-aiding tools to align with the human operator work process can significantly improve their acceptance [32]. Future studies should consider increasing the transparency of the filtering to match the operator’s interpretation of relevant flights while controlling the traffic and setting the color-coding / luminance of the filtered results according to their preference.

B. Expediting the Traffic Flow

Objective data analysis revealed no statistically significant differences in safety or operator’s performance to issue efficient clearances between conditions with and without filtering. Interestingly, few participants prioritized directing flights toward sector exits without thoroughly considering the safety concerns of their actions, resulting in more frequent STCAs. The findings reveal that despite instructions to balance efficiency with avoiding STCAs, the very presence of the STCA tool to warn of imminent safety violations might have inadvertently impacted their control strategies to create secondary conflicts while issuing efficient clearances.

The first clearance time analysis offers valuable insights into participant behavior to issue efficient clearances, but it has limitations when evaluating overall operational efficiency within the sector. This metric primarily focuses on participants’ ability to issue efficient clearances rather than the broader impact on traffic flow (e.g., total time spent in the sector, additional track miles flown by flight). Additionally, the analysis only considers the initial clearances issued. It does not account for subsequent actions like flight level adjustments or additional direct-to-exit clearances issued to reroute the flights after providing initial headings while resolving conflicts.

While objective measurements analysis revealed no statistically significant differences between experiment conditions, participants indicated a positive user experience with the flight filtering concept. However, it is primal to note that while filtering reduces the cognitive load in comparing flight parameters, it may not necessarily improve decision-making. This observation likely derives from the combined effect of high traffic complexity and the subject matter experts as participants.

C. Human Tasks Analysis

Objective data analysis revealed no statistically significant differences in the operator’s workload or control activity between conditions with and without filtering. The data exhibits high variability due to the diversity in strategies employed by participants to meet operational demands, leading to insignificant differences. For the filtering condition, the data spread for the objective measures was more extensive than for no-filtering, raising questions about the comprehension of the flight filtering concept among participants.

The human operators remain primarily responsible for the decision-making and issuing the clearance with the proposed flight filtering concept. Filtering plays a minor role, essentially capturing the pre-attentive phase of information processing for ATCOs while executing the clearance, which they might have done already before selecting the flight for clearance. The increased safety margin highlighting additional flights is suitable during lower traffic conditions, providing sufficient time for participants to evaluate the filtered results and issue safe and efficient clearances. While participants preferred maintaining vertical separations between flights, as perceived by their frequent vertical conflict resolutions, a considerable amount of mental calculations are still required for participants to issue flight level clearances to ensure adequate horizontal separations with other flights during transitions. During heavy traffic situations and for flights with substantial flight level transition requirements to meet operational demands, assessing the filtered results concerning conflict detection becomes challenging with this conservative approach.

Future studies should consider designing a system that dynamically adjusts the spatio-temporal proximities of the filter to highlight relevant flights based on the sector complexity and the operational demands of the selected flight of interest while issuing clearances, simplifying the evaluation of filtered results concerning safety. Another research could explore developing a system complying with the human operator's workflow, offering visual cues for flights requiring clearances to ensure safe and efficient traffic flow. A combination of systems directing attention to flights needing clearances and highlighting relevant flights according to the operator's interpretation during clearance issuance would enhance human-machine collaboration in the enroute ATC workspace.

D. Experiment Design Drawbacks

The scenario utilized a hypothetical sector encompassing flights necessitating climbs, descents, and direct-to-exit clearances to expedite traffic flow. Flights clustered upon exiting the sector, and since the speed parameter was disabled, this led to multiple secondary STCAs generated by participants. Typically, flights do not cluster upon exiting the sector, but the experiment did not utilize adjacent sectors, resulting in the clustering phenomenon. Additionally, participants lacked flight characteristics information, such as rate of climb/descent, which may have influenced their issuance of flight level clearances. Measurement scenarios were reported to have higher complexity with increased simulation speed, hindering participants from thoroughly evaluating the filtered results while controlling traffic.

Eight subject matter experts participated to experience the full complexity of controlling traffic in the upper airspace. Seven participants had previously received simulator training in Area Control, which may have influenced their strategies in issuing clearances. For instance, in Area Control in the Netherlands, ATCOs are advised to issue the climb/descend clearances as early as possible because of smaller sector sizes, in contrast to maintaining flights at higher flight levels for prolonged periods in the upper airspace. Additionally, few participants received Area Control training several years ago, and their skills may have eroded over time. They are not explored to controlling air traffic frequently and were provided comprehensive training only for one hour before controlling the full complexity of upper airspace traffic. These factors likely contributed to the variation in data among participants in the filtering condition and experiencing a higher workload.

More frequent STCAs triggered for the filtering condition during clearance issuance indicates few participants utilized filtering as a guidance tool to improve efficiency rather than critically evaluating the filtered results concerning safety. Professional ATCOs, regardless of expertise, would likely prioritize reviewing all highlighted flights to ensure safety. Future studies should consider designing experiments with the right balance between traffic complexity and participant expertise to evaluate the flight filtering concept.

E. Real World Applications

The filtering remains inactive during general traffic monitoring and activates only when a flight is selected for route inspection or clearance issuance. While monitoring the traffic, the human operator maintains awareness of the traffic situation within the sector. Filtering could serve as a valuable tool to train novice ATCOs, enabling them to narrow their focus and allocate attention to relevant flights during clearance issuance, thus emulating expert ATCOs.

Participants reported that adhering to their expectations by filtering out flights expected to play no role and highlighting flights perceived to impact the selected flight builds trust in the flight filtering concept. With fine-tuning the thresholds and personalization, filtering could still serve as a confirming tool for expert ATCOs to cross-check the perceived impact before issuing clearances.

VII. CONCLUSION

This paper investigates the potential of the flight filtering concept to enhance ATCOs' decision-making abilities within the en-route ATC domain. The research model focuses on capturing the pre-attentive phase of information processing experienced by ATCOs while controlling a single flight. By fading irrelevant (non-interacting) traffic from view, the filtering aims to make relevant (interacting) flights visually salient, potentially simplifying the decision-making process for ATCOs during conflict detection and previewing clearances. Eight subject matter experts performed the within-participant experiment of managing the full complexity of air traffic in upper airspace for filtering and no-filtering conditions.

The aggregated objective data for safety, operator performance, and perceived workload did not reveal significant differences between conditions with and without filtering. The task requirements of managing highly complex air traffic with subject matter experts as participants lead to these objective results. Data variation among participants in the filtering condition arose from the different traffic control strategies and interpretations of the filtered flights with the filtering's conservative approach. However, participants provided positive feedback for the assistance provided by filtering while controlling the traffic. The absence of significant performance differences between conditions with and without filtering, alongside positive participant perceptions of filtering, suggests a potential benefit of the flight filtering concept. To reiterate, filtering did not negatively affect performance, and participants favored it while controlling the traffic.

Future research endeavors should aim to construct experiments striking an optimal balance between the complexity of air traffic scenarios and the expertise level of participants. The experiment should utilize various methods to measure efficiency, such as time spent in the sector or additional track miles flown, rather than focusing solely on the operator's ability to issue efficient clearances through clearance time. These approaches will facilitate a more comprehensive evaluation of the flight filtering concept in enroute ATC operations.

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Part II

Preliminary Report
(Graded for AE4020)

1

Introduction

Global air traffic is predicted to grow 4.7 % annually, making over 9.8 billion passengers in 2070, compared to the 3.7 billion passengers in 2017 [1]. The cause of this increased traffic is because of global economic growth and fierce competition among airlines. The Air Traffic Controller (ATCo) job becomes more critical as they have to maintain the minimum separation between the aircraft with this increased traffic. Air Traffic Management (ATM) authorities are introducing new strategies to tackle the situation and make aviation operations safe and efficient.

The predicted increase in air traffic, safety, and environmental concerns, and the introduction of autonomous vehicles in the airspace demand the reform in ATM, leading to the formation of the Single European Sky ATM Research (SESAR) project. Currently, the airspace is divided into multiple sectors based on geographical and diplomatic limitations, managed by Air Navigation Service Providers (ANSP), who are responsible for providing air traffic services to flights flying within them. The equipment used for the air traffic flow based on the current system has rarely varied over decades and is not keeping up with current requirements and developments. This approach follows the structured traffic routes to fly within the airspace rather than direct routes, resulting in suboptimal operation. SESAR aims to develop an ATM system within a unified European Framework that emphasizes traffic demands and not geographical borders to increase efficiency and reduce environmental footprints [2]. The Trajectory-Based Operations (TBO) principle is utilized in the new ATM system, allowing involved stakeholders to plan and fly their flights with preferred 4D trajectory with predictable information. The Free Route Airspace (FRA) is one of the several developing concepts researched to enhance airspace efficiency by allowing flights to directly navigate towards their exits without the need for intermediate waypoints.

The evolution of the current ATM system with increasing air traffic poses a threat of increasing workload for ATCos while expediting the flow safely and efficiently in their sector. ATCos can enhance their ability to manage increased air traffic within their sector by implementing automation tools at their workstations, thereby reducing their perceived workload. ATCos can typically handle 33% more flights in their sector than the current capacity by utilizing automation tools [3]. However, automation tools degrade human operators' manual and cognitive skills to generate new strategies during unusual situations while operating under time pressure [4]. The challenge is to develop technology that enables operators to manage increasing air traffic without compromising their workload or other human performance factors.

1.1. Problem Statement

En-route ATCos determines the appropriate course of action by scanning radar displays to identify and select a flight of interest that requires attention to ensure safe and efficient operations within their airspace sector. Selecting a flight of interest can be motivated by multiple reasons, including expediting air traffic, ensuring minimum separation between flights, and facilitating flights to reach their target levels, which are some criteria for assigning attention to a particular flight. After selecting a flight of interest, ATCos visually compares the flight parameters such as altitudes, headings, and speeds displayed on the flight labels to assess the impact of potential flight control action on the sector safety [5].

An expected surge in global air traffic will make it difficult for ATCos to compare flight parameters, leading to delayed responses and increased workload. The strategies ATCos adopt for expediting the flow in the sector are deeply affected by the increased workload, forcing them to make less efficient decisions in the increased traffic [6]. Additionally, human operators have limited attention capabilities to distribute in any situation, and ATCos pay less attention to specific flights and their parameters to maintain a competent awareness of the entire sector during high workload traffic [7]. Inadequate attention toward flight parameters might affect the sector's safety, lead to inefficient solutions, or divert a flight from its assigned trajectories.

Ohneiser et al. [8] stated that developing an attention guidance model by providing visual cues to ATCos based on the Air Traffic Control (ATC) events, such as handover or minima separation violation events, decreases their workload and increases their awareness. The proposed model guides the ATCo's attention toward urgent tasks but does not contribute much toward the sector's efficiency. For example, flights following the flight plan will not trigger any visual cue to make them fly directly toward the sector exit in the safer scenario. There has not been extensive research to identify the specific characteristics of an individual flight and streamline its flow efficiently.

The research in this report proposes a mechanism based on spatial and temporal parameters with certain thresholds to filter relevant flights relative to the potential control action for the selected flight of interest. By applying this filtering approach, ATCos will be able to identify the possible interacting flights more promptly, as irrelevant flights will fade after selecting a flight of interest during control action implementation. The proposed model aims to capture the ATCo's pre-attentive phase of visual processing relative to the selected flight of interest, alleviating the additional perceptual and cognitive efforts required to interpret the consequence of a potential control action on the interaction with other flights. By investigating the effectiveness of this approach, the research aims to enhance the decision-making process for ATCos, improving the overall safety and efficiency of ATC operations and reducing ATCo's workload amidst the anticipated surge in global air traffic. The suggested model can provide a foundation for enabling inexperienced ATCos to exhibit the skills and competence expected of experienced professionals in the ATC field.

1.2. Research Objective

Based on spatial and temporal parameters, the proposed model aims to capture the ATCo's pre-attentive phase of visual processing relative to the selected flight of interest, alleviating the additional perceptual and cognitive efforts required to interpret the impact of a potential control action on the interaction with other flights. With this goal in mind, the primary research objective is:

To develop a model that guides the ATCo's visual attention toward relevant flights relative to the potential control action for the selected flight of interest during ATC operations and evaluate it with a simulator experiment.

This research is limited to en-route traffic in upper airspace, meaning it does not consider flight operations to and from nearby airports. One assumption is that Controller Pilot Data Link Communication (CPDLC) is installed in the flight deck to clear the flights, ruling out the use of radio links for this purpose. The second assumption is that planned 4D TBO will provide the information required for necessary predictions.

1.3. Research Questions

The main research question for this research is:

How does a visual attention guidance model for En-route ATCos toward relevant flights relative to the potential control action for the selected flight of interest affect the safety and efficiency of ATC operations and human factors of the ATCos?

Several sub-questions are required to answer the prime research question. The first sub-question will be articulated through a literature study and provide a base for the research, while the second sub-question is related to the design of a model and project it on the radar display. The third sub-question is related to analyzing the results of the filtering flight mechanism through an experiment.

1. **What characteristics are relevant to controlling an individual flight and guiding the ATCo's attention ?**
    (a) What are the factors that contribute to the selection of a ”flight of interest” by ATCos?
    (b) How do sector and traffic characteristics contribute to the complexity of an individual flight in a dynamic environment?
    (c) How do ATCo's strategies vary over situations while making efficient decisions?
    (d) What are the current methods in guiding ATCo's attention toward relevant and urgent tasks?
2. **How can we guide ATCo's attention only to relevant flights relative to a selected flight of interest?**
    (a) How do the ATCos arrange the information perceived from the radar screen to characterize it as a relevant flight relative to the selected flight of interest?
    (b) What parameters contribute to the relevant flights relative to the selected flight of interest?
    (c) What are the parameter's thresholds, and how do they vary over dynamic situations?
    (d) How can relevant flights be displayed to make it salient to en-route ATCos?
3. **How does the proposed visual attention guidance model relative to the selected flight of interest impact the decision-making process of ATCos?**
    (a) What are the impacts on the sector's safety after guiding ATCo's attention to relevant flights relative to the selected flight of interest?
    (b) How does the visual attention guidance model impact the response time and decision-making process of ATCos compared to regular operations?
    (c) How does the visual attention guidance model affect the ATCo's workload compared to the regular operations?

1.4. Report Outline

The literature covers three distinct topics related to the proposed research. Chapter 2 discusses the current en-route ATC work domains, safety standards, and task analysis. This Chapter analyses the parameters and procedures ATCos consider in maintaining sector safety. Chapter 3 introduces the models of measuring sector complexity to determine the individual flight complexity and modeling the ATCo cognitive processing. These factors are relevant in determining the workload perceived by the ATCo while expediting air traffic. Chapter 4 introduces the current developments in developing tools to alleviate the ATCo's workload by designing the visual displays, and interface design, with a special focus on attention guidance.

Chapter 5 introduces two distinct flight filtering mechanisms to guide rn-route ATCo's attention toward relevant flights relative to the selected flight of interest. Chapter 6 provides a preliminary experiment design to determine the effectiveness of the proposed model in terms of safety, efficiency, control activity, and workload. Lastly, Chapter 7 provides a conclusion of the report.

2

En-route ATC Task Definition

Innovators develop decision support tools to assist ATCos in their tasks and mitigate their workload. The first approach while designing tools is to make the proposed model understand the ATC work process and coordinate accordingly to be accepted by the human operator. The prime task of the ATCo is to expedite the flow of air traffic safely and efficiently while minimizing delays. En-route ATCos provides services to flights at their responsible upper airspace called a sector. They are responsible for flights leaving the sector according to their assigned flight plan. The ATCo maintains the required separation between flights to achieve safety in the en-route airspace. ATCos predict situations that may lead to separation violations and provide resolutions accordingly. This chapter discusses the current ATC work domain, focusing on the safety parameter.

Section 2.1 defines the airspace organization and safety standards followed in en-route airspace. Section 2.2 focuses on the work environment and teamwork between two ATCos responsible for en-route airspace. Section 2.3 provides a detailed analysis of task processes carried by en-route ATCos. Section 2.4 and Section 2.5 describe the methods for predicting safety infringement in the en-route airspace and the medium ATCos use to solve it. Section 2.6 describes the emerging concepts regarding ATC services in en-route airspace. Lastly, Section 2.7 provides the conclusion of this chapter.

2.1. Airspace Organisation and Safety Standards

Airspace is a section of the atmosphere controlled by the country's administration above its territory. The most extensive division of airspace is known as a Flight Information Region (FIR), with typically one FIR covering a small country. Airspace classification includes four primary types based on the services provided: controlled, uncontrolled, special use, and other airspaces. Controlled airspace is the classification of airspace in which the ATC provides service following the airspace classification. In Uncontrolled airspace, ATC has no authority or responsibility to control air traffic. Special use airspace (SUA) is a region where few activities happen, limiting its usage for ATC services. Such activities include military airspace, warning areas, or spaceship re-entry. Other airspace areas refer to the activities that include published VFR routes, military training routes, and parachute jump aircraft operations.

Controlled airspace has various types of airspace, and different controllers are responsible for these subtypes of airspace regions. These subtypes of airspace regions are the Control Zone (CTR), Terminal Control Area (TMA), Control Area (CTA), and Upper Control Area (UTA). The Maastricht Upper Area Control Centre (MUAC) is an ANSP providing civil-military air traffic services to flights in the upper airspace region of North-Western Europe. The UTA airspace, also called en-route airspace, ranges the flights flying at altitudes between FL 245 to FL 660. The other three airspaces are categorized as lower airspace, specifying the flights flying at altitudes lower than FL 245. Controlled airspace, including CTA, TMA, and CTR airspaces, is managed by the Area Control Centre, Approach/Departure Control, and Tower Control, respectively. Luchtverkeersleiding Nederland (LVNL) is another independent ANSP responsible for ATC services to civil and military air traffic in the lower airspace of the Netherlands.

Air traffic services and geographical characteristics determine the division of airspace regions into sectors. In UTA airspace, the Air Traffic Controller (ATCo) is responsible for the safe and expedient flow of air traffic in their sector. Flights should be separated by at least 5 NM and 10 FL in the horizontal and vertical dimensions, respectively, in the UTA airspace. An aircraft safety cylinder is assumed to be formed around an aircraft, as shown in Figure 2.1. If single or multiple flights enter the aircraft safety cylinder, the ATCo has failed to maintain the minimum separation, leading to the loss of separation (LOS) situation [9]. Separation infringement might lead to a collision between aircraft or injury to passengers because of the last-minute maneuver action to avoid a collision. A conflict is called a prediction of a loss of separation and is a key parameter for the overall safety of the airspace.

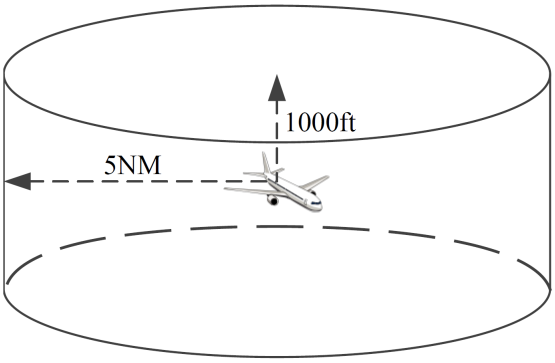

Figure 2.1: Safety Cylinder around aircraft [9]

Separation standards are critical while designing the trajectories and phases of flight. The separation standards are required to prevent aircraft from getting affected by the wake turbulence of other flights during the cruise. During designing flight plans for operations, considerations include safety, efficiency, operational requirements, and airspace availability. However, the flight plans designed might have a few LOS situations with other flights that need to be predicted and resolved by ATCos in real-time, depending on the flight phase. Following are the safety standards considered during designing the flight plans [1]:

1. **Vertical Separation:** An advised altimeter setting maintains vertical separation between flights for maintaining different altitudes. The flights should be separated vertically by 1000 feet for the operations below FL 290. If not, they are separated by 2000 feet unless reduced vertical minima separation is applied.
2. **Lateral Separation:** Aircraft fly towards different geographic locations called waypoints or reporting points to maintain lateral separation. Additionally, the minimum diverging angle between flight tracks based on navigational aid points provides the required lateral separation by locating one flight distanced more than 15 NM from the aid.
3. **Longitudinal Separation:** Flights following the same trajectory achieve safety by maintaining the separation through time. Reporting time of flights passing through the same waypoints is noted, and a time difference of 15 minutes will obtain the required safety. The speed of the trailing flight should be less than that of the forwarding flight to guarantee separation.

2.2. Work Environment

Pfeiffer et al. [10] stated that two ATCos are responsible for expediting air traffic safely and efficiently in the en-route airspace. The Executive Controller is responsible for the safety of flights within the sector while communicating with the pilot, and the Planner Controller is responsible for accepting/handing over the flights from/to other sectors. Communication between the Executive Controller and the pilot occurs through radio, with the Planner Controller overseeing and possibly stepping in if necessary. The study further revealed that ATCos experience time pressure while executing their tasks because of their limiting cognitive abilities, leading to a stress response. Svensson et al. [11] researched important

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[1] `https://www.skybrary.aero/articles/separation-standards`

teamwork factors between en-route ATCos for routine work and stressful situations to execute a good team performance. The Planner ATCo has a supporting role rather than a leadership role during task execution. Mutual performance monitoring and team leadership were negatively correlated, implying that high mutual performance monitoring leads to lower team leadership in ATC systems. The most critical factors for successful teamwork are adaptability and mutual trust, while team leadership and orientation are the least crucial in en-route ATC operations. Figure 2.2 shows the team of en-route ATCos operating in the German ATC center in Munich.

Figure 2.2: Team of two enroute ATCos [10]

En-route ATCos uses a multi-layered structure for executing the same tasks while considering the team intent and collective mind [12]. The collective mind groups up the intentions and beliefs of individual team members to form a group's intentions and cognition. The first layer is an individual's thought processes, the second layer is an individual's belief in the partner's thought processes, and the third layer is an individual's belief in the partner's belief. Two ATCos sit together to obtain information regarding the situation from the radar screen and flight data strips, avoiding verbal communication for situation recognition. After situation recognition, ATCos allocate tasks implicitly among them beforehand, considering both complex situations and heavy traffic to execute them [13].

As mentioned earlier, the pilot and ATCo communicate over voice via radio. Increasing miscommunication between the ATCo and the pilot is predicted because of growing traffic and workload. Skaltas et al. [14] revealed that dynamic frequency occupancy and communication transfer are prime reasons for the miscommunication between the involved entities. Message length and content significantly impact these parameters, with response delays and radio frequency congestion often occurring when managing aircraft across various airspaces. Controller Pilot Data Link Communications (CPDLC) transfers commands to pilots by visual display unusual to voice communications mitigating these issues. There are several advantages of CPDLC over voice communication, such as reducing operational errors and workload distribution among ATCos. Implementing 4D TBO in modern aviation concludes that passing commands over CPDLC is more feasible over voice communications [15].

ATCos derive sector geometry, flight state, and flight path information from a Plan View Display (PVD) or radar display. Flights under ATCo's responsibility are highlighted based on their current position, target states, and tasks for achieving target states. The flight not falling under ATCo's responsibility and passing through different sectors will be highlighted in light grey.

The following flight information comes from the flight label description [16]:

- **Aircraft Callsign:** A group of alphanumeric characters to recognize the flight.
- **Current Flight Level:** The current cruising altitude of the flight.
- **Cleared Flight Level:** The altitude for which the flight is cleared.
- **Exit Flight Level:** The target altitude for the flight while exiting the sector.
- **Arrow:** Indicates if the flight is ascending or descending.
- **Heading:** Indicates the direction or waypoint the flight is currently heading.
- **Exit Point:** The waypoint at which the flight must exit from the sector for the adjacent sector.

En-route ATCo's operation is to assume control over incoming aircraft and clear them to their target altitude and sector exit point. Once flights enter the sector, ATCo maintains the minimum separation between them while expediting the flow. The flight label is in green color for the flights under the responsibility of ATCo. After clearing the flights to their target altitude and exit point, they get transferred to the adjacent sector [16]. Figure 2.3 shows a screenshot of a section of PVD of a controller working position operated at the MUAC [2].

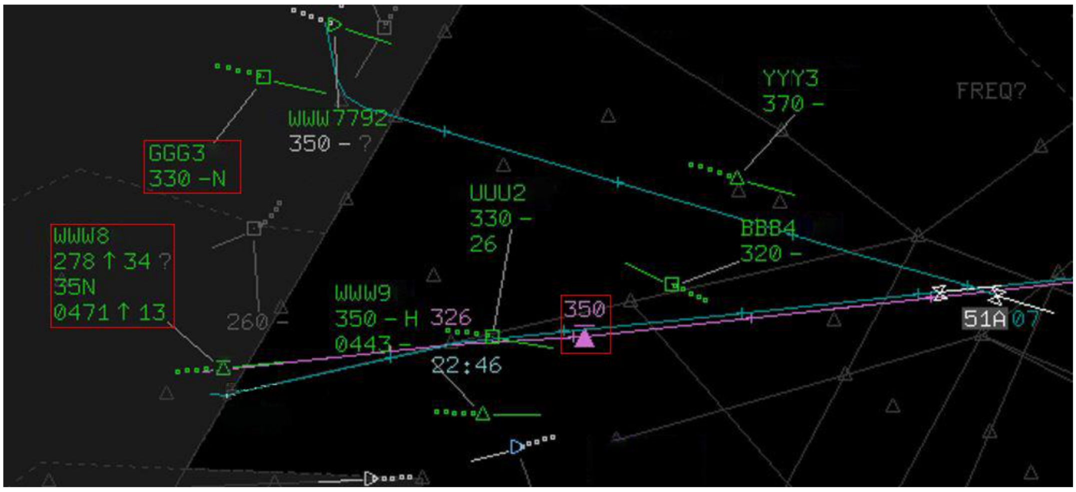

Figure 2.3: Screenshot of a section of PVD operated at MUAC

2.3. Task Analysis

Kallus et al. [17] identified the task processes involved in en-route ATC operations. Figure 2.4 shows the interrelations of these task processes based on the limiting cognitive aspects of the ATCo. Following are the descriptions of these task processes:

1. **Taking over position / Building up mental picture:** A pre-shift briefing is recommended but not mandatory, provided ATCo works regularly while no major update happens from their previous shift. ATCos familiarise themselves with the current situation based on sector density and weather and observe the radar screen before being briefed by the preceding ATCo. If there are unsolved conflicts, ATCo adapts preceding ATCo's sector plan until resolving conflicts. If there are no conflicts, ATCo establishes their sector plan and mental picture by integrating the obtained information.
2. **Monitoring:** The monitoring task implies updating their mental picture and searching for potential conflicts in the sector. The sector plan is updated regularly along with their mental picture to determine their action hierarchy. This hierarchy relies on the urgency of resolving conflicts, assisting pilots, or managing routine traffic.
3. **Managing routine traffic:** Checking and searching conflicts and issuing lateral or vertical clearances for flights complying with predetermined routes.

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[2] `https://www.aviation24.be/`

4. **Managing requests / Assisting pilots:** Additionally, the pilot appeals not in flight plans can be processed based on ATCo's workload and safety criteria. Alternate schemes are generated between ATCo and the pilot if sufficient time is available, but the pilot's particular requests lead to potential conflicts.
5. **Solving conflicts:** After spotting a potential conflict, ATCo decides to either solve it immediately or monitor the situation for some time, leading to an efficient solution. An ATCo generates additional and backup solutions in available time if a typical solution strategy proves to be undesirable. The solution strategies derived are from their differences, including training and experience.
6. **Switching attention:** ATCos switch their attention between multiple tasks while updating their mental picture of the situation. ATCo prioritizes these task processes based on their current mental picture and completes high-priority tasks before unfinished tasks by setting a time window. ATCo might forget unfinished tasks, and regular attention switching updates ATCo with the current situation and task processes.

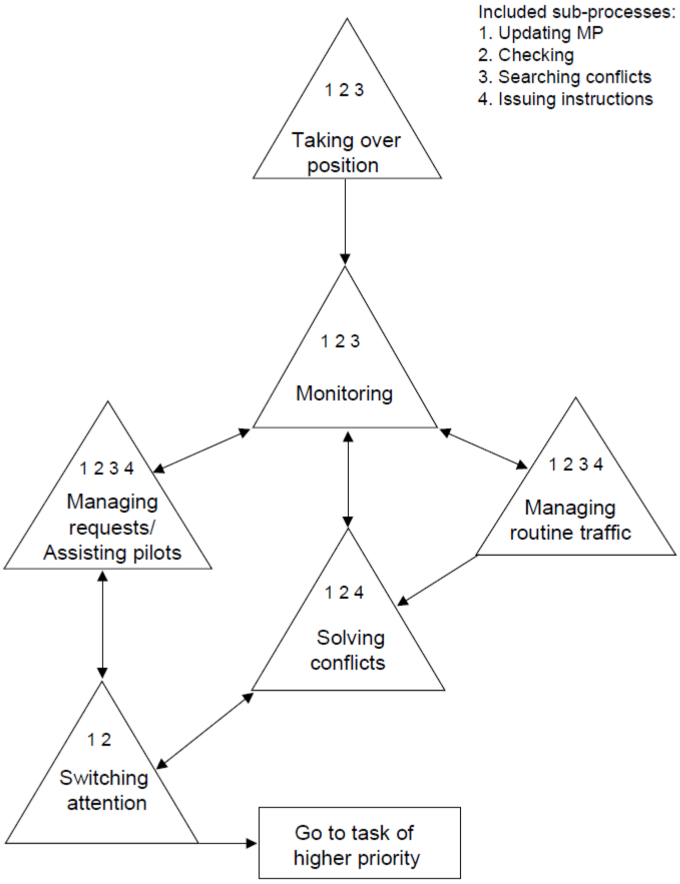

Figure 2.4: Relation between en-route ATC task processes [17]

Following are the sub-processes happening in the background helping ATCos in completing these primary task processes:

1. **Updating mental picture:** ATCos need to maintain their situation awareness while updating their mental picture. ATCo's situation awareness and mental image are well established if their prediction is accurate. Inefficiency in identifying situations can lead to disasters, and precise reasoning is crucial for diagnosis.
2. **Checking:** ATCos obtain information from the radar screen and flight progress strips to check their anticipation regarding the situation. Retrieving new or uncertain situations makes ATCo check their information sources.

3. **Searching conflicts:** ATCos scans radar screens to retrieve flight and route information to detect potential conflicts in the airspace. ATCos adopt strategies to integrate information efficiently and anticipate future situations.
4. **Issuing instructions:** ATCos provide clearances in particular timespan to pilots for maintaining necessary safety in their sector. ATCos repeats the instructions process immediately if the pilots fail to maneuver the flight due to miscommunication.

2.4. Conflict Detection

The realization of a conflict during the conflict search process is termed conflict detection. ATCo predicts and solves conflicts by extrapolating the flight path based on the current state and intent of the flights. ATCos uses a look-ahead time strategy to foresee the possibility of conflicts based on the current situation and choice of maneuver to implement. The ATC domain performs three different conflict detection levels. Long range is inspected every day for making flight plans and airline schedules. The medium range undergoes an examination every hour to provide changes based on an actual flight plan. Short range is inspected every few seconds by ATCo and onboard flight equipment. A usual look-ahead time of 20 minutes is considered for the medium range by ATCo to predict the future states of flight [18]. Elyferth [19] researched the relationship between the influence of look-ahead time and conflict detection accuracy. Conflicts were detected accurately for shorter look-ahead times compared to prolonged ones. The study further revealed that vertical maneuver conflicts as descending aircraft were easily detectable compared to horizontal maneuvers such as crossing or coupled level, irrespective of the timeframe.

Conflicts are usually recognized for a pair of flights if they do not meet the separation requirements. The pairwise algorithm is an uncomplicated method forming pairs of all flights with each other to detect the probability of them having conflicts. Sui et al. [20] argued that developing a pairwise algorithm demands high power computations, unable to meet real-time requirements for a higher number of flights. Hence, various machine learning algorithms are designed for the conflict detection task to keep up with increasing air traffic. Perez-Castan et al. [21] stated that developing machine learning models with ensemble methods can result in higher conflict detection accuracy. While machine learning models hold promise for improving the accuracy of conflict prediction, they do come with certain limitations for their practical usability. The minimum separation requirements for these models are increased for reliability and training purposes, defying real-world rules. Additionally, designing machine learning models requires a big data set to get familiar with all situations for training, which may not be feasible.

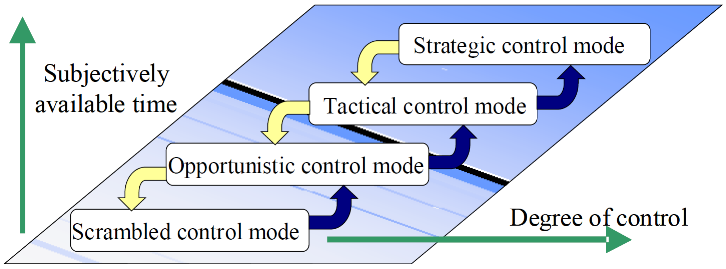

Figure 2.5: Control modes of COCOM [22]

Contextual Control Model (COCOM) depicts the routine decision-making tasks and performance of the en-route ATCo modes shown in Figure 2.5. The separation commands process through priorities based on the relative distances, the velocity of the flights, and the situation [22]. ATCo usually operates in the range of strategic mode to tactical mode. ATCos are more likely to make errors when they have limited freedom of action and insufficient time to respond due to reduced situational awareness. The study further revealed that Executive ATCo adapts a look-ahead time of 5 to 10 minutes for their sector, while Planner ATCo issues separation commands considering the coordination with adjacent sectors. Conflict detection cannot be done in a strategic timeframe because the operations will lack accuracy due to increasing error tolerance, the time factor, and computational requirements [23]. Aircraft Collision Avoidance Systems (ACAS) are installed in the flight deck to avoid the risk of collision if ATCo fails to provide minimum separation with an available time of fewer than 2 minutes. However, ACAS does not consider the flight intent, resulting in non-optimal and unreliable resolution maneuvers [23]. Hence, Conflict detection is done in a tactical timeframe by Executive ATCo while providing clearances and navigating through assigned intent.

Rantanen [24] experimented with narrowing down the cues perceived by the ATCo based on a hierarchical structure for the conflict detection task. The ATCo's response time depends on the position of the aircraft pairs in the sector and the information processing strategy regarding them. ATCo adapts the following hierarchical structure for acquiring information for flight pairs to reduce cognitive demand:

1. **Altitude:** Altitude is checked initially to inspect the appropriate vertical separation between the flights because of its low cognitive effort for processing. If the required vertical separation between flights is present, ATCo no longer needs to check for horizontal separation while meeting required safety standards. ATCo unmasked altitude details at higher times than heading or speed information during an experiment.
2. **Heading:** The heading parameter comes into consideration when the flights are at the same altitude. ATCo extrapolates the flight trajectories to determine if the flights are diverging, converging, or parallel. For diverging tracks, the relative distance keeps increasing, implying they will be free of conflicts. There will be no conflicts in parallel tracks, provided they are separated by a minimum distance. Converging tracks are cognitively demanding because of inspecting distances from the point of intersection. The convergence angle between the tracks determines the conflict detection accuracy, stating that a larger convergence angle leads to smaller accuracy because of the extended distance between them, implying longer monitoring time.
3. **Speed:** Speed parameter is preferred less because of its demanding cognitive efforts related to its integration in the mental picture. The flight reaching the intersection point first can be predicted, and a maneuver is performed accordingly by using speed-distance computations. During convergence, if flights are traveling at the same speed, estimation is done considering relative distance, else, relative speed. The latter option demands more cognitive effort because ATCo has to process two pieces of speed information and integrate them into their mental picture rather than one. Slower flights require longer monitoring time, leading to less prediction accuracy than faster flights.

Pejovic et al. [25] experimented to find a relationship between traffic demand, safety, and complexity in the FABEC airspace. Increasing traffic leads to higher complexity and workload experienced by the ATCo. The study further concluded that most conflicts last at most 30 seconds, and only a few conflicts might lead to a minute. Conflict duration impacts the ATC system and ATCo workload. An unresolved conflict or a missed alert would limit the maneuvers available to the flight and aggregate errors by deviating the flight from the assigned flight path or altitude [26]. Hence, the ATCo should respond on time while solving conflict to mitigate workload and keep flights on their allocated trajectories. Remington et al. [27] stated that conflict time, conflict angle, and traffic load are prime factors affecting the response time of ATCo while detecting conflicts. Less traffic coupled with a small conflict angle and short conflict time had a faster response than high traffic coupled with a large conflict angle and longer conflict time. Conflicts are easy to detect when flights are near each other. In simpler words, overtaking conflicts is detected sooner over head-on conflicts. The study elaborated on implementing Free Route Airspace (FRA) by removing route and altitude restrictions. Removing route restrictions had no significant effect on conflict detection time, whereas removing altitude restrictions affected conflict detection time, providing insurance against conflicts at higher closing rates.

ATCos at MUAC currently has some automation tools available, assisting ATCos in detecting conflicts promptly visually on the radar display. These tools use the lowest level of automation while supporting ATCos in information acquisition and analysis by examining the traffic scenario and finding potential threats in the sector. The Short-term Conflict Alert (STCA) is a safety net tool warning ATCos of immediate LOS situations within a short look-ahead time of 2 minutes based on the radar data or ATCo input, assuming they remain on the current track [3]. The Verification and Resolution Advisory (VERA) tool ex-

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[3] https://skybrary.aero/articles/short-term-conflict-alert-stca

trapolates the future flight position based on the radar data and assists ATCos in determining whether the flight pair will be in conflict, provided they continue on their current headings [28]. The standard rule for ATCos is to use the VERA tool to detect and solve possible safety infringements before an STCA is triggered.

2.5. Conflict Resolution

After detecting a potential conflict in the sector, en-route ATCo solves the conflict by providing a resolution maneuver by changing the flight's altitude, heading, or speed. In contrast to conflict detection, which is a binary value (yes or no), conflict resolution occurs in multiple ways. After identifying a conflict pair, ATCos provide a resolution maneuver to either one flight or both, depending on the circumstance and individual differences. Eyferth et al. [19] stated that selecting a flight and providing them with a maneuver is subjective, and due to a few uncertainties, it is tough to build a standard model for the same purpose. The study further stated that the Executive ATCos provide resolutions to the conflicting pair 7 to 12 minutes before violating the separation minima.

Spaeth et al. [29] suggested a few factors responsible for selecting the preferred resolution maneuver. Destination and aircraft performance are the dominant parameters for providing the required maneuver. Flights reach their destination by passing through reporting points with target altitude at each sector. ATCos issue commands to flights for climb based on their aircraft performance, which the ATCos are usually aware of or request from pilots via radio. En-route ATCos are responsible for clearing the flights to their target exit point and altitudes present in their sector. ATCos perform necessary procedures and coordination with the adjacent sector's ATCos for special situations, such as flights arriving early or late towards their sector entry point.

ATCos provide resolution maneuvers to flights based on spatial, temporal, and technical parameters, which may not be independent [29]. ATCos usually provide heading change to flight if they are separated at an immense distance, implying they have sufficient time to provide a resolution. En-route ATCos provide altitude change for flights closer to each other by position, inferring they have less time to maintain separation minima. Additionally, providing an altitude or speed change does not influence course projection on the radar screen, whereas a heading change does [29]. Following are the implications of the resolution maneuvers available and their influence on the en-route airspace:

1. **Altitude:** ATCos initiate a vertical maneuver by clearing a flight for a new altitude in the cruising phase. ATCos scans altitude information initially to verify the vertical separation between a flight pair. Rantanen et al. [30] stated that vertical separation requires the least attention from ATCos because a flight pair will not have a conflict if they maintain their flight levels. However, implementing an altitude change may violate the horizontal or vertical separation with other flights during the transition, leading to a safety infringement. ATCos initiate altitude maneuvers by clearing the flight for the available flight level or a step climb/descent approach to avoid safety infringement and follow the assigned flight trajectory [31].
2. **Heading:** ATCos initiate a lateral maneuver by clearing a flight for a new heading in the cruising phase. Providing a heading change would require ATCos to update their mental picture as the flight diverts from its trajectory [29]. An additional heading change is needed to put the flight on track unless cleared toward its exit point. Rantanen et al. [30] stated that initiating lateral maneuvers while solving one conflict may trigger secondary conflicts for the same flight level and divert them from their assigned trajectory. Lateral maneuvers available for the flight will be limited if the sector shape is too shallow. ATCos assign a track parallel to the current route and avert them to the current track at the right time [31].
3. **Speed:** ATCos initiate a speed change during a cruising phase or flight transitioning in lateral or vertical maneuver. ATCo requires substantial cognitive efforts to process speed information and integrate it into their mental picture. Speed adjustments are significantly less over rest parameters because of their slower profiles and narrowness at higher altitudes and were only preferred during overtaking scenarios [32]. ATCos utilize the speed parameter by steering the slower flight behind the faster flight to solve the conflict early and leaving ATCo to focus on remaining tasks [31].

Additional external factors affecting the resolution methods are poor weather and SUA. Both scenarios minimize a few portions of airspace available for ATCos to provide resolutions, limiting maneuver choices. Sperandio [6] stated that the strategies human operator use depends on the operator's characteristics, task characteristics, and workload experienced based on operative strategy. The study further showed that ATCos work efficiently at their work capacity, regulating their workload by preferred methods and time pressure.

Assigning a maneuver to a conflicting pair of flights does not ensure the comprehensive safety of the entire sector and can potentially result in emerging secondary conflicts involving other flights shortly. Lillo et al. [33] observed that a significant portion of STCAs are not isolated events but interconnected, leading to a torrent of aggregated alerts based on a provided resolution maneuver, triggering a chain reaction. The study further revealed that ATCos generate solutions to ensure local optimality in the sector over a demanding global optimal solution for conflict-free trajectories.

2.6. Emerging Concepts

Various emerging concepts are researched in ATM systems to handle increasing air traffic demands, meet sustainable goals, and collaborate with autonomous air traffic systems. The new concept proposes providing more authority to the pilots and ATCos to plan their routes efficiently while meeting safety standards. This section highlights the emerging topics of Free Route Airspace (FRA) and Flight Centric related to ATC operations.

2.6.1. Free Route Airspace

Currently, Europe has divided its airspace into multiple small divisions known as FIR, with each encompassing specific country airspace and being responsible for providing air traffic services to aircraft flying within them. However, this existing approach has proven inefficient and unsustainable in meeting the increasing demands of air traffic, and experts anticipate it will exacerbate further soon. The shortcomings of the current ATM system are evident in the form of recurring delays, heightened fuel consumption, and increased carbon emissions. Single European Sky initiative has been introduced in response to these challenges, aiming to transform the existing FIR approach into a more efficient and cohesive Functional Airspace Block approach, enabling ATC services to be practiced seamlessly within a unified European framework [34].

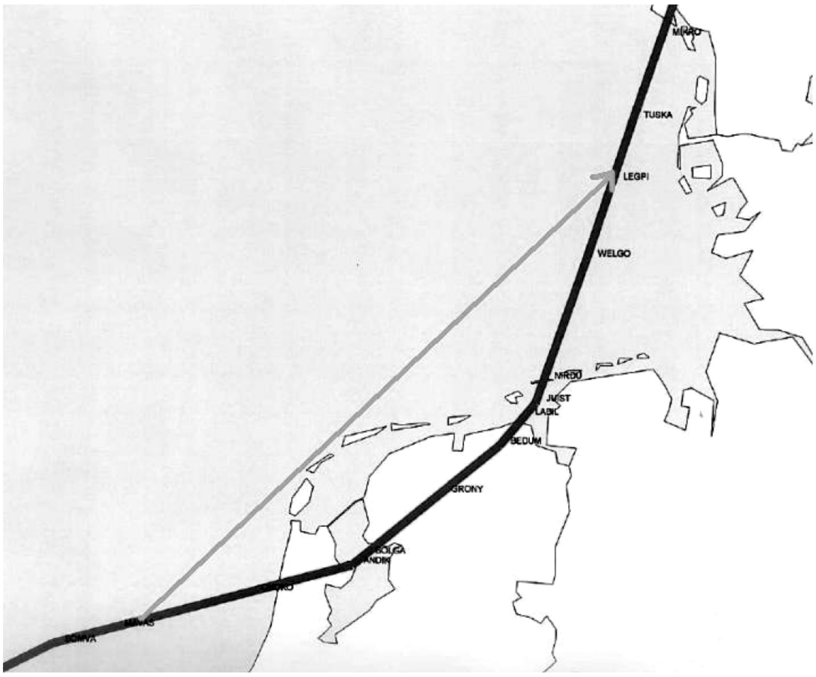


Figure 2.6: Free Route Airspace concept with direct route [35]

The FRA concept gives the operator the freedom to maneuver the flight freely in the sector without the obligation to follow the provided intermediate waypoints in the upper airspace. The FRA concept entails replacing predefined route information with airspace availability information [35]. In other words, instead of following specific predetermined routes, operators choose their trajectories within the designated airspace. In practice, flights follow a Standard Instrument Departure (SID) procedure by flying through the waypoints from the departure to the entry point of the upper airspace. They reach the entry point of the upper airspace with the assigned altitude and are free to vector toward the exit point of the upper airspace. After arriving at the exit point of upper airspace, they follow the Standard Terminal Arrival Route (STAR), maneuvering their flight through the STAR waypoints to arrive at the destination [34]. The upper airspace contains a set of waypoints for the flight to follow, which the operator can skip to increase efficiency, as shown in Figure 2.6.

Several physical factors impose restrictions on the intended use of FRA, including the utilization of military airspace, SUA, and geographical constraints such as mountains and terrains [34]. These elements limit the extent to which aircraft can fully exploit the benefits of FRA and might require alternative routes or considerations to ensure safety and compliance with regulations. Beyond the physical limitations, several aspects are taken into consideration concerning ATC when managing airspace under FRA [35]. Most ATCos are reluctant to change their current operation and must adapt to the new style of expediting air traffic safely and efficiently within the sector. ATC systems must have equipment capable of processing the data and planning the route with just entry and exit points of the sector and must dynamically update the system if flight diverts from their planned trajectories.

2.6.2. Flight Centric

Currently, Europe has divided its airspace into sectors, where Executive and Planner ATCos are responsible for expediting the flow safely and efficiently within their designated sector. When noticing an increasing workload within the airspace, authorities divide it into further sectors and assign additional ATCos to distribute the workload. However, this leads to increasing coordination and handoff events among the ATCos and limits the resolution maneuvers within their designated sector. The flight-centric concept proposes an alternative to the conventional ATC system, wherein instead of assigning a sector to an ATCo, they are allotted certain aircraft and made responsible for their flow within the flight-centric airspace, as shown in Figure 2.7. The primary objective of the flight-centric concept is to enhance the efficiency of the ATM system, reduce ATCo's workload, and increase the overall airspace capacity [36].

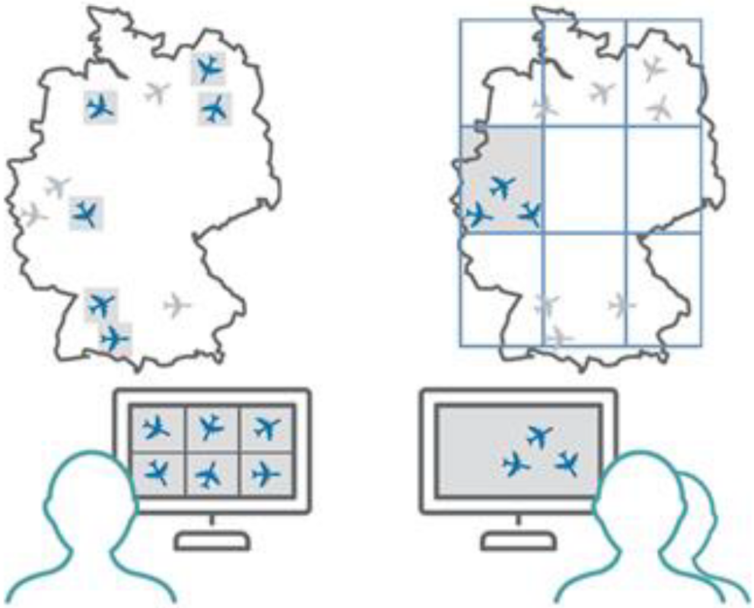


Figure 2.7: Flight Centric ATC (on-left) and Conventional ATC (on-right) approaches [36]

Flight-centric ATC operations share similarities with conventional ATC systems in assuming and handing over flights between adjacent sectors but not in conflict detection and resolution (CDR) tasks. In the current ATC system, the Executive ATCo solves conflicts in the tactical timeframe, and the Planner ATCo solves conflicts in the strategic timeframe while coordinating with adjacent ATCos. However, in a flight-centric approach, CDR tools are implemented in the ATC system to solve conflicts between all aircraft in the sector. Conflict is detected and notified to the involved ATCos along with the resolution maneuver. Based on the provided resolutions, one or both ATCos maneuver the flight to resolve the conflict. Additionally, involved ATCos can ignore the provided solution and execute their preferred maneuver through mutual understanding and coordination [36].

The introduction of the Extended ATC Planner (EAP) represents a new role alternative to the Planner ATCo in the flight-centric ATC system. EAP is responsible for correlating the flights before entering them into flight-centric airspace and allocating them to the Executive ATCos. They also search for the most complex situations in the airspace and resolve them to alleviate the ATCo's workload and reduce the possibility of using coordination between them [36].

Birkmeier et al. [37] provided insights into designing displays and controller work position setup related to the flight-centric ATC system. The research stated that a geographic overview display is suitable for smaller airspace with a proper information filtering model, such as zoom and tiled display. Similarly, additional ATCos might be required in the flight-centric ATC if there are more handoffs/transfer tasks.

2.7. Conclusion

The work environment of en-route ATCos plays a crucial role in determining the factors that require ATCo's attention. The primary goal of the ATCos is to maintain the separation standards between flights while expediting their flow efficiently through the sector. The ATC workplace consists of two ATCos: the Executive ATCo focuses on solving conflicts in their sector, while the Planner ATCo focuses on the conflicts near the sector boundaries and initiating a smooth flow with the adjacent ATCos. ATCos perform multiple tasks such as monitoring, managing pilots' requests, and solving conflicts in their task processes, and their attention to these tasks varies based on priority and urgency.

ATCos adopt a look-ahead time strategy to extrapolate the flight trajectories based on their state and intent parameters to detect a conflict in the sector. The look-ahead time is subjective, depending on multiple factors such as traffic density and sector shape. Flights maintaining sufficient vertical separation between them demand the least attention from ATCos, so the altitude parameter is the first parameter checked when detecting conflicts. Flights sharing the same altitude are further analyzed to determine their convergence within the sector to ensure horizontal separation by inspecting their heading and speed. ATCos have some automation tools, such as STCA and VERA, assisting them in detecting conflicts promptly based on the radar data or ATCo input, provided they continue on their current track. Ideally, ATCos utilize the VERA tool to identify and resolve conflicts before triggering alerts from the STCA tool.

Conflict resolution involves ATCo changing the flight's altitude, heading, speed parameters, or combination. After conflict detection, the number of available maneuvers is limited by the subjective time available to resolve the conflicts, so conflicts with shorter conflict times demand immediate attention. ATCos adopt a shorter timeframe while providing resolution maneuvers to a conflicting pair in the sector, triggering secondary conflicts shortly, based on implemented action.

3

ATC Complexity and Cognitive Modeling

Human cognitive abilities and current airspace characteristics restrict the implementation of new automation tools or redesigning airspaces to manage increasing air traffic. Measuring current sector complexity is the initial step to provide changes to the ATC system, such as changing airspace configuration or implementing a new interface design. Sector and traffic characteristics formulate task load demands affecting the Controller's mental load. ATCo workload measurement is possible through subjective ratings or objective techniques such as eye-tracking or control activity implemented in the sector. Other examples of measuring sector complexity include defining a complexity score based on the sector and traffic characteristics. Additionally, individual differences of ATCos to adapt the information for decision-making construct a cognitive processing model. This chapter discusses various means of measuring sector complexity and modeling the ATCo cognitive processing.

Section 3.1 explains the theoretical concepts of ATC complexity affected by the task load demands and the mental load experienced. Section 3.2 provides a few examples of measuring sector complexity through a complexity score by trading the sector and traffic characteristics. Section 3.3 defines the problem-solving strategies and factors affecting decision-making. Section 3.4 and Section 3.5 constructs the cognitive processing model of en-route ATCos during decision-making. Lastly, Section 3.6 provides the conclusion of this chapter.

3.1. ATC Complexity

Human operator's limiting factors are crucial while implementing new Air Traffic Management (ATM) systems. The feasibility of the new ATM systems is validated by experimenting with human operators in a loop and measuring their workload. In the ATC domain, the human limiting factor is ATCo workload, measured through sector complexity [38]. Researchers examine to establish and evaluate a relationship between ATC complexity and ATCo workload. Initially, Mogford et al. [39] proposed to derive complexity factors associated with the sector through direct and indirect methods by collecting and analyzing related data. Individual ATCos respond differently to complex factors, and a model could not be derived. The research further embellished to measure ATC complexity based on the subjective workload rating of ATCo through their perception and interaction with the sector. The feasibility of the new ATC system receives validation through ATCo workload rating while considering the sources of traffic and sector complexities [40].

The solutions and strategies ATCo adapt are limited to their individual differences and cognitive state. Hilburn [38] proposed a model finding a relation between the ATCo workload and complexity based on their mental state. The subjective human factors and objective task demands in the working environment provide a distinction of workload experienced among ATCos, limited to their cognitive abilities.

The model [38] depicts a simplified relation between task load and operator workload, as shown in Figure 3.1. The task load is influenced by sector boundary, traffic distribution, and interface tools for decision support, whereas the operator workload is affected by individual differences such as skill and experience.

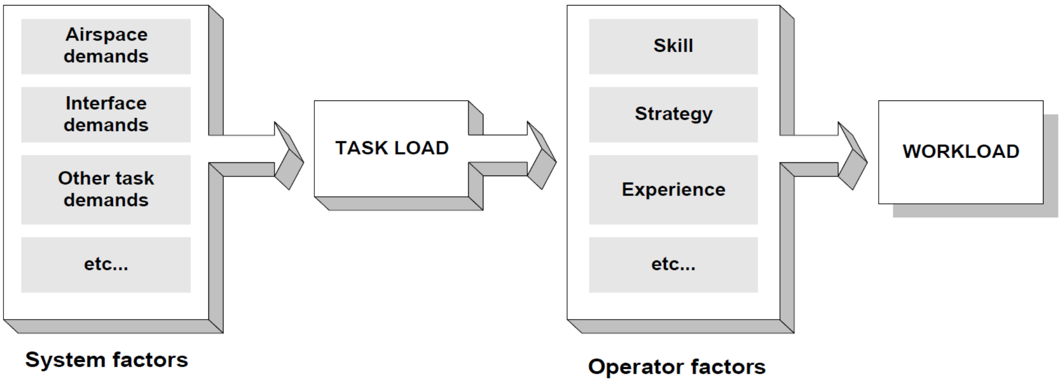


Figure 3.1: ATC workload model [38]

3.1.1. Task Load

Sector and traffic-related factors contribute to the objective en-route ATCo's task load demands. Previous research stated that the number of aircraft and the sector design are the prime contributors to the en-route ATCo's workload. However, Hilburn [38] revealed that additional factors, such as aircraft mix, altitude overlap, weather, conflicts at sector boundaries, etc., contribute to the overall sector-related complexity. Additionally, traffic structure implying the traffic flow passing through waypoints in airspace has a prime impact on the ATCo perceived workload. Less dense airspace with unstructured traffic flow may be more complex than high-density airspace with structured traffic.

The tools acquired for information display regarding system requirements play a crucial role in processing information for human operators. Mogford et al. [40] stated that a deviation between the system requirements and human information processing increases ATC complexity. A few of the display tool factors include the radar display scale, the separation between tracks on the radar display, and relevant flight information. Aircraft count, information display, and human processing shape the strategies ATCos adapt and provide a maneuver influencing a sector activity.

Manning et al. [41] used sector activity and complexity to predict the en-route ATCo task loads. Sector activity is defined as the number of flights that received commands from the en-route ATCos for maintaining safety and efficiency in airspace, whereas sector complexity describes airspace and traffic-related factors assumed to affect the task load. Neither sector activity nor complexity predicts the task load accurately in an en-route ATC system. However, ATCo's subjective rating and sector activity behaved similarly, implying that the ratings provided by ATCo may be related to their activity instead of the sector. The activity rating does not necessarily have to represent the sector's complexity, and a reasoning-based approach while providing ratings might be promising.

The factors considered while measuring sector-related complexities do not account for the trajectory uncertainties. Clearance provided in tactical time frames, delays in departure, and frequency congestion during radio communication are fewer examples of scenarios leading to trajectory uncertainty. Knorr et al. [42] revealed that the complexity and workload of ATCo while expediting the flow are reduced with higher accuracy trajectory prediction. The study further revealed that accounting trajectory prediction enables assessing individual flight complexity contributed by a single aircraft.

3.1.2. Mental Load

The mental load is the calculation of the impact on the cognitive aspects of the human operator while completing task demands. Humans have limited cognitive abilities for information processing, a restriction factor while increasing the task demands or implementing new ATC systems. Hilburn [38] stated that researchers employ these limitations to develop models that measure human operator's parameters, such as attention and effort, during task execution. Efficiency reduces when task requirements exceed limits, whereas spare mental capacity is measured when task requirements are less than limits.

Mogford et al. [40] stated that personal differences might not be practical to describe ATC complexity but rather measure performance and workload. Individual differences such as age had a direct influence on the performance, whereas experience seemed to be irrelevant for ATCo's performance. The study further revealed that anxiety, misery, and confidence might be personality traits affecting ATCo's performance during task execution.

ATCos adopt strategies to meet the task demands depending on their work capacity, task prioritization, and performance regulation. Loft et al. [43] reveal that the ATCo adapts strategies to match the desired and actual workload level with a feedback loop. The desired workload level is the ATCo's efficient work capacity, leading to selecting a strategy for task execution. The strategy solution passes through the task load demands to produce the actual workload. The control strategies further selected rely on the adjustments between the desired and actual workload levels, and the loop continues. The study further concluded that developing new ATC systems with a mental load-centered approach has advantages over a task load-centered.

The mental workload can be measured objectively through eye-tracking techniques while allocating attention during task execution [44]. Fixation count and pupil diameter derive the amount of attention ATCos assign to the radar screen and its entities. Fixation count categorizes the flights in the scenario, and the amount of fixations varies for the conflicting and non-conflicting flights. Pupil diameter is measured for a specific event during task execution and is higher for the conflict event in the ATC system. The study technique proves to be valid for guiding the ATCo's attention in the ATC system.

3.2. Current Complexity Measurements

Developing new ATC systems requires measuring sector complexity with task environment and human cognitive limiting factors. Measuring sector complexity involves considering airspace, traffic characteristics, and the impact of task demands on the human operator. Following are a few proposed models determining sector complexity from the literature.

3.2.1. Input Output Approach

Lee et al. [45] proposed the Input Output approach to measure sector complexity through the control activity required to maintain the separation minima between the flights when new aircraft enters the sector. The sector and the traffic inside it are considered a closed input-output control system, where the entering flight is the input signal, and the maneuver provided to flights to meet safety standards is the output signal. A complexity map displays the current system state and the impact of the control activity with a possible set of input signals. In this scenario, the sector is not a specific geographical location but rather an area surrounding a group of aircraft.

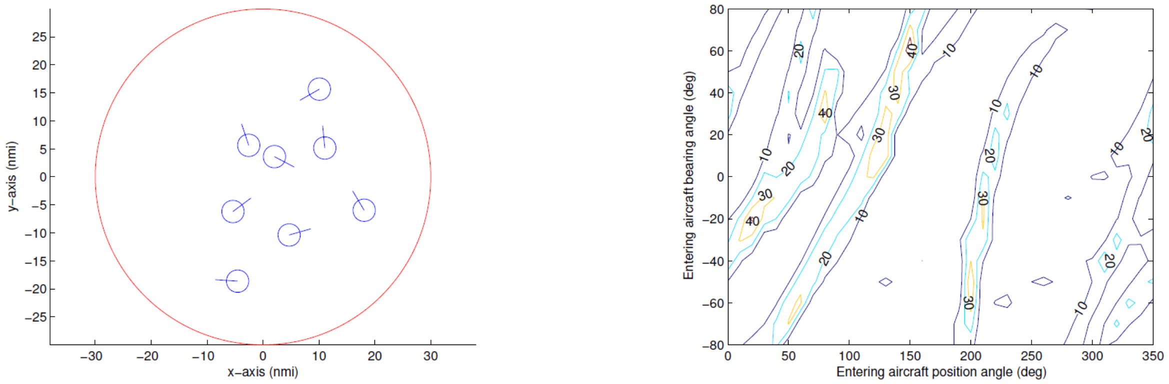


Figure 3.2: A traffic situation and corresponding complexity map from Input-Output approach [45]

The input signal of the system is regarded as aircraft entering into the sector, having two parameters for its entrance. The entry aircraft position angle is the angle between the aircraft entry position and the center of the sector. The entry aircraft bearing angle is the angle between the track of the entering aircraft from the line connecting the sector center to the aircraft. Possible sets of entry aircraft position angle and entry aircraft bearing angle exist to establish the complexity map of the scenario.

The output signal is the complexity influenced by heading change required for all aircraft in the sector, cruising with a constant speed to maintain the minimum separation between them concerning entering aircraft. Multiple architecture solvers can be used to obtain the required control activity and complexity. In optimal solver, a single heading change is provided to necessary aircraft in the sector, avoiding conflicts concerning the entering aircraft. In sequential solver, aircraft entering sequentially into the sector are provided with a change in their trajectory to avoid conflicts with multiple preceding aircraft.

The complexity map represents the results of the control activity of aircraft (complexity) concerning the entering aircraft with possible sets of their entry position and bearing angles. Figure 3.2 displays an example of a traffic scenario and its respective complexity map. The sector complexity derives from the complexity map for that particular scenario using different methods. Lee et al. [45] recommended probabilistic measures, values above certain thresholds, and worst-case value methods for calculating sector complexity from complexity maps. The proposed model can account for various uncertainties, such as weather and partial sector closure.

3.2.2. Dynamic Density Model

Kopardekar et al. [46] created the Dynamic Density model accounting for multiple variables, such as traffic and sector-level characteristics, for developing a comparable alternative to task load factors. Factors included in the literature while creating the dynamic density model are safety standards, traffic distribution, aircraft count, aircraft performance, sector shape, and weather. The model accounts for both time-dependent and time-independent factors in the sector, and the complexity produced is for any instantaneous condition.

The model accuracy highly depends on the subjective ATCo factors and sector geometry [46]. The standard rule is to solve possible conflicts ahead of 2 minutes, violating the separation minima and preventing STCA. The look-ahead time and minimum separation adapted by the ATCo depend on the current traffic situation and individual characteristics to foresee the possibility of conflicts in the scenario. For example, during heavy traffic, ATCo prefers safer solutions with a shorter look-ahead time, whereas during lesser traffic, ATCo favors efficient solutions with a longer look-ahead time. Similarly, the look-ahead time also depends on sector size, implying a shorter look-ahead time for narrow sectors and vice versa. ATCos use the closest point of approach (CPA) to determine the minimum possible distance between flights and the time required to attain it by trajectory extrapolation.

Kopardekar et al. [46] implemented a linear regression method to develop a relationship between the complexity and dynamic density variables to determine the potential factors describing the ATCo workload. The potential variables from the dynamic density model are as follows:

1. **Aircraft count:** ATCo accepts the incoming flights to their sector, expedites their flow, and transfers towards their sector exits. Immense traffic increases the supplementary task of scanning, even if the sector safety remains unaffected [27]. Resolution maneuvers in airspace are limited because ATCo has to avoid secondary conflicts.
2. **Aircraft density:** The aircraft count factor can be represented alternatively as the aircraft density, implying the number of aircraft over a sector space. The space considered can be an entire sector or a specific portion. Less available space for a single flight increases the perceived complexity because of limiting resolution maneuvers.
3. **Relative speed:** Relative speed determines the first flight reaching the intersection point on the convergence track. Different speed values increase the perceived ATCo complexity because the speed parameter is cognitively demanding.
4. **Distance proximity:** Flight pairs maintaining sufficient vertical separation will require less attention than flights positioned closer to one another in horizontal dimension or expecting to violate

the safety standards.

5. **Time to LOS:** Shorter conflict time aircraft pairs are positioned closer to each other and are easily detectable [27]. A shorter conflict time signifies that the LOS situation is nearer and should be solved quickly to maintain safety.
6. **Conflict detection based on crossing angle:** The convergence angle between two flights for their crossing intent adds to the overall perceived complexity. A higher convergence angle conflicts are harder to detect [27].
7. **Flights requiring altitude change:** Flights requiring a vertical maneuver to reach their target values are more complex than ones not needed because of the possibility of generating additional conflicts during the transition. Unlike heading change, vertical maneuvers are not easily detectable on the radar display, leading to difficulty while monitoring.
8. **Aircraft count within a threshold distance to sector boundary:** The available resolution maneuvers for flights nearing the sector boundary are limited, thus increasing the perceived complexity.

3.2.3. Relational Complexity

Boag et al. [47] introduced a method for computing sector-level complexity by examining the interactions between pairs of aircraft. Conflicts are recognized pairwise by predicting their distance to CPA and the time available to resolve them. The approach is to minimize the number of processing variables to detect conflicts accurately and analyze the complexity.

The study stated that humans process up to 4 variables parallelly in their cognition to implement efficient strategies in the task environment [47]. Human operators use conceptual chunking to compress the exceeding variables by developing relations between them. ATCos require variables such as relative level, speed, and heading of an aircraft pair, but the scanning techniques and priorities might differ. Additionally, various types of these variables interlinked with one another between aircraft pairs in a scenario represent a relation regarding conflict detection accuracy. The model proposed violates the horizontal and vertical safety standards between aircraft pairs and restores them.

A transition is recorded in working memory when a single flight enters/exits the conflict geometry of another flight, considering both horizontal and vertical dimensions. A total of 5 transition values exist, varying from 0 to 4 for a single aircraft pair. Transition value 0 signifies that the required safety has been maintained between the aircraft pair in both dimensions, while transition value 4 indicates that the flight has entered and exited the conflict geometry in both dimensions of the other flights. Higher transition values for a flight pair imply a shorter conflict duration, indicating that they are more complex than pairs with lower transition values.

Overall sector complexity is measured by summing the transition values of all aircraft pairs. The proposed relational complexity model detects conflicts early and accurately, providing sufficient time for ATCos to provide resolution and assure safety [47].

3.3. Problem Solving Strategies

The primary role of ATCo is to expedite air traffic safely and efficiently through the sector. ATCos aims to minimize the delays by reducing the additional track miles flown, but following the separation minima. ATCo adapts different strategies to expedite flow based on individual differences such as training, age, and experience under constant time constraints [6]. Another factor other than individual differences affecting the ATC's actions is traffic distribution. Teuler et al. [48] identified altitude crossings and adjustments between the flight pairs, especially descending flights, as critical factors impacting the ATCo actions. Heading change to flights passing through the assigned navigational points resolves conflicts in the horizontal dimension. Providing a trajectory shift to aircraft in a tactical time frame might reduce time costs and save fuel costs, which ATCos consider in real-time operations [49]. Hence, principles and factors ATCos observe while solving conflicts are critical for the safety of the overall task environment. This section describes the methods ATCo appraises while making decisions and the factors affecting it.

3.3.1. Memory Enhancement

Spatial parameters such as sector boundaries, waypoint locations, and temporal parameters as flight position update along the route shape en-route ATCo's memory. However, memory has a supporting role rather than a dominant role regarding performance or situational awareness in the task environment. Gronlund et al. [50] stated that ATCos perceive the gist rather than the exact flight data information during the operation and decision-making. Additionally, flight position updates are temporal, and ATCos do not rewrite their memory in the future, making them process information comfortably. ATCos focuses on the traffic situation by retrieving the data tag information for the series of aircraft rather than rescanning the entire airspace. The information order ATCo processes are flight position, callsign, flight data information, and clearance provided [51]. ATCo anticipates the new flight positions of flight by extrapolating their trajectory based on their parameters. ATCo adapts prospective memory strategy by holding a critical flight for a limited time and passing the clearance later at an appropriate time. ATCos might hold a flight for multiple reasons, including providing an efficient solution or assigning the flight to its original trajectory after deviation. ATCos usually ignore prospective memory strategies during higher workload conditions because of their demanding cognitive condition [52].

En-route ATCos perceive visual information from radar screens to guide the flights toward their target exits and altitudes. The radar screen displays enormous information related to ATC tasks that might not be relevant to performing tasks efficiently. Different methods to perceive the information and comprehend its meaning might vary among ATCos based on age and experience, affecting task performance. Meeuwen et al. [53] describe three visual problem strategies differing among ATCos based on expertise as follows:

1. **Attention Focusing:** Attention focusing separates relevant task-related information from irrelevant details, effectively streamlining the available data. For instance, experts tend to concentrate their attention on airspeed rather than the altimeter, as the required altitude information can be deduced from the true horizon, exemplifying this selective attention process.
2. **Perceptual Chunking:** Chunking involves consolidating several significant elements into a single unit that can be processed more efficiently, demanding reduced cognitive effort. ATCos group multiple aircraft based on shared characteristics and manage them as a cohesive entity. For example, flights flying in a queue are grouped and interpreted as one entity.
3. **Means-end analysis:** A means-end analysis is an effort-demanding strategy where an operator works backward from the goal rather than working towards the goal. An alternate version of this is working forward analysis, where an operator will decide ahead of the actions to take to reach the final goal.

The study [53] further stated that expert ATCos adapt work-forward analysis by focusing more on relevant information, such as flight parameters, and chunking perceived information. Meanwhile, novice ATCos adapt means-end analysis by focusing on sector exit and chunk less information than experts.

3.3.2. Decision Making Process

ATCos perform multiple steps ahead before providing a resolution maneuver to a flight. ATCos perceive relevant information from the radar display and understand the elements before making a final decision. Kang et al. [5] proposed an integrated model of scanning radar display, selecting an aircraft pair of interest and comparing its parameters, as shown in Figure 3.3. There are numerous ways to carry out these tasks, as mentioned below.

Visual Scanning methods involve perceiving flight information from the radar display during conflict search tasks with limiting perceptual and cognitive resources. Circular, linear, augmented, regional, density-based, and proximity-based are six visual scanning methods currently identified and practiced among en-route ATCos. The chosen method to scan display is subjective based on training, age, and experience. ATCos commonly use circular scanning to cover the entire sector, and they can perform it in clockwise, anti-clockwise, or spiral directions.

Aircraft Selection involves selecting a flight pair or pairs for that particular scenario. Flight pairs are determined to increase the overall sector safety and efficiency. The hierarchy followed by ATCos for conflict detection are altitude, heading, and speed. ATCo checks altitude initially, to verify minimum vertical separation between a flight pair. After scanning the display, ATCo will select an aircraft pair if they share the same altitude. Other criteria for selecting flight pairs include proximity and convergence parameters for flights sharing the same flight level.

Aircraft comparison involves comparing flight parameters after aircraft selection. ATCos compares the flight parameters to detect conflicts in the sector by extrapolating their current states and intent. Altitude overlap, speed, speed and bearing, overtake, and projection are five methods for aircraft comparison during conflict detection. Projection is the most common method for aircraft comparison, utilizing the speed and heading parameters. Altitude overlap inspects possible conflicts in the sector between the cruising altitude and cleared altitude if a vertical maneuver is in place.

ATCos scan flight parameters efficiently such that frequent interrogation is not required for all aircraft pairs in the sector. An additional repeat process exists for scanning, selection, and comparison methods for increasing accuracy and efficiency by changing scanning strategies before implementing a safety maneuver [5].

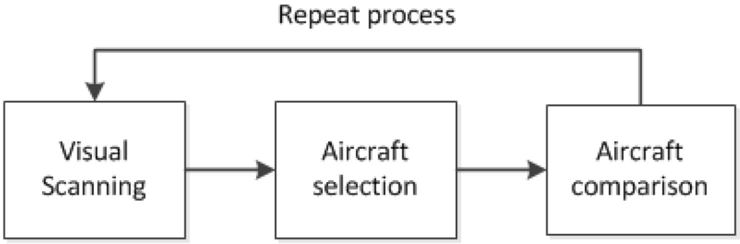


Figure 3.3: Integrated scanning, aircraft selection, and aircraft comparison [5]

3.3.3. Factors affecting Decision Making

En-route Controllers decide to provide a maneuver to flight by scanning the radar display, selecting a flight pair, and comparing its parameters. An error in ATCo's judgment regarding decision-making may lead to operational or controller errors. An operational error occurs when ATCo violates separation minima during operation execution, such as miscommunication between controller and pilot or extended time of controller's duty [54]. Controller error occurs when secondary errors, such as the loss of situational awareness, arise with the introduction of decision support aids in the workspace [55].

D'Arcy et al. [56] stated that multiple factors influence decision-making strategies adapted by en-route ATCos during task execution as follows:

1. **Individual differences related:** Age parameter is critical for projecting decision-making strategies in the en-route airspace. Experienced ATCos initially formulate additional strategies during task execution, resulting in fewer errors when more backup plans are in place. Motivation, stress, and anxiety are secondary parameters affecting safety and efficiency in the sector. Similar solutions are adopted by experienced ATCos with high performance compared to intermediate or novice ATCos [53].
2. **Operations related:** Information processing variables are increased for ATCos when they implement a direct route with less traffic load rather than following a standardized trajectory. Employing the provided route can be advantageous for ATCos as it allows them to manage their workload effectively and work efficiently within their capacity [6]. Pilot's flying requests at their preferred route for saving time and fuel impact ATCo's operative strategy because of additional processing variables.
3. **Work environment related:** Teamwork between the Planner and Executive controller is crucial during heavy traffic load conditions. Overconfidence and lack of surveillance are observed in combined functions, thus endangering the operative strategies. During training, instructors were forbidden to teach their personal resolutions and encouraged apprentices to develop their own approach irrespective of the provided training.

Fothergill et al. [57] stated that a tradeoff between safety and efficiency exists in the en-route sector with varying workload levels. ATCos implement less efficient maneuvers while expediting the traffic flow under high workload conditions. The reason provided was that ATCo prefers a quick-safe solution over strategies requiring high monitoring time.

3.4. Mental Picture - MoF1 model

The mental picture represents ATCo's cognizable image formed while executing tasks in the work environment. ATCo formulates the mental image by integrating the information from available sources, identifying potential conflicts, and resolving them under required time constraints. The integrated information includes the static conditions as sector boundary and dynamic information as new states of the moving flight. The mental image formed is subjective to individual differences such as training, age, and experience. The framework developed to recognize the mental representation of ATCo is validated using situation awareness, a parameter describing the ability of an operator to identify the situation of object states in a dynamic environment. However, ATCo's attention to the flights varies based on urgency and flight states. For example, flights depicting conflict in shorter duration will receive more attention than that of longer. A mental picture makes ATCo stay active in the operation loop while executing tasks, and any disruption in the mental picture would make ATCo process incorrect information, leading to errors [58].

Models developed to depict the mental picture of the ATCo captures the characteristics of the dynamic environment. The dynamic environment is changed regularly irrespective of the ATCo's input, implying additional demands on the ATCo cognition. Moreover, ATC goals change actively during task execution based on the present situation of updating flight positions. The constant addition of new objectives leads to the issue of sequencing and prioritization with the existing goals. However, the working memory requirements among parameters are different during task execution. Long-term memory deals with spatial parameters, such as sector boundaries and the positioning of the waypoints, which could be necessary for upcoming traffic. Short-term memory deals with the temporal parameters as flight position updates, which are not required to replicate later [58].

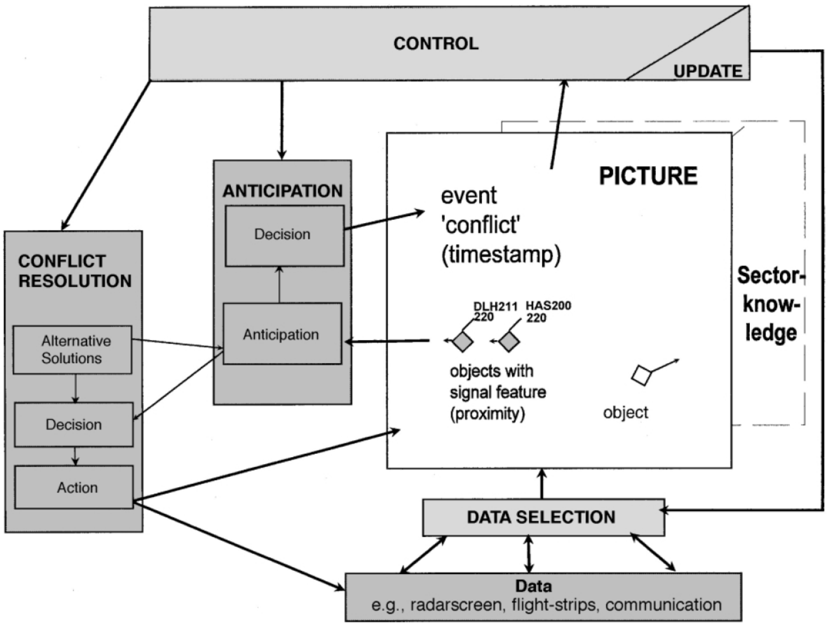


Figure 3.4: Mental Picture of ATCo by Niessen et al. [58]

Niessen et al. [58] proposed the Modell der Fluglotsenleistungen Model (MoF1) model representing Executive ATCo's cognitive activities during decision-making as shown in Figure 3.4. The model uses spatial and temporal parameters to identify the conflicts between aircraft pairs and resolve them. The components involved in the MoF1 model are data selection, anticipation, conflict resolution, update, control, and sector knowledge. The events in memory have different priorities and are accessed sequentially through different attention activation levels in the control module. These components are interlinked to form three information processing cycles representing the mental picture as follows:

1. **Monitoring Cycle:** The monitoring cycle consists of data selection from the resources and updating it in their mental picture. ATCos perceive relevant information as vertical positions and proximity to other aircraft for allocating attention between aircraft. These features are updated more frequently than less relevant features because these features require more attention based on conflict or climb/descent events.
2. **Anticipation Cycle:** The anticipation cycle utilizes the anticipation module to deduce the aircraft's future state. ATCos comprehend the integrated information from radar screens and project their future states to determine the relationship between aircraft pairs. After detecting a conflict, a timestamp is introduced in the mental picture, determining the remaining time to solve the conflict. An event activation between multiple conflicts revolves around the remaining conflict resolution time.
3. **Conflict Resolution Cycle:** The conflict resolution cycle identifies and solves conflicts based on urgency. A solution is selected cognitively from various resolution strategies in a mental library for the most urgent conflict. The selected conflict solution undergoes a mental simulation to check its impact on generating secondary conflicts. The resolution with a minimal negative impact on the traffic scenario is finalized and executed.

3.5. Cognitive Process Model

Developing a new ATC system for meeting the safety, efficiency, and task demands requires understanding the coordination between human operators and the available information sources. A mismatch between the controller's perceived information and task requirements increases ATC complexity and may lead to erroneous inputs [40]. Inoue et al. [59] constructed a cognitive processing model of ATCos in the en-route ATC task environment to understand the human factors and develop strategies to assist them during operation. The proposed model uses a distributed cognition framework to understand the interconnection between the agents in the task environment.

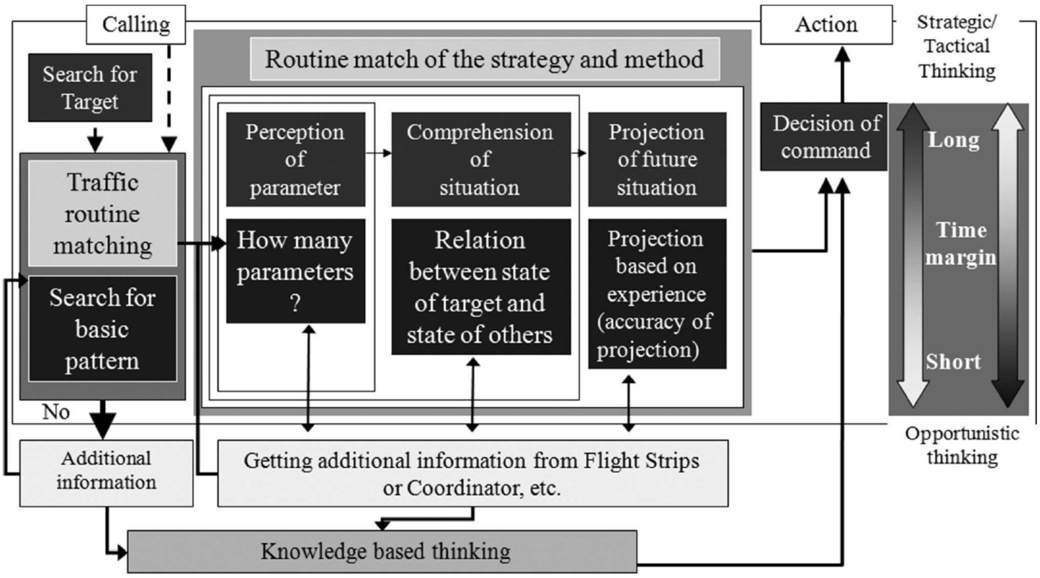


Figure 3.5: Cognitive model of Radar ATCo by Inoue et al. [59]

En-route ATCo's provided resolution maneuvers are restricted by traffic and sector characteristics, operating with constant time pressure. Traffic routine matching and strategy selection are two phases for constructing the cognitive processing model of en-route ATCos, as shown in Figure 3.5. In the traffic routine matching phase, ATCo searches for a matching model in their cognition based on the aircraft position and route displayed on the radar screen and collects additional information while taking over the controller's working position. After selecting a model matching the current situation, en-route ATCos proceed to the strategy selection phase through the decision-making process. The decision-making process relies on situation awareness, where the human operator perceives the relevant information, comprehends its meaning, and projects their states into the future. En-route Controllers collect additional information for better situation judgment and decision selection. Later, the control mode for ATCo's cognitive process depends on the time available to implement the resolution maneuver and provide safety. The proposed controller cognitive model uses the rule-based approach for decision-making and shifts to a knowledge-based approach if the appropriate model does not match the current situation.

Distributed cognition promises humans and machines to operate in the same environment by implementing the common strategies shared between them. Other advantages of creating computer models based on cognitive processing models are testing new situations and improving knowledge of ATCos during training [59].

3.6. Conclusion

Researchers measure the perceived workload by manipulating the sector complexity, including its shape, traffic characteristics, procedures, and interface design. Sector characteristics related to an individual flight are studied to build a model for guiding the ATCo's attention toward the relevant flights. The dynamic density model describes the complexity concerning the sector and traffic characteristics at any instant during conflict detection. On the other hand, the Input-Output and Relational Complexity model relates to the possible interactions of other flights relative to an individual flight by considering the sector and conflict geometry.

Personal differences such as strategies, experience, and age affect the perceived workload and the decision-making process related to ATC operations. The first step for ATCos in effective decision-making is to manage their memory efficiently while perceiving the relevant information from the radar display. Then, ATCos scans the radar display, selects a flight requiring attention, and compares its flight parameters with the rest to determine the appropriate action. To achieve this, operators can utilize several methods, and they follow a repetitive process to efficiently allocate their attention before implementing a maneuver.

ATCos develop a mental picture depicting their awareness and attention toward capturing information from the radar screen and updating it. ATCos perceive information from the radar screen, comprehend its meaning, and project its state in the future before implementing a maneuver. Routine tasks can be resolved by deriving their solution from memory storage, while new situations require additional information and knowledge-based thinking. Hence, efficient decision-making relies on the interface design and the personal skills of the ATCos.

4

Decision Support Tools

Innovative designs and approaches are introduced in the ATC domain to counter the limiting human cognitive abilities and increasing air traffic demand to expedite the flow safely and efficiently. Several models are initiated and researched to assist ATCos in conflict detection and resolution tasks. Nevertheless, ATCos use subjective strategies for these tasks, making it difficult to develop a definitive model. One way to aid ATCos in their work environment is by designing the user interface or displays to facilitate their decision-making process. ATCos scan radar displays to acquire their spatial memory of sector shape and route points and update their temporal memory of flight parameters and trajectories in determining the best action. Designing a display or implementing a tool to process information effortlessly would alleviate ATCo's workload in making suitable decisions. This chapter discusses the taxonomies of developing a CDR model and designing visual displays while focussing on attention guidance.

Section 4.1 explains the taxonomies for developing a CDR model and design system. Section 4.2 provides an overview of information and visual aspects required to design a display system for en-route ATCos. Section 4.3 defines the three approaches of developing HMI tools to alleviate ATCo's workload with examples. Section 4.4 explains the current literature on guiding ATCo's visual attention to relevant tasks and flights. Lastly, Section 4.5 provides the conclusion of this chapter.

4.1. CDR Modeling

Aviation authorities achieve aircraft separation by creating and modeling structured traffic routes. The increasing air traffic demand has led aviation authorities to consider redesigning the airspace structure, changing traffic routes, and implementing automation tools. Automated sensor-equipped systems are installed in cockpits and ground stations to alert crews during separation violations. Researchers introduce models to assist human operators in providing efficient solutions without compromising safety standards. Kuchar et al. [60] presents a synopsis of 6 taxonomies used for developing CDR models for state-based information as follows:

1. **State Propagation:** ATCos can predict future flight positions by projecting flights from their current position in 3 ways. In the nominal method, the future flight position is anticipated by projecting its current state, considering current velocity, and assuming no uncertainties. The worst-case projection method predicts conflicts by considering flights performing any possible maneuver and extrapolating their positions. In the probabilistic method, the model predicts future flight positions by accounting for and tuning the uncertainties.
2. **State Dimensions:** The current state information used in the model considers horizontal or vertical plane information or both.
3. **Conflict Detection:** Models use specific criteria and thresholds, such as look-ahead time, to detect the possibility of conflict in the scenario. Few models provide detailed information on the situation and metrics, leaving ATCos to predict conflict.

4. **Conflict Resolution:** Models provide resolution maneuvers in 4 ways. Prescribed resolution maneuvers are predefined maneuvers ATCos are trained with to reduce response time. The optimization method uses cost functions to implement a strategy with the least cost to increase efficiency. The force-field method treats each flight as a charged particle to trigger a resolution maneuver and prevent a collision. Manual solutions provide ATCos with the flexibility to devise resolutions based on human intuition, proving valuable, especially in novel or uncertain situations.
5. **Resolution Maneuvers:** The resolution maneuvers implementation involves modifying the altitude, heading, or speed parameters. While combining these maneuvers might enhance efficiency, it can also lead to increased workload and response time.
6. **Multiple Conflicts:** There are two ways to resolve numerous conflicts relative to a single flight. In the pairwise approach, human operators continuously modify an original solution to create a conflict-free resolution while avoiding secondary conflicts. On the other hand, the global solution method considers all flights in the sector to generate a robust maneuver.

The proposed model based on these taxonomies is validated by creating a deterministic trajectory model, setting up alerting thresholds, and running Monte Carlo simulations. Uncertainties are tuned to increase the robustness of the proposed model by recording the number of false alarms and LOS situations. This system design procedure applies to one scenario, and the general thresholds are set by executing multiple situations and averaging the parameters. The system performance for a few scenarios might be affected because the averaged threshold parameters do not capture the necessary performance [60].

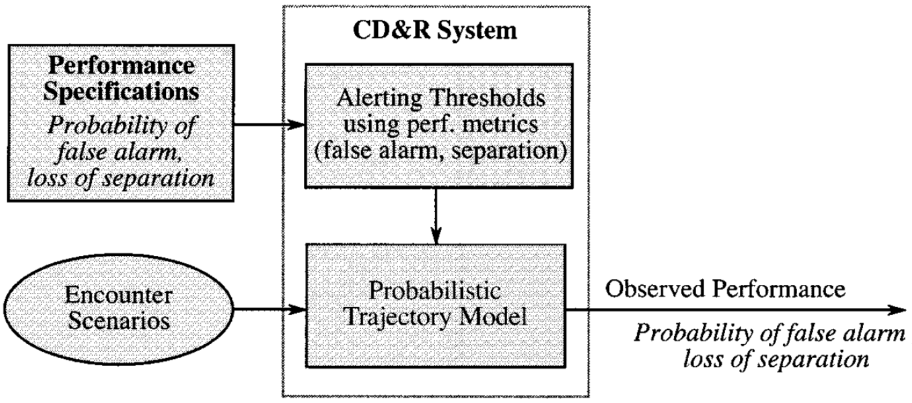


Figure 4.1: CDR design system based on performance [60]

Kuchar et al. [60] proposed an absolute approach to creating a probabilistic trajectory model based on real-time simulation information. Multiple scenarios served as the basis for evaluating the proposed model, as shown in Figure 4.1. The system design sets alerting thresholds, treating false alarms or LOS situations as criteria for computing and comparison against the desired performance through Monte Carlo simulations. The substitute alerting thresholds are no longer necessary as real-time estimation probability produces reasonable results when implementing accurate trajectory models. However, ATCo's strategies and methods of conflict resolution are entirely subjective, making it tough to model the preferred CDR system.

4.2. Display Design

Designers create displays to convey messages in the best possible way, match the human's visual form, and not trigger any erroneous inputs from them. The radar displays have sufficient information that ATCos processes before issuing a resolution maneuver. ATCos perceive flight position, meteorological, and task-related information from radar displays while operating their task environment. Additionally, the visual and graphical design should assist ATCos in meeting the task requirement of expediting air traffic flow in their sector safely and efficiently.

4.2.1. Information Complexity

En-route ATCos relies on multiple sources to get relevant information and picture the current situation. Radar displays act as an intermediary between ATCos and their task demands, and their design significantly influences the overall operation. The information from radar displays guides ATCos to adapt strategies while operating under constant time pressure. Designers consider human factors and task requirements when designing radar displays for different ATC facilities.

Friedman-Berg et al. [61] developed design principles to make future information display systems more effective and efficient compared to the current information display system. These principles consider the human factors for finalizing the information displayed on the radar screen. The four principles based on the human factors for designing the display system are as follows:

1. **Accessible:** The information within the system and the physical appliance displaying it should be accessible to human operators. The physical accessibility of the unpreferred angle and height of the display system might result in difficulty while seeking information. Poor information organization on the display leads to inefficient operations or not utilizing the display to its fullest.
2. **Current:** The display should have updated information depicting the real-world scenario to increase the operator's trust and acceptance of the display system. En-route ATCos operate in a dynamic environment, and obsolete information will lead to erroneous inputs and unbefitting decisions.
3. **Comprehensive:** The information displayed should be absolute and relevant depending on the domain and its operation. Adjacent domain information can be visible to increase overall operational efficiency. The display system should help en-route ATCos to utilize the information significantly and make appropriate decisions.
4. **Standardized:** Standardization secures other design principles clinging to the human factors, including practical implications such as training and operation management. The design schemes should be consistent throughout the domain and have minimal colors and significant organization.

Misjudgment of the information on the radar display impacts the safety and efficiency of en-route ATC operations. Measuring information complexity is relevant while designing the display system based on human factors and system requirements. Xing [62] proposed metrics to measure the information complexity by developing a relationship between the information elements factors and human information processing stages. Proposed metrics used the quality, variety, and relations between information elements and assess their significance in perception, cognition, and action stages of human information processing. Following are the complexity measuring metrics throughout these stages:

1. **Perceptual Complexity:** Humans can perceive text and graphic-related information from the displays. Text-related display attributes include display density, local character density, character size, and arrangement complexity. Graphic-related complexity can be measured through display clutter caused by irregular brightness and color, reducing human task performance.
2. **Cognitive Complexity:** Cognitive complexity relies on task characteristics such as difficulty, demands, and time pressure and human aspects such as strategies, planning, and situation awareness. Three proposed metrics to measure cognitive complexity are functional unit frequency, relations frequency, and unpredictable changes frequency.
3. **Action Complexity:** Humans are adaptive, implying they develop new strategies through their interface. Action complexity can be measured by recording and analyzing ATCo's actions and the cost of these actions. Other metric includes aggregating the task accomplishment time in sequential operations.

4.2.2. Visual Aspects

After finalizing the relevant information for operators' safe and efficient tasks, the next job is to express the display content optimally. Color schemes, chromaticity, and luminance are crucial for visual perception. Colored display elements make humans attentive and access information quickly, but focusing intensely on them might distract from other safety-critical tasks running in the background. Models that explain how the brain processes color information are currently lacking, so the chosen color palette is validated based on task performance.

During display design, the colors are selected based on human visual factors and are familiar to the en-route ATCos. Xing [63] provided guidelines for choosing colors in ATC facilities based on human cognitive abilities and task demands. Colors are primarily utilized in the en-route sector to attract attention, discern, and arrange information for meeting safety standards. The color red is employed to capture the attention of ATCos, while white, green, and yellow are favored for identification. Interruption, text directness, and visual fatigue are a few disadvantages of using colors inaccurately, affecting the task environment. Also, using multiple color schemes does not guarantee effectiveness in ATC displays and might reduce task performance.

Weather effects, SUA utilization, transitioning aircraft, and navigational radar failure are complex factors that might be mitigated by redesigning displays [64]. For transitioning aircraft, flights not requiring a vertical transition in the sector or flights arriving near the airport destination were color-coded (flight label data text) accordingly to draw ATCo's attention. Color-coding flight labels decrease information processing time for ATCos, resulting in improved situation awareness for ATCos and ensuring compliance with necessary safety standards. Although with these advantages, display clutter, legibility, and salience among an immense number of display elements question the reliability of the color-coding technique.

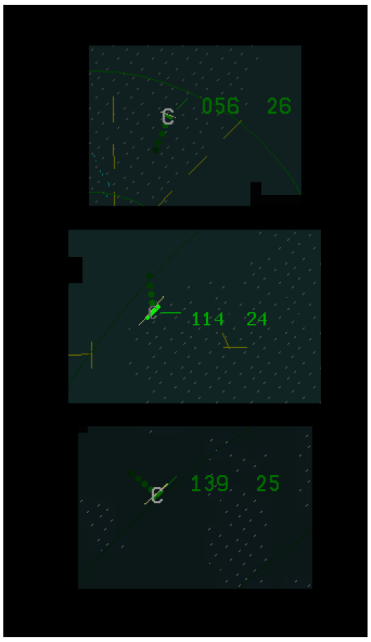


Figure 4.2: Varying luminance contrast of aircraft blips [65]

Luminance contrast is a proposed alternative to color-coding for guiding ATCo's attention and reducing their information processing time. Critical task-related display elements' brightness is relatively higher over less critical elements. Ahlstrom et al. [65] proposed user-adjustment luminance contrast for aircraft location clusters, weather symbols, and precipitation to enhance legibility and salience features. Figure 4.2 displays a few examples of varying luminance contrast of aircraft location clusters favored by ATCos. The first and second picture displays the dimmest and utmost luminance contrast concerning the background components. The third picture possesses a stable luminance contrast, satisfying legibility and salience features. Redesigning displays by adjusting the individual element's luminance based on background and user preferences seems promising in capturing ATCo's attention.

4.3. HMI Approaches

In the modern world, human operator achieves the task demands through interaction with the computer interface. The shift of interacting with the natural environment through a computer interface increases the complexity while pursuing the operation. On the other hand, Human Machine Interface (HMI) can act as a cognition tool, alleviating ATCo's mental load to expedite air traffic safely and efficiently in their sector. Hence, humans and machines collaborate as a single entity to provide decision support to human operators in complex work environments. Reynolds et al. [66] stated that a successful decision support tool (DST) system requires the human operator's acceptability and should meet the complex operational requirements. User input is a key parameter, and the developed system interface should not make human operators erroneous input.

Zingale et al. [67] provided guidelines for designing a DST based on the user interface (UI) principles and human-computer interaction (HCI) design standards. UI determines the visual and perceptual design of the elements involved in the task. A few prime principles for designing UI include minimalist design, the similarity between the actual world and the system, and the operator's choice to terminate the decision aid tool when required. HCI deals with displaying elements to make operators reach their goals without negatively affecting the operation. DST provides relevant recommendations depending on the operator's situation awareness, workload, and information reliability.

A collaborative approach between humans and technologies raises the issue of setting the priority between tasks during the operation. Flach et al. [68] proposed a few proposals to design a reliable HMI operating in a complex environment as follows:

4.3.1. Technology Centered Approach

In a technology-centered approach, the prominence is set on the competence and restrictions of the technology while developing HMI machine systems [68]. Machines are better for handling routine and repetitive tasks, saving up the time and energy of the human operator using automation. Additionally, this approach strives towards optimal solutions, and further technological developments increase operation efficiency. The underlying principles in this approach are usually black-box, provided explanations are vague, thus increasing difficulties for humans to process information. Bainbridge [4] stated that automation expands work errors and human efforts rather than reducing them. Skill degradation and passive monitoring are ironies affecting human cognitive skills and problem-solving strategies.

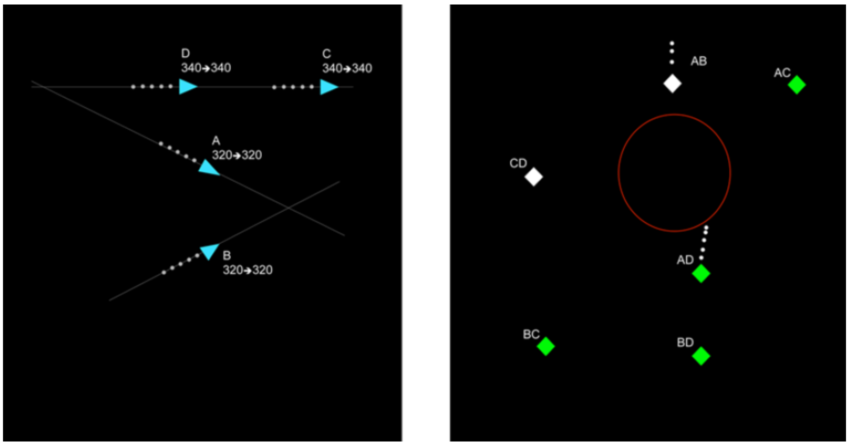


Figure 4.3: Relative position vectors - Regular radar display on left and corresponding MCD in right [69]

Vuckovic et al. [69] proposed a Relative Position Vectors (RPV) tool to enhance conflict detection, helping ATCos handle increasing traffic. An additional Multi-Conflict Display (MCD) paired with a radar display captures potential conflicts shown in Figure 4.3. MCD displays blips representing the separation between an aircraft pair, and the red circle represents the zone of minimum separation. A blip entering the red circle zone signifies that ATCo has failed to provide the minimum separation for that aircraft pair, leading to an LOS situation. The history dots alongside blips represent the aircraft separation over time. The blip color varies if the aircraft pair maintains sufficient vertical separation, as shown in Figure 4.3. In addition, selecting a blip or an aircraft highlights the necessary flights in the display. The appropriate color variation and the possibility of detecting multiple conflicts guide ATCo's attention to urgent situations. A few drawbacks include loss of situation awareness due to dual displays, no conflict resolution tool support, and separation based on current states instead of intent.

4.3.2. User Centered Approach

In a user-centered approach, the prominence is set on the competence and restrictions of the human operators while developing HMI machine systems [68]. The human factors involved while designing the HMI systems are their ability to perceive information, recollect pending tasks, identify errors, and rectify them. New technology demands in the work environment should not exceed the limiting capacities and expectations of the human operator. Landry [70] stated that developing a suitable human system integration, acknowledging situation awareness, and displaying complex information effectively under a high workload is necessary for a user-centered approach. Misunderstanding the underlying working principles or providing inappropriate support during uncertain situations are drawbacks of this approach.

Figure 4.4: Human-centered interface design proposed by Inoue et al. [71]

Inoue et al. [71] created a prototype interface design for the ATCos by considering the user's cognitive perspective. In the user-centered approach, the interaction between humans and machines is very similar to the interactions among humans. The interface design accounts for the visualization of the physical tasks and mental load as maintaining safety in the sector. The display design comprises six panels, designed by human cognitive capabilities, as depicted in Figure 4.4. The radar display panel highlights the location and flight parameters of all flights in the sector. The display control panel allows the users to change the display and examine the user input to flights. The quick action panel allows the user to issue instructions to flights and see the reminders along with instruction time. The predict area panel displays the future flight state based on the user's preferred time. The predict fix panel shows the route of the new flight entering the sector with the estimated arrival time at waypoints. The predict time panel displays the necessary information and reminders related to sector safety along a timeline. This interface design provides the independence users desire to revise their input, project future flight states, and meet system requirements. Although with numerous advantages, users can get overwhelmed with six panels in a single display, affecting their workload and situation awareness.

4.3.3. Ecological Centered Approach

In an ecological-centered approach, the prominence is set on the competence and restrictions of the work domain while developing HMI machine systems [68]. Humans are appraised as creative problem solvers, adapting to the work situation rather than having a limited working memory. Borst et al. [72] explored the impact of ecological interface design (EID) on task safety and efficiency parameters. EID allows human operators to compare the intentional and physical boundaries to make safer solutions in uncertain or new situations. EID considers the workspace constraints over constraints related to particular solutions generating sub-optimal but robust solutions. EID follows a multi-disciplinary approach, stating that the user-centered and technology-centered practices can act as supporting roles to provide an in-depth perspective [68].

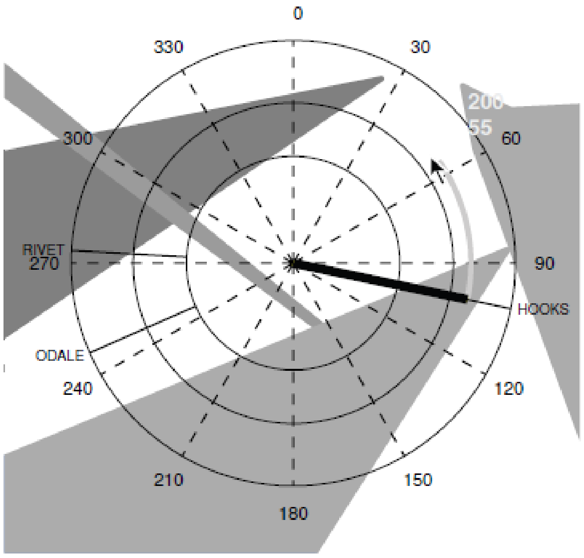


Figure 4.5: SSD for multiple conflicts [73]

Solution Space Diagram (SSD) is an EID tool that considers the set of velocities and headings to identify conflict zones for an aircraft, as shown in Figure 4.5 [73]. Smaller and larger circles around the flight represent the minimum and maximum velocities the flight can attain, and the tip represents the predicted flight position after a minute with the current speed. The shaded region is the conflict zone representing the possible sets of headings and velocities that lead to the LOS situation with another flight. The shaded areas can overlap, indicating that the selected flight has multiple conflicts. The clearance provided outside the conflict zone with a minimum deviation of the assigned route will lead to safe and efficient operation. A joint solution can allow aircraft to remain free from conflict with multiple aircraft. The conflict zones are implicitly encoded in the SSD tool, implying that the location, flight paths, and proximity of surrounding flights affect the size and orientation of the conflict zones. For example, the conflict with far-away aircraft will have a smaller conflict zone contrary to the nearby flight. Unlike the RPV tool, conflict detection is limited to the selected aircraft but provides the resolutions.

4.4. Attention Guidance

En-route ATCos continuously scans radar displays to detect conflicts within their sector and expedite the flow by assuming control of incoming flights and handing them over to the adjacent sector's ATCos. ATCos have a finite amount of attention that they can allocate to various ATC tasks, leading them to prioritize the safety between flights over memorizing their specific parameters. Inadequate attention in the ATC system leads to lower situation awareness, triggering operational errors [7]. Developing visual guidance attention displays would assist ATCos in prioritizing their tasks by limiting information processing and improving situation awareness. However, implementing automation tools affects ATCo's attention negatively by decreasing their vigilance over time and shifting their role from active decision-making to passive monitoring of ATC tasks [74].

Niessen et al. [75] explained that among the extensive information obtained during radar display scanning, objects with pertinent features are frequently activated and updated in the ATCo's mental representation. Focal objects demanding more attention are flights with vertical movement or a flight pair with high conflict probability during convergence. Extrafocal objects demanding relatively less attention are flights maintaining the required safety with no vertical maneuvers. Flights regarded as focal objects with sufficient separation are changed to extrafocal objects and demand less attention at this point. MUAC uses the VERA tool to assess flight pairs having a potential conflict. VERA tool extrapolates future flight positions based on the current radar data, predicting the distance CPA and time CPA for selected flight pair [28]. En-route ATCos can shift their attention to the next flight pair once the selected flight pair diverges.

Ohneiser et al. [8] proposed an attention guidance model to guide ATCo's attention toward important flights based on conflict alerts and handover events via visual cues. The model utilizes eye-tracking equipment and a mouse cursor on the radar display as input, representing the current area of attention. The attention guidance system has four escalation levels (Level 0 - 3) concerning ATC handover events, as shown in Figure 4.6. Level 0 identifies the state without additional cues, and Level 3 recognizes the most salient visual state. In cases of multiple unsolved ATC conflicts, the attention guidance system prioritizes them based on urgency, with the ATCO's attention directed to the conflict of the highest priority. ATCos can deescalate the attention levels of aircraft by glancing at the flight level or moving the mouse over the flight label. However, the attention guidance system will remain active in the background until the ATC resolves the event within the required threshold time. If the flight remains unnoticed for a certain time, their levels escalate, making them salient. The study further concluded that ATC systems equipped with an attention guidance system have improved situation awareness and decreased workload for ATCos.

Figure 4.6: Escalation level visual cues for handover events [8]

Object-based attention cueing differs among individuals, and increasing object-based cueing validity might negatively affect guiding attention [76]. ATCos process flight blip information through short-term memory and inadvertent cues might increase ATCo's cognitive efforts to derive information at inappropriate times. To alleviate cognitive stress and improve visual perception, replacing color-based schemes with luminance-based schemes can enhance the effectiveness of attentional suppression for task-irrelevant stimuli [77].

4.5. Conclusion

The interface design in the ATC operations to expedite the flow safely and efficiently should have the information in the radar display that is accessible, current, comprehensive, and standardized. The radar displays should support the cognitive abilities of ATCos by directing their attention to relevant information, making it salient to the ATCos via visual cues.

Machines and Humans work collaboratively to help human operators make decisions during complex work environments. The RPV tool guides the ATCo's attention toward the most urgent conflict by displaying the involved conflict flights in blips without providing resolution support. Meanwhile, the SSD tool guides ATCo's attention toward implementing an efficient solution concerning multiple conflicts for the selected flight of interest. VERA tool provides the freedom for ATCos to choose and guide their attention toward relevant flight pairs and determine their distance CPA and time CPA in supporting their decision-making and implementing the action at the right moment.

An interface model can guide ATCo's attention to relevant flights based on ATC events, such as conflict detection or handover events, via visual cues. Color coding and luminance contrast are the most suitable visual cues to direct the ATCo's attention toward the relevant flights. Color coding cues possess the risk of display clutter, whereas luminance contrast enhances the salient features of human operators.

5

Filtering Flights Mechanism

Two different flights filtering mechanisms have been formulated based on the research objective:

To develop a model that guides the ATCo's visual attention toward relevant flights relative to the potential control action for the selected flight of interest during ATC operations and evaluate it with a simulator experiment.

Section 5.1 provides a general filtering structure to find relevant flights relative to the selected flight of interest. Section 5.2 and Section 5.3 introduce state-based and intent-based filtering mechanisms with their preferred parameters. Section 5.4 provides an attention guidance model to make relevant flights salient to en-route ATCos. Lastly, Section 5.5 provides the conclusion of this chapter.

5.1. Filtering Structure

En-route ATCos scans the radar display to find and select a flight requiring attention and compare its flight parameters to relative flights before decision selection and action implementation. The flight location is depicted and represented in the guise of blips on the radar display, where each blip corresponds to the position of an individual aircraft in the airspace, providing valuable real-time information to ATCos for effective operations, as shown in Figure 5.1.

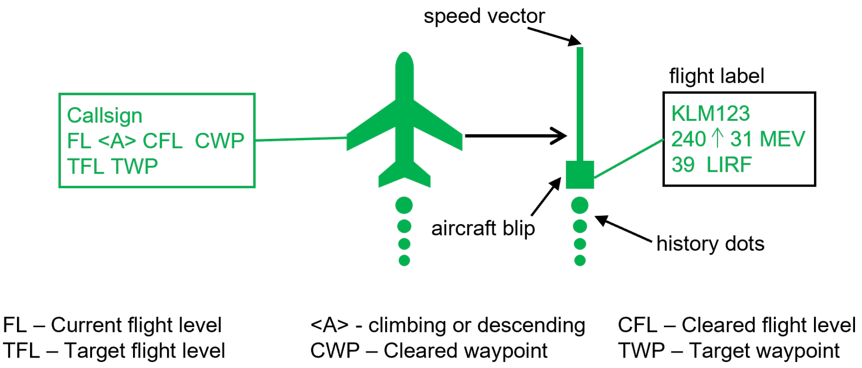


Figure 5.1: Flight label description with parameters

Selecting a flight of interest can be motivated by multiple reasons, including expediting air traffic, ensuring minimum separation between flights, and facilitating flights to reach their target levels. These are some criteria for assigning attention to a particular flight. After selecting a flight of interest, ATCos visually compares the flight parameters displayed on the flight labels to assess the impact of potential flight control action on the sector safety and avoid secondary conflicts. A filtering flight algorithm suggests assisting ATCos in neglecting the flights that do not have potential interaction with the selected flight of interest during control action implementation. The structure of the algorithm is as follows:

1. **Altitude Overlaps:** ATCos conducts a preliminary assessment of the flight altitudes displayed on the radar to ensure adequate vertical separation between flights. Sufficient vertical separation obviates the necessity of further inspecting the flight headings as long as the vertical separation is maintained. Consequently, flights that share overlapping altitudes between the current and target flight levels of the selected flight of interest are considered relevant and require closer examination.
2. **Space Overlaps:** Further advancement is applied to narrow down the flights that share overlapping altitudes with the selected flight of interest. The heading parameter determines the convergence criteria of the flights to check whether their trajectories are parallel, converging, or diverging to the selected flight of interest, ensuring horizontal separation. Flights sharing a common waypoint or suspected to have a crossing to the chosen flight of interest are critical.
3. **Time Overlaps:** The subset of flights possessing overlapping altitudes and spatial proximity undergoes further refinement through additional temporal considerations. The flights first reaching the intersection point relative to the selected flight of interest are determined using speed-distance calculations. Estimated arrival time to the waypoint or intersection point assists ATCos in determining the closest relative position the potential interaction flight will obtain relative to the selected flight of interest.

Flights that satisfy all three mentioned criteria receive the designation of potential interaction flights relative to the potential control action for the selected flight of interest, and the remaining flights are considered irrelevant.

5.2. State Based Filtering

In state-based trajectory prediction, flights are projected forward based on their current parameters to ascertain the nearest point of approach with other flights in the future. The VERA tool relies on the CPA principle, enabling the determination of the minimum distance and the time required to reach that minimum distance between two dynamic objects, assuming flight parameters remain unchanged. For this prediction, the model presumes that flights follow a straight path from their current position and do not consider their flight plans, as shown in Figure 5.2.

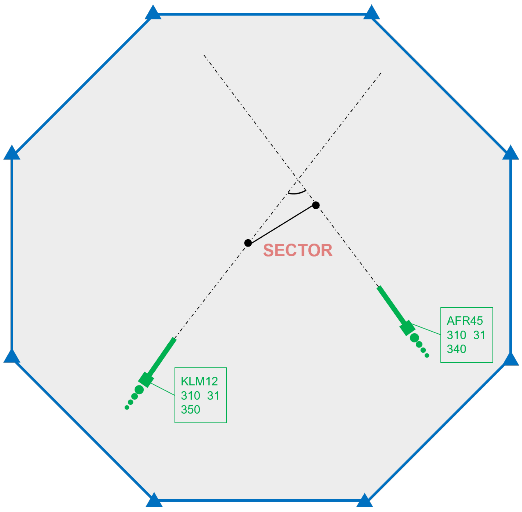


Figure 5.2: State-based flight extrapolation

Flights with overlapping altitudes relative to the potential control action for the selected flight of interest are extrapolated based on their current parameters to assess the possibility of a horizontal separation violation. These subsets of flights can undergo further refinement to include only relevant flights by applying appropriate thresholds to the following state-based parameters.

1. **Distance:** The relative distance between the potential flight and the selected flight of interest is determined based on the current flight position on the radar display. Flights closer to the flight of interest capture attention more quickly than those positioned farther away.

2. **Distance CPA:** The closest distance between the potential flight and the selected flight of interest is determined by extrapolating their trajectories from their current positions. Flight pairs with a CPA distance between 7 NM and 10 NM are classified as critical, requiring attention.
3. **Time CPA:** Time CPA is the time required for flights to reach their minimum distance from the current position update. ATCos usually adopt a look-ahead time of 5 to 10 minutes to foresee the possibility of LOS situations depending on the sector shape and traffic density.
4. **Crossing Angle:** The angle between two crossing flights or possible interaction points is termed the crossing angle. Flights having a small crossing angle acquire attention sooner than flights with a larger crossing angle. In other words, overtaking flight pairs are detected sooner than head-on flights.

The mentioned parameters serve as essential criteria for ascertaining the convergence of a flight pair. In cases where the flight pair has already diverged, the distance CPA and relative distance exhibit an increasing trend, leading to the absence of potential crossing point detection ahead. Flights that fulfill specified or calibrated thresholds of these parameters qualify as having possible interaction, thereby categorizing them as relevant to the potential control action for the selected flight of interest. Figure 5.3 displays the flowchart of the state-based filtering mechanism.

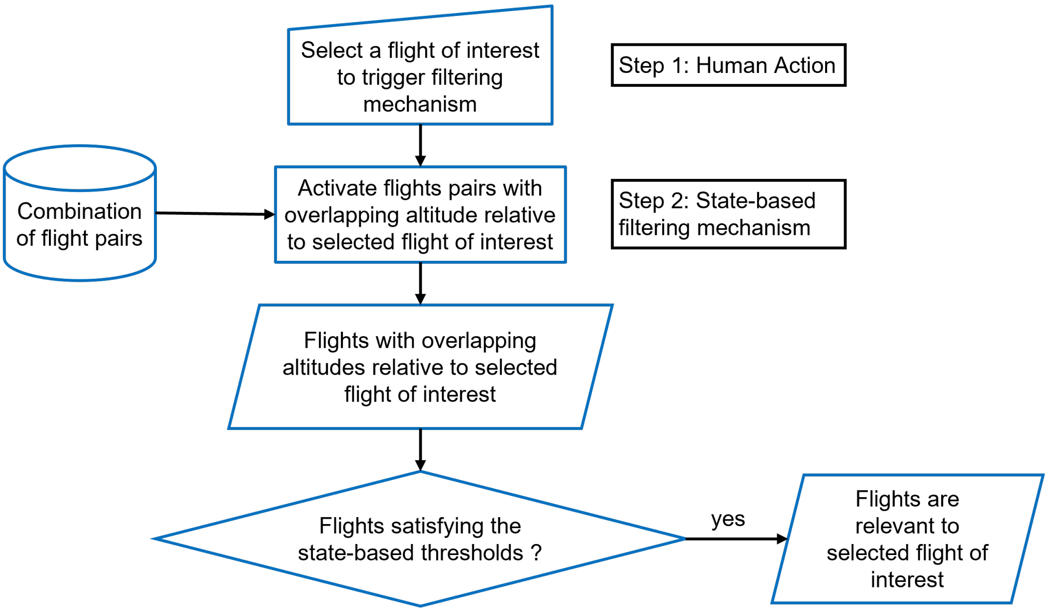
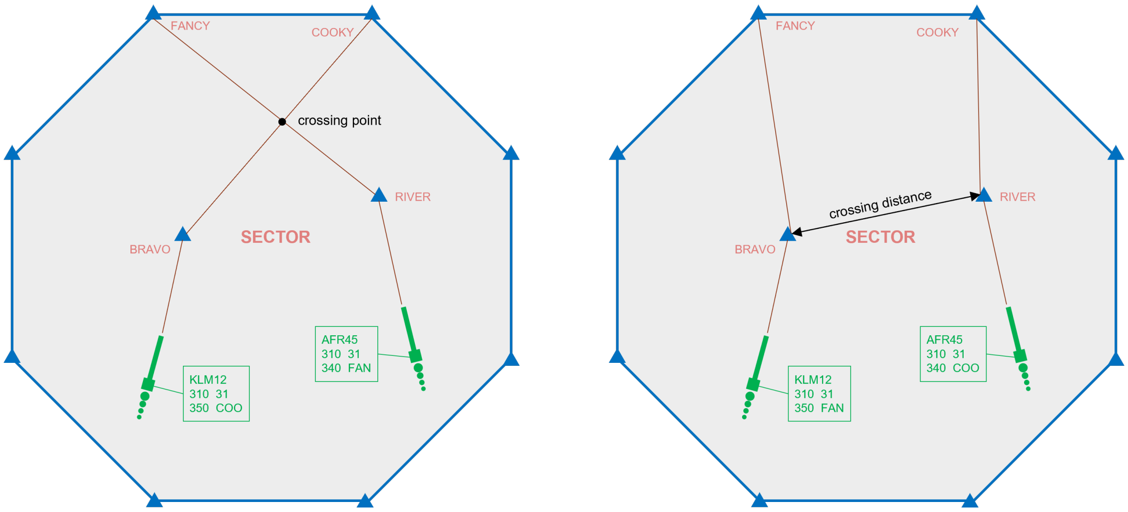


Figure 5.3: State-based filtering mechanism flowchart

5.3. Intent Based Filtering

In a state-based approach, the failure to consider flight intent leads to the possibility of false conflict alerts or potential interactions relative to the potential control action for the selected flight of interest. ATCos receive flight plans of the flights operating in the sector, which state the routes flights will travel, along with their estimated arrival time at waypoints. TBO implementation in future ATM systems will substantially mitigate uncertainties and enhance flight predictability to make better ATC decisions.

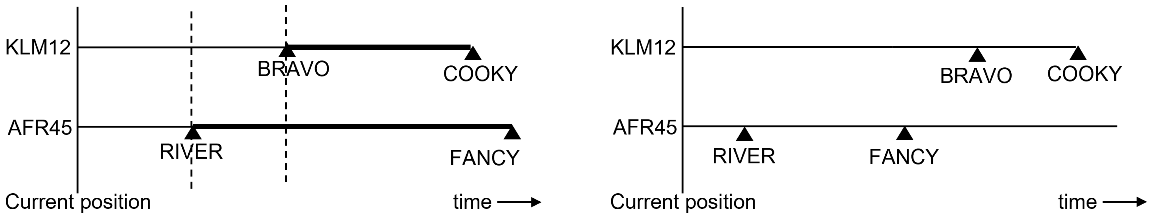
Flights with overlapping altitudes relative to the potential control action for the selected flight of interest are extrapolated based on their flight intent and using a geometrical approach to assess the possibility of horizontal separation violations. Subsequently, potential interaction flights undergo further refinement based on spatial parameters, treating the path between two route points as a line segment. The flight paths of the selected flight of interest and potential interacting flight are then thoroughly examined to determine their minimum distance, representing the initial step in clarifying the flight relevance to the chosen flight of interest. Figure 5.4 illustrates two distinct possibilities of spatial conditions: flights with a crossing point through their intent and flights with trajectories closer to each other but without intersection.



(a) Crossing flights trajectory **(b)** Non-crossing flights trajectory

Figure 5.4: Intent-based flight extrapolation - Spatial condition

After evaluating the spatial parameters, the model analyzes the temporal aspects of the flight path to improve the accuracy of identifying flights relevant to the potential control action for the selected flight of interest. The estimated arrival time of the flight path through the route points is considered for the potential interaction flight and selected flight of interest to inspect if they are overlapping. Figure 5.5 shows the two possibilities of flights having an overlapping time and flights not having an overlapping time through the flight intent.



(a) Overlapping time through trajectory **(b)** Non-overlapping time through trajectory

Figure 5.5: Intent-based flight extrapolation - Temporal condition

A threshold value for intent-based extrapolation is required to specify how close the potential interaction flights are relevant to the potential control action for the selected flight of interest. The **crossing distance** threshold parameter, a subset of spatial conditions, is then employed to refine further the potential interaction flights relevant to the chosen flight of interest after inspecting spatial and temporal parameters. In cases where flights exhibit an actual crossing point through intent, the CPA distance from the preceding waypoint is computed and assigned to the crossing distance parameter. Alternatively, for flights that have trajectories nearby but do not intersect, the minimum distance between their flight paths (represented as line segments) is calculated and assigned to the crossing distance parameter. Flights that satisfy the crossing distance threshold qualify as having possible interaction, categorizing them as relevant to the selected flight of interest during control action implementation.

Figure 5.6 displays the flowchart of the intent-based filtering mechanism. Flight plans are updated regularly through the expediting operation or preferred maneuvering choice, meaning that the flights satisfying the conditions earlier are now irrelevant, considering they have already diverged. The intent-based filtering captures a broader aspect of the relevant flights relative to the selected flight of interest based on a geometrical approach stating that non-urgent flights also require attention during control action implementation.

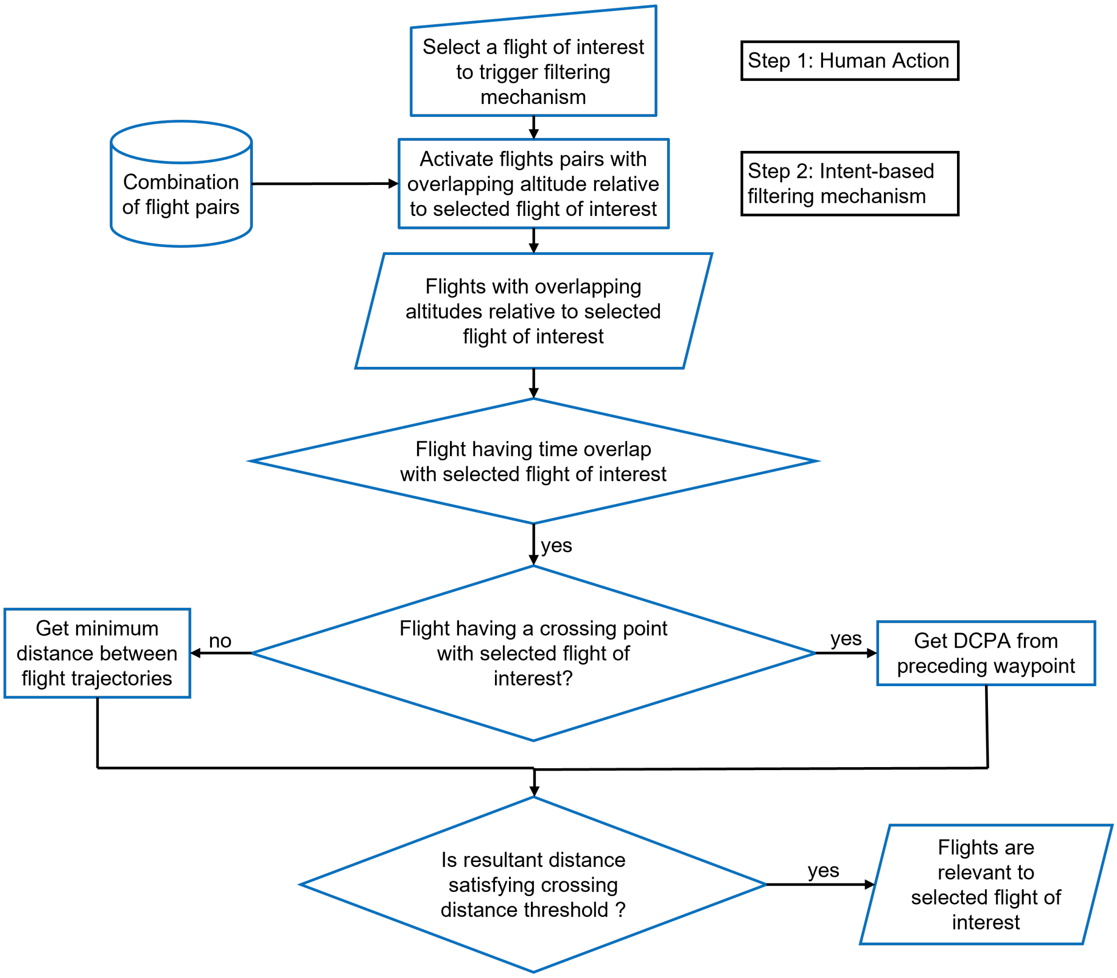


Figure 5.6: Intent-based filtering mechanism flowchart

5.4. Attention Guidance

The state-based and intent-based filtering mechanism plays a crucial role in identifying and filtering flights within the sector that have the potential to impact the selected flight of interest, thus signifying their relevance during control action implementation. En-route ATCos attach significant importance to determining relevant flights concerning the control action to the selected flight of interest, as it directly supports their visual and cognitive abilities to compare the flight parameters displayed in the flight label in effectively managing air traffic.

Providing visual cues to the relevant flights is crucial for mitigating the ATCo's workload when searching for and processing flight parameters information. Among various methods for guiding visual attention, color coding and luminance contrast are two prominent approaches used to direct the attention of ATCos toward specific objects on the radar display. In this context, luminance contrast is the preferred method for directing visual attention, making flights relevant to the potential control action for the selected flight of interest more noticeable to ATCos.

Rather than increasing the luminance of relevant flights in the sector, the model adopts a different approach by decreasing the brightness of irrelevant flights concerning the potential control action to the selected flight of interest. This method supports the salience feature, as depicted in Figure 5.7.

Importantly, reducing the irrelevant flights' luminance does not cause them to vanish completely in the background; rather, they gradually fade to avoid startling effects on ATCos during visual processing.

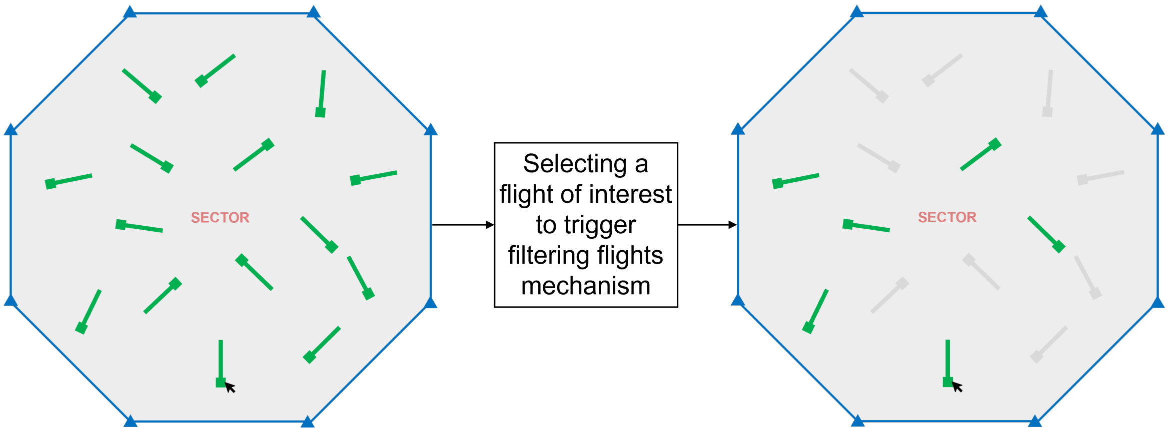


Figure 5.7: Visual attention guidance relative to potential control action for selected flight of interest

5.5. Conclusion

Two flight filtering mechanisms have been proposed based on the spatial and temporal parameters to filter the relevant flights relative to the potential control action for the selected flight of interest. The initial step of both filtering mechanisms is to consider the flights having overlapping altitudes relative to the potential control action for the selected flight of interest.

The state-based mechanism filters flights based on the current parameters using distance, distance CPA, time CPA, and crossing angle parameters. The state-based filtering mechanism is accurate for the shorter-time scale, implementing a locally optimal solution in the sector. The intent-based mechanism filters flights based on the flight intent, considering space-time overlaps and the crossing distance parameter. The intent-based filtering mechanism motivates ATCo to implement a global conflict-free trajectory solution for the selected flight of interest by considering the flight's entire trajectory. These parameters are tuned to match ATCo's preference while expediting the flow through the sector.

To make the relevant flights salient to ATCos, the irrelevant flight fades away by decreasing its luminance after selecting a flight of interest. Researchers need to experiment to measure the effectiveness of these filtering models in terms of safety, efficiency, and workload compared to regular operations.

6

Preliminary Experiment Design

Chapter 5 provides the state-based and intent-based filtering mechanism to filter out the relevant flights relative to the potential control action for the selected flight of interest. The irrelevant flights will reduce their luminance, making relevant flights more salient to ATCos to the chosen flight of interest. An experiment design is required to check the feasibility and the effectiveness of the provided Attention Guidance Model in the current ATC operations to answer the following research question:

How does a visual attention guidance model for En-route ATCos toward relevant flights relative to the potential control action for the selected flight of interest affect the safety and efficiency of ATC operations and human factors of the ATCos?

In the experiment phase, participants expedite the air traffic safely and efficiently with their en-route sector. Section 6.1 provides the experiment variables required to test the hypotheses. Section 6.2 provides the experiment hypotheses to test the proposed attention guidance model's effectiveness based on filtering mechanisms relative to the control action for the selected flight of interest. Finally, Section 6.3 presents the experiment setup, encompassing participant requirements, apparatus, and procedure.

6.1. Experiment Variables

In this experiment, we validate our hypotheses by manipulating the independent variables to measure the dependent variables while considering the control variables.

6.1.1. Independent Variables

Independent variables are manipulated in the experiment to study their significance in operation by measuring corresponding dependent variables' value and verifying hypotheses. In this research, the filtering mechanism used for expediting the flow safely and efficiently in the sector undergoes manipulation to measure the dependent variables as follows.

1. In no filtering-based mechanism, participants are provided with no visual guidance support relative to the selected flight of interest.
2. In a state-based filtering mechanism, visual attention guidance is provided to participants by fading away irrelevant flights relative to the potential control action for the selected flight of interest based on the current parameters. The state-based filtering mechanism displays relevant flights accurately over a shorter time horizon for implementing local optimal solutions in the sector for the selected flight of interest. The parameters for the state-based filtering are distance, distance CPA, time CPA, and crossing angle. The thresholds for these parameters are set appropriately before the start of the experiment and are equal among all participants.
3. In an intent-based filtering mechanism, visual attention guidance is provided to participants by fading away irrelevant flights relative to the potential control action for the selected flight of interest based on flight intent. The intent-based filtering mechanism is effective over an extended time

horizon for implementing global conflict-free solutions in the sector, as it accounts for the entire trajectory of the selected flight of interest. Flights with overlapping spatial and temporal parameters are refined further by applying the crossing distance parameter. The threshold for this parameter is set appropriately before the start of the experiment and is equal among all participants.

Humans are adaptive in nature and can recognize situations effortlessly, leading to a possibility of confounding in the experiment design. Participants can avoid repetition in experiment scenarios by changing a few segments, such as rotating or mirroring the sector shape, changing callsigns, and providing the altitude change. Since there are three experimental conditions, there must be a minimum of three scenario re-designs.

6.1.2. Dependent Measures

Dependent variables are the measures influenced or impacted by manipulating the independent variables in an experiment study. The dependent variables' values validate the experiment hypotheses and provide a conclusion to the research. This research records and compares the effects of guiding visual attention to relevant flights, relative to the control action for the selected flight of interest, on the safety, efficiency, control activity, and workload of ATC operations contrasted to regular operations. The variables available for use in this research, along with their data types, include:

Safety:

- Number of conflict alerts - represented as ratio data type.
- The minimum separation between flights in the sector - represented as ratio data type.
- The conflict resolution time - is represented as a ratio data type.

Efficiency:

- Average heading deviation from the flight trajectory - represented as ratio data type.
- Additional track miles covered by flights - represented as ratio data type.

Workload and Control activity:

- Number of times VERA tool activated - represented as ratio data type.
- Number of flights cleared to target waypoints - represented as ratio data type.
- Number of flights cleared to target altitudes - represented as ratio data type.
- Subjective workload ratings - represented as interval data type.

The research will measure the dependent variables by manipulating the independent variable, the filtering flight mechanism, to test the hypotheses and draw conclusions for the research question. Additionally, the questionnaire session utilizing the data related to trust, reliance, and boredom will be represented as an ordinal data type, recording the feedback of the visual attention guidance tool relative to the selected flight of interest.

6.1.3. Control Variables

The control variables are held constant throughout the experiment because they might influence the results, making the research biased. They have the potential to become independent variables in the supplementary experiments but are not of prime interest in this current experiment. If the control variables design is inadequate, it may lead to confounding factors that could correlate with the independent and dependent variables. In this research, the identified control variables are Traffic and Sector Shape.

Sector Shape is maintained constant throughout the experiment while manipulating the independent variables to measure dependent variables. ATCos have a lower look-ahead time in narrow sectors compared to broad sectors. The chosen sector shape would be an eight or ten-sided polygon geometrical shape. The selected sector shape should be symmetrical, preventing participants from recognizing the sector after rotating or mirroring it for different experiment scenarios to restrain confounding factors.

Traffic is maintained constant throughout the experiment while manipulating the independent variables to measure dependent variables. ATCos have a lower look-ahead time in high-density traffic compared to the lower-density. Higher traffic density scenarios are derived from the SESAR documents to make participants rely on the visual attention guidance tool while expediting the traffic in the sector to check its validity. The number of flights in the scenario will be the same throughout the experiment. However, the experiment scenarios require further clarification regarding the traffic distribution and aircraft types.

Participants can devise their strategies and provide resolution maneuvers to flights by adjusting their speed, altitude, and heading or a combination of these maneuvers to ensure a safe and efficient flow within the sector. Additionally, participants have access to the VERA tool, enabling them to ascertain the relative heading, relative distance, distance to CPA, and time to CPA of a flight pair based on the current flight parameters.

6.2. Hypotheses

A hypothesis is the researcher's tentative prediction towards the research, which is testable during the experiment. They provide a link between the manipulative independent variables and measurable dependent variables. Following are the hypotheses related to this research:

Hypothesis 1: Number conflict alerts will be lowest when using intent-based visual attention guidance, followed by state-based visual attention guidance, and highest when using no visual attention guidance.
Reason: Displaying relevant flights relative to the potential control action for the selected flight of interest prevents ATCos from implementing maneuvers that induce secondary conflicts while expediting the flow in the sector. Intent-based filtering has a broader time horizon by considering the complete flight intent, making ATCos choose resolutions with fewer secondary conflicts over state-based filtering.

Hypothesis 2: Efficiency will be highest when using intent-based visual attention guidance, followed by state-based visual attention guidance, and lowest when using no visual attention guidance.
Reason: Displaying relevant flights relative to the potential control action for the selected flight of interest assists ATCos in implementing efficient maneuvers with fewer trajectory deviations and additional flown track miles. Intent-based filtering has a broader time horizon by considering the complete flight intent, providing ATCOs to skip intermediate waypoints and clear the flight to a globally optimal solution over state-based filtering of locally optimal solutions.

Hypothesis 3: State-based and Intent-based attention guidance tools will have improved control activity compared to no attention guidance by clearing more flights to their target waypoints and altitudes.
Reason: The attention guidance tool based on a filtering mechanism alleviates the ATCo's additional cognitive and perceptual efforts of comparing visual flight parameters displayed on the radar screen while expediting the flow. It should lead to a noticeable improvement in awareness and control activity of ATCos to clear the flights to their target states while maintaining safety and efficiency.

Hypothesis 4: Workload will be highest when using no visual attention guidance, followed by intent-based visual attention guidance, and lowest when using state-based attention guidance.
Reason: Displaying relevant flights relative to the potential control action for the selected flight of interest assists ATCos in using lesser times of the VERA probe tool to identify the possible proximity between the flight pairs. Intent-based filtering having a broader time horizon leads to increased relevant flights relative to the selected flight of interest, relying more on the VERA probe tool, leading to a higher workload than state-based filtering.

6.3. Experiment Setup

This section provides a formal overview of the practical aspects of the experiment design, encompassing the necessary apparatus and participants' requirements for data collection, as well as detailing the specific procedures and tasks they are required to undergo.

6.3.1. Participants and Apparatus

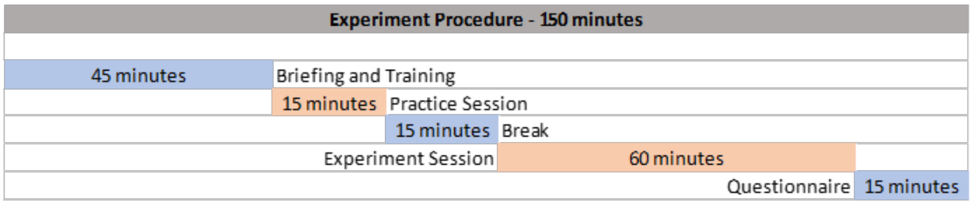
Professors and Ph.D. candidates well-versed in ATC operations from the Faculty of Aerospace Engineering at TU Delft are the selected participants for this experiment. The experiment utilizes a within-participants approach, where each participant experiences three conditions: no filtering, state-based filtering, and intent-based filtering visual guidance tools during the experiment task. This approach is adopted to eliminate personal differences between participants and to facilitate an objective comparison of the experimental outcomes. Participants will sign a consent form before the experiment, permitting us to use their experiment data for present and future research studies.

The experiment utilizes SectorX, a Java-based simulator developed by TU Delft, to accurately replicate a valid en-route radar display. Throughout the experiment phase, participants engage with the simulated flights by issuing clearance commands through CPDLC and no radio communication. Participants navigate the simulation interface using conventional computer input devices, specifically a standard mouse and keyboard. The experiment occurs at the ATM Laboratory within the Faculty of Aerospace Engineering at TU Delft.

6.3.2. Experiment Phase

In the experimental phase, researchers collect data to empirically test hypotheses by guiding participants through the following experimental procedure and involving them in corresponding tasks:

1. **Briefing and Training:** The briefing process entails familiarizing the participants with the simulator and the experiment while refraining from disclosing potentially sensitive information. During this phase, participants are informed about the flight label description, expediting air traffic safely and efficiently, and the application of the VERA tool in the experiment. Subsequently, participants undergo training to use this information within the simulator experiment, and researchers intervene to address potential self-fulfilling prophecies. The briefing and training phase would take approximately 45 minutes.
2. **Practice Session:** Participants undergo a low-traffic density simulation scenario lasting approximately 15 minutes to practice and enhance confidence for the experiment task. The researcher exposes the participants for practice sessions by having either multiple short scenarios or a single long scenario without implementing the filtering flights mechanism. The training and practice session provided effectively fosters motivation for experimentation without inducing fatigue.
3. **Break:** After the briefing and practice sessions, the researchers provide a 15-minute break for participants to energize themselves with snacks and drinks before proceeding to the experiment session.
4. **Experiment Session:** The experiment session comprises three individual experiments, each lasting approximately 20 minutes, resulting in a total duration of 60 minutes. The three individual experiments are simulations with no filtering, state-based, and intent-based filtering mechanisms relative to the selected flight of interest. The data collected during the experiment sessions validate the hypotheses and provide a conclusion to the research question. The order of the individual experiments among the participants is jumbled to prevent the confounding factor.
5. **Questionnaire:** Finally, participants are encouraged to provide 15 minutes of feedback related to the human factors, such as trust, reliability, and boredom, and the operational factors, such as strategies and feasibility concerning the filtering flight mechanism.



Experiment Procedure - 150 minutes	
45 minutes	Briefing and Training
15 minutes	Practice Session
15 minutes	Break
Experiment Session	60 minutes
Questionnaire	15 minutes

Figure 6.1: Experiment Procedure Planning

Each participant will partake in one session lasting approximately 150 minutes, as depicted in Figure 6.1.

7

Conclusion and Next Steps

This chapter provides a closure to the research related to guiding visual attention to relevant flights in supporting en-route ATCos to make efficient decisions by interpreting the consequences of their potential control action for the selected flight of interest that affects the sector. Section 7.1 provides a conclusion, and Section 7.2 provides the next steps required to make the research effective.

7.1. Conclusion

Increasing global air traffic has made ATCo's job critical for expediting air traffic safely and efficiently within their sector, provided with their limited perceptual and cognitive abilities. One of the challenges for ATCo is to distribute their attention toward the relevant information displayed on the radar display during decision-making, leading to inefficient responses and increased workload. The SESAR project aims to develop HMI tools, assisting their vision of reforming the current ATM system and implementing direct routes within unified European Airspace.

The literature revealed that selecting a flight of interest demanding attention can be motivated by multiple reasons, such as maintaining minimum separation, expediting its flow, and clearing it to its target altitudes. After selecting a flight of interest, ATCos visually compares the flight parameters displayed on the flight labels to assess the impact of potential flight control action on sector safety. The parameters inspected are altitude, heading, and speed while extrapolating their flight trajectories based on a subjective look-ahead time. Flights maintaining sufficient vertical separation and diverging flights require the least attention from ATCos during radar scanning. The factors such as the flight's current position, converging angles, and the possible closest approach point are the trigger points of capturing the ATCo's attention. ATCo's attention to specific flights is not always fixed and frequently changes with the updated flight positions.

The proposed model operates on a filtering mechanism that guides ATCo's attention toward relevant flights relative to the potential control action for the selected flight of interest. The relevant flights are the flights that may have a possible interaction with the selected flight of interest in the future while implementing the control action. To make the model salient to ATCos, the irrelevant flights relative to the selected flight of interest will lose their luminance while implementing the control action. The proposed model captures the ATCo's pre-attentive phase of visual perceptual and cognitive information required to interpret the consequences of control action for the selected flight of interest while expediting the air traffic safely and efficiently through the sector. The proposed visual attention guidance tool can enable inexperienced ATCos to exhibit behavior similar to that of professionals. Hypotheses posit that capturing the ATCo's pre-attentive phase relative to the potential control action for the selected flight of interest will enhance overall safety and efficiency while reducing control activity and workload.

Researchers experiment using SectorX, a Java-based simulator developed by the Faculty of Aerospace Engineering at TU Delft. Participants in this experiment include Professors and Ph.D. candidates experienced in ATC operations. The goal is to validate the hypotheses and assess the proposed visual attention guidance model's impact on safety, efficiency, control activity, and workload.

7.2. Next Steps

Amber et al. [78] performed exploratory research to identify the traffic characteristics contributing to the complexity of an individual flight. The research aimed to divide a set of flights as ”basic” and ”non-basic” based on the subjective complexity ratings to assign certain flights to automation. The research introduced a single flight of interest in a static scenario, and ATCos had to choose other flights that may potentially interact with the defined flight of interest while expediting its flow. The researcher manipulated specific traffic characteristics to identify the relevant flights that could influence the complexity of the introduced flight of interest as follows:

Time to LOS:

- Short - 0 to 300 seconds
- Medium - 300 to 600 seconds
- Long - 600 to 900 seconds

Conflict-free direct route:

- Interactions on current trajectory (I)
- Interactions on current trajectory (II)
- Interactions on current flight level

Flight level change:

- Small descent - 0 to 4000 feet
- Small climb - 0 to 4000 feet
- Large climb or descent - greater than 4000 feet

Four distinct ATCos assigned to each sector had to choose flights that they thought were relevant to the introduced flight of interest. The position of flight of interest varied to four locations in the scenario, tallying up to 36 distinctive experiment scenarios for the Brussels sector.

Researchers chose the Brussels sector for the examination because of its narrow shape and higher traffic density. Researchers extract the relevant flights selected by the ATCos relative to the introduced flight of interest for the 36 experiment scenarios, along with their proximity values relative to the flight of interest. The values extracted from the relevant flights were the relative distance, distance CPA, time CPA, crossing angle, and the number of ATCos selecting that flight. The preference for the relevant flights varies individually based on their experience and traffic scenario, making it tough to build a ”One Size that Fits All” model.

Researchers propose a global approach to define the required parameter thresholds for the relevant flights considering these 36 experiment scenarios. They can set the number of relevant flights that relatively decreases as a threshold to define a flight relevant for that particular parameter. As the parameter values increase, there is a natural decrease in the number of flights that appear to be relevant. The derived threshold of the distance CPA sets the threshold for the crossing distance parameter in the intent-based filtering mechanism.

The knee method is well-suited for identifying an optimal value or threshold for parameters that display a decreasing trend. Researchers plot a metric (e.g., the sum of squared distances or variance) against a range of parameter values and identify the ”knee” point, where the curve levels off or changes slope significantly as the optimal parameter or threshold value. They use the knee method to fix thresholds for a filtering parameter from the derived proximity values of selected relevant flights relative to the introduced flight of interest for 36 traffic scenarios and 4 ATCos. They measure the success rate of filtering algorithms by comparing the flights displayed by the algorithms and the flights selected by the ATCos relative to the introduced flight of interest. An experiment takes place after finalizing the thresholds and calculating the success rates of the filtering algorithms.

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Part III

Appendices

A

Invitation and Consent Form

Participant Invitation - Thesis Research

You are being invited to participate in research titled **Guiding Visual Attention to Relevant Flights in Supporting Air Traffic Controller Decision Making**. This study is being done by Ajay Kumbhar Vijay Kumbhar from the TU Delft under the supervision of Dr. Ir. Clark Borst.

The research study aims to investigate the interpretation of the consequence of action while expediting the flow in the sector, with special attention to the performance, safety, and efficiency of the proposed system and the participant workload. This experiment will take approximately 3 hours to complete. The experiment is structured as follows:

1. Training and Briefing - 50 minutes
2. Practise Phase - 30 minutes
3. Break - 10 minutes
4. Measuring Phase - 60 minutes
5. Questionnaire - 15 minutes

The data will be used to analyze a new Visual Attention Guidance tool based on a flight filtering mechanism relative to the preferred clearance command, and the results will be published as part of an aerospace engineering master thesis. Your task will be to expedite the traffic in the Upper Control Area (UTA) in the simulation environment called SectorX. After each run, you will be asked to indicate the experienced workload during the last task. Finally, at the end of the experiment, a questionnaire will be provided, which you are kindly asked to participate in.

Your participation in this study is entirely voluntary, and you can withdraw anytime. You are free to omit any questions. Since a copy of the informed consent form will be stored by the responsible researcher, the participant has the right to be forgotten.

Thank you in advance for participating in this experiment and do not hesitate to contact me in case of questions or remarks.

Contact Information
Researcher

Ajay Kumbhar Vijay Kumbhar
a.k.vijaykumbhar@student.tudelft.nl
+31 6 13954232

Contact Information
Supervisor

Dr. Ir. Clark Borst
c.borst@tudelft.nl
+31 15 2789099

Consent Form

Please tick the appropriate boxes.

Taking part in the study	**Yes**	**No**
I have read and understood the study information dated xx/01/2024, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	○	○
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	○	○
I understand that taking part in the study involves having simulation data automatically stored in an anonymous manner when completing the experiment.	○	○
I understand that taking part in the study involves me answering questions to surveys.	○	○
I understand that taking part in the study involves taking notes about the things I do or say during the experiment.	○	○
Use of information in the study	**Yes**	**No**
I understand that information I provide will be used for analysis and scientific publications on an anonymous basis.	○	○
I understand that personal information collected about me that can identify me, such as name and email address, will not be shared beyond the study team.	○	○
I agree that my simulation data can be quoted in research outputs on an anonymous basis.	○	○
Future use and reuse of information by others	**Yes**	**No**
I give permission for the recorded simulation data and answers to survey that I provide, to be archived in secure folders, so it can be used for future research and learning. All data is stored anonymously. Access is safeguarded and not to be used for commercial use	○	○

Signatures

________________________ __________________ ___________

Name of participant Signature Date

----- To be completed by researcher -----

I have accurately read out the information sheet to the potential participant, and to the best of my ability, ensured that the participant understands to what they are freely consenting.

________________________ __________________ ___________

Name of researcher Signature Date

Ajay Kumbhar Vijay Kumbhar | +31613954232 | a.k.vijaykumbhar@student.tudelft.nl

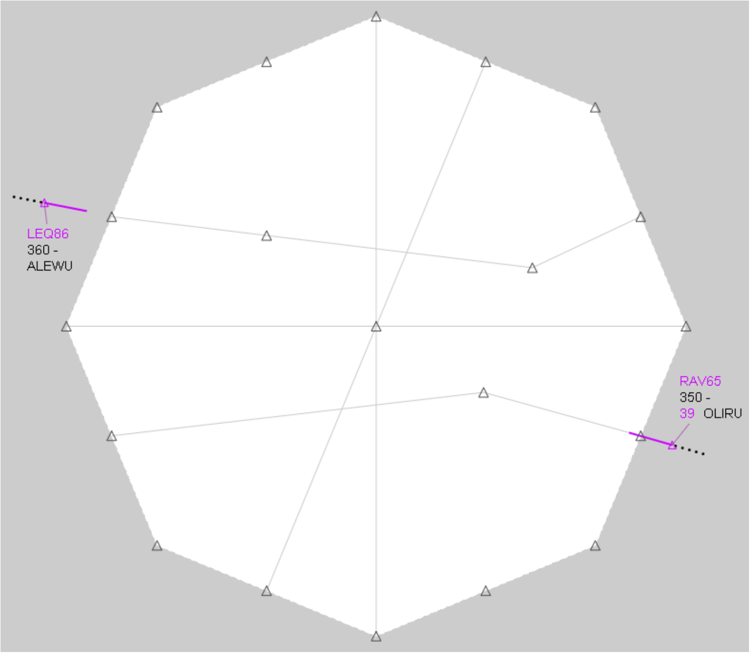
B

Experiment Procedure

The Experiment session lasted approximately three hours and was divided into four phases. The participants were provided with the briefing manual displayed in Appendix E, explaining the simulator interface and the flight filtering interface three to five days before their experiment session. The manual also served as a script for the researcher to train participants.

The first phase was a training phase consisting of seven training scenarios, lasting around one hour. The participants, irrespective of their previous experience with the simulator, underwent comprehensive training to control the traffic. The training scenarios are explained below:

TS 1 The first scenario focussed on teaching participants the basic functionality of the simulator. Participants learned about flight labels and their significance in the control action required to meet operational demands. They underwent training to assume control over incoming flights and transfer control of outgoing flights. Further, they underwent training to control flights by inspecting their routes and issuing flight levels, heading, and direct-to-exit clearances. Figure B.1 shows the initial traffic positions of training scenario 1.



5

Figure B.1: Initial position of flights in training scenario 1

TS 2 The second scenario motivated participants to perform tasks they learned in the first training scenario. Initially, participants had to hover the mouse cursor over flight labels and indicate the action required to expedite the flow. Following this, participants executed the clearances accordingly. Figure B.2 shows the initial traffic positions of training scenario 2.

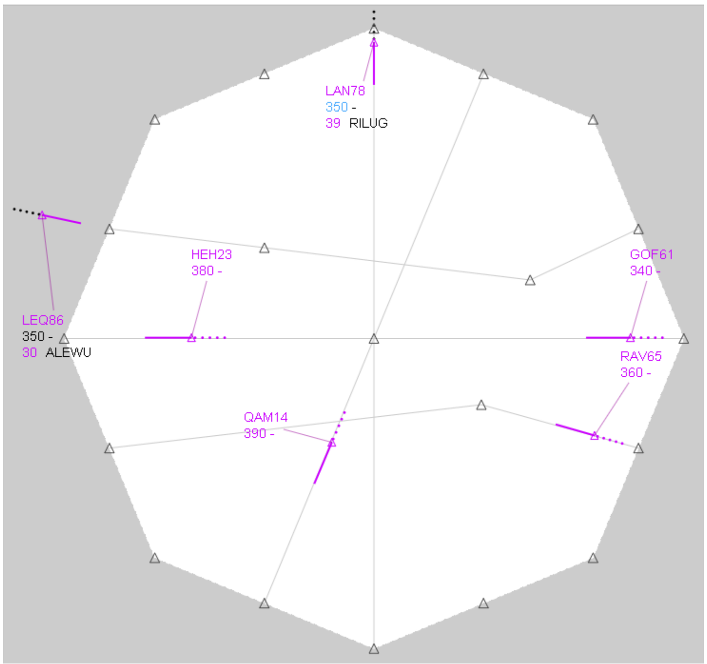


Figure B.2: Initial position of flights in training scenario 2

TS 3 The third scenario introduced two safety violations, with one triggering due to providing the clearance at the wrong time. They learned about the STCA tool and its significance in preventing safety violations. Lastly, they learned about resolving conflict through flight level clearance. Figure B.3 shows the initial traffic positions of training scenario 3.

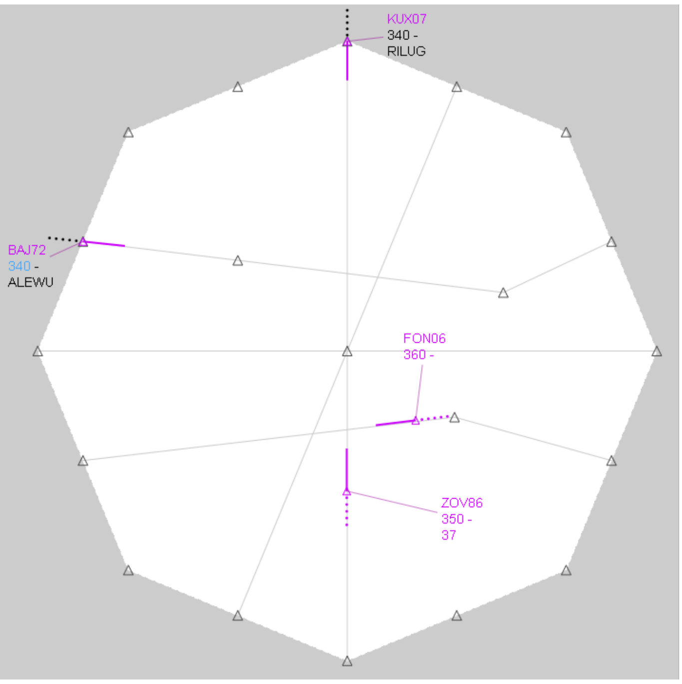


Figure B.3: Initial position of flights in training scenarios 3, 4 and 6

TS 4 The fourth scenario introduced the VERA tool, explaining its significance in examining the separation characteristics between flight pairs for conflict detection. Following this, they learned about resolving conflict through heading change by previewing separations for preferred heading clearance. The scenario contained the same traffic as training scenario 3.

TS 5 The fifth scenario introduced more flights inside the sector with one planned safety violation. Participants had to identify which flight pairs required VERA inspections while expediting their flow safely through the sector. Lastly, they had to perform tasks they learned throughout the training session. Figure B.4 shows the initial traffic positions of training scenario 5.

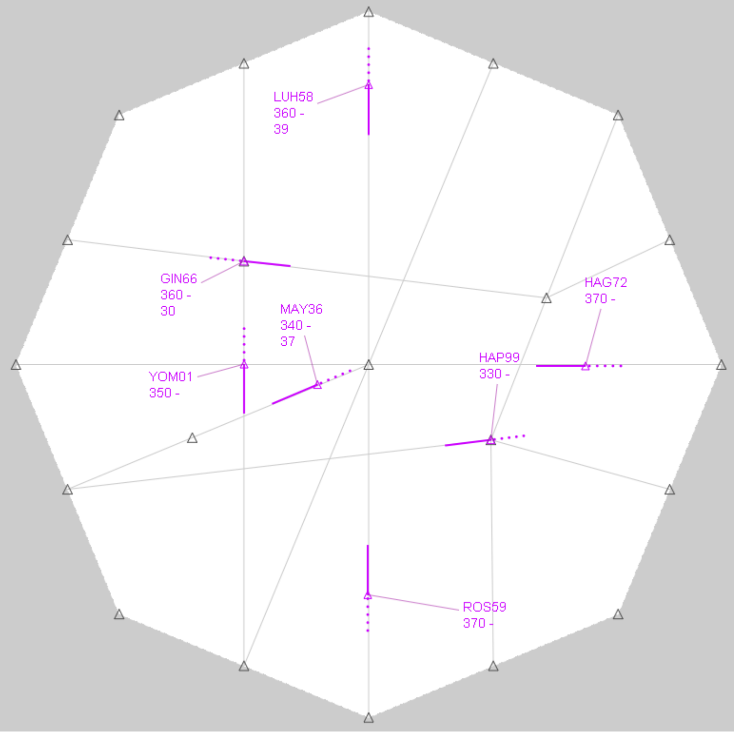


Figure B.4: Initial position of flights in training scenario 5

TS 6 The sixth scenario introduced the flight filtering concept to determine relevant flights for the selected flight of interest through route inspection. Following this, they perceived filtered flights while previewing the flight level and heading clearances. The scenario contained the same traffic as training scenario 3.

TS 7 The seventh scenario introduced perceiving the filtered results while previewing direct-to-exit clearances. Participants had to expedite the flow safely and efficiently with filtering enabled. Further, they were introduced to the ISA rating scale, providing perceived workload at a given time and the overall difficulty experienced through the HMI scale while controlling the traffic at the end of the five-minute simulation. Figure B.5 shows the initial traffic positions of the training scenario 7.

After completing the training phase, participants received tips and tricks for expediting the flow safely and efficiently through the sector. Following this, a break of five minutes was scheduled for participants to relax, process the information, and clear any doubts.

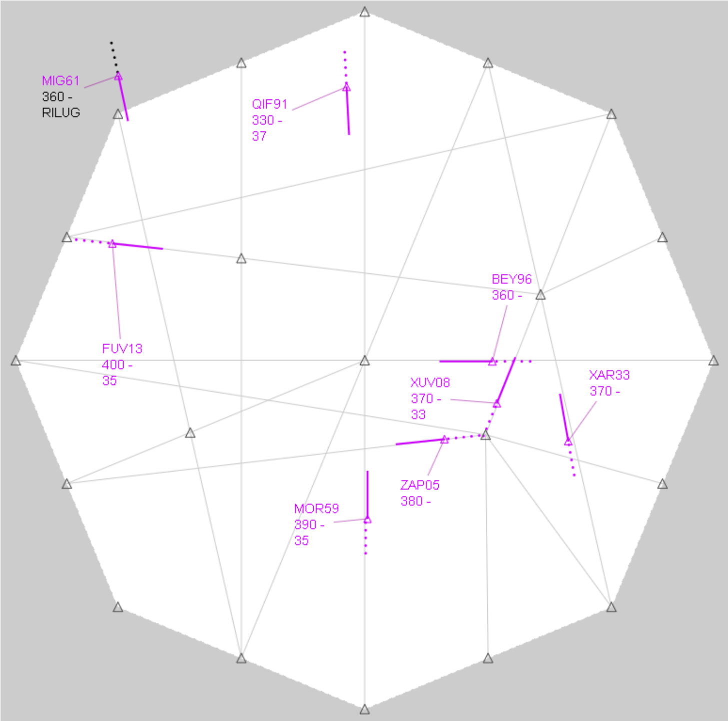


Figure B.5: Initial position of flights in training scenario 7

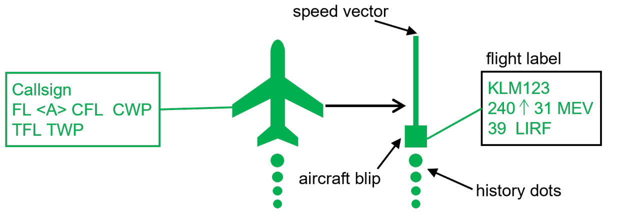
Before beginning the second phase, the practice phase, participants received the following briefing:

> You are an Air Traffic Controller (ATCo) tasked to expedite the air traffic safely and efficiently in your controlled sector. You have to assume control of an incoming flight, provide the clearances to reach their target states, and transfer its control to the adjacent ATCo.
>
> The flights should be cleared to their sector exit (DCT) soon and made to fly at higher altitudes for maximum time (clear to higher flight levels soon and to lower flight levels late) to expedite the air traffic safely and efficiently while **not receiving alerts** from the STCA table and violating separation minima.
>
> Remember that during flight filtering, the relevant flights highlighted while clearing a flight indicate closer proximity rather than guaranteeing the loss of separation.

In the practice phase, participants controlled traffic for 30 minutes, spending 15 minutes each with and without filtering. The order of scenarios was fixed, with participants first experiencing no-filtering, followed by filtering. Participants explored all tasks they would encounter during the measurement phase, which included assuming/transferring flight control, providing clearances, indicating the perceived workload through the ISA scale at a given time, and the overall difficulty experienced throughout the scenario. Following the practice phase, participants had a break of 15 minutes before beginning the third phase, the measurement phase.

The measurement phase comprised two scenarios, each lasting approximately 25 minutes, one with and the other without filtering. However, the order varied, and the participants were informed about their order before the beginning of the measurement phase. There was a five-minute break between the scenarios. Appendix C mentions the scenario design for practice and measurement runs. Following this, participants had to fill out a questionnaire (fourth phase), provided in Appendix D, marking the end of the experiment session. Participants had access to a cheat sheet for reference during practice and measurement runs, as shown on the next page.

1. Flight label and Control action



FL – Current flight level
TFL – Target flight level

<A> - climbing or descending
CWP – Cleared waypoint

CFL – Cleared flight level
TWP – Target waypoint

Figure 1: Flight label description with parameters

Label	**Control Action**
KLM12 370 - 30 RADEP	Assume control over incoming flights by clicking **Callsign** label item.
KLM12 370 - 30	Clear flight to their target level by clicking **CFL** label item
KLM12 300 - H	Reroute the flight by clicking **HDG** label item and opening **DCT** clearance menu
KLM12 300 -	Transfer control of outgoing flights by clicking **Callsign** label item

Figure 2: Flight labels and corresponding control action required in expediting their flow

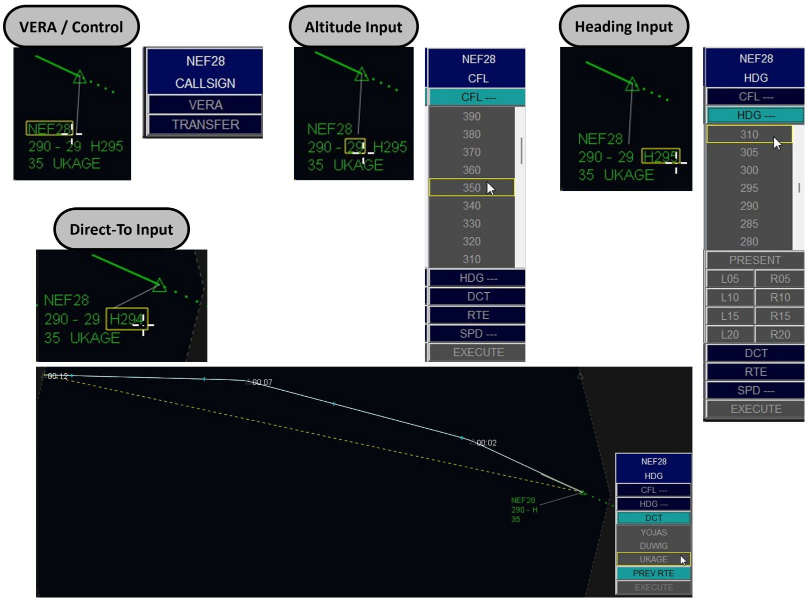


Figure 3: Means to execute the ATC control tasks

2. Expediting flow safely and efficiently

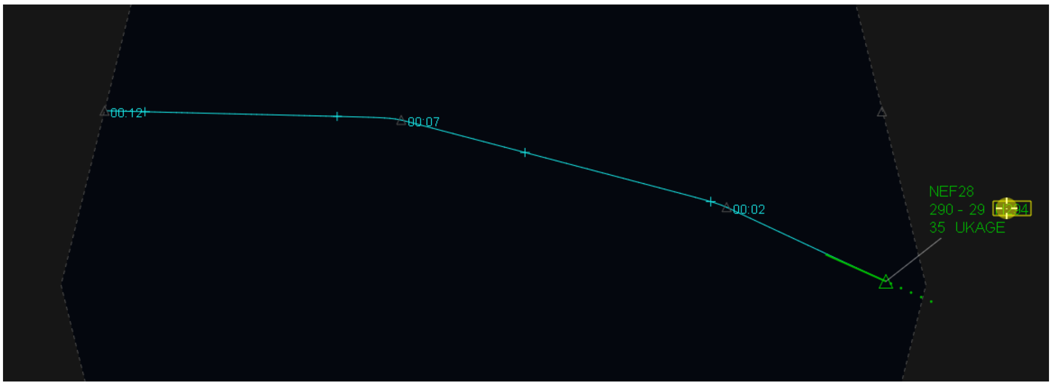
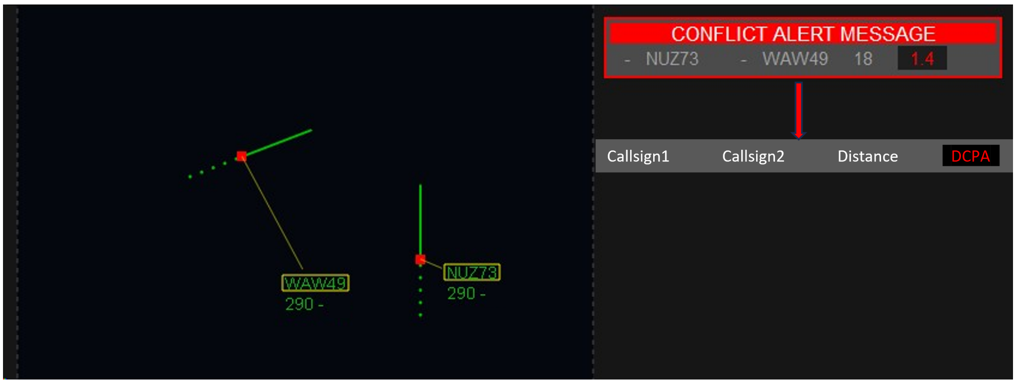


Figure 4: Inspecting flight route - single long left mouse click

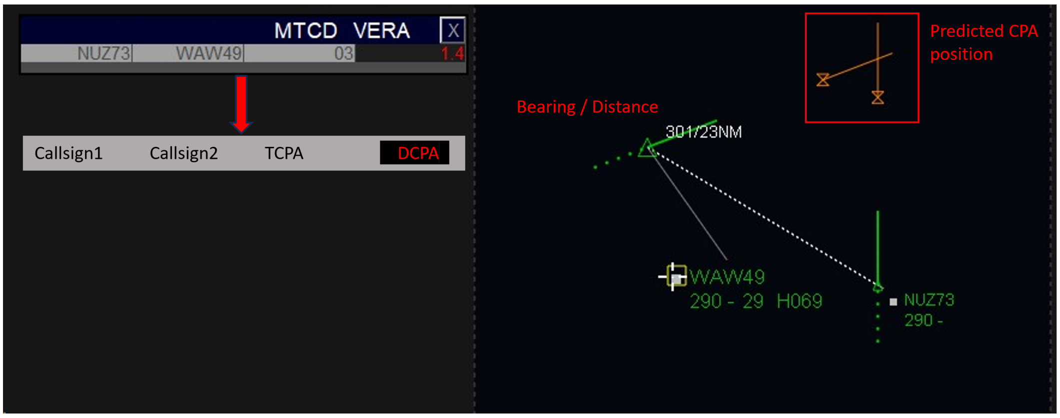


CONFLICT ALERT MESSAGE

-	NUZ73	- WAW49	18	1.4

Callsign1	Callsign2	Distance	DCPA

Figure 5: STCA table and its significance



MTCD VERA

NUZ73	WAW49	03	1.4

Callsign1	Callsign2	TCPA	DCPA

Figure 6: VERA table and its significance

C

Scenario Design

Figure C.1 and Figure C.2 displays the Brussels sector and its corresponding radar data recorded on 02-September-2023 from 14:00 to 18:00 UTC, which is the inspiration for designing practice and experiment scenarios.

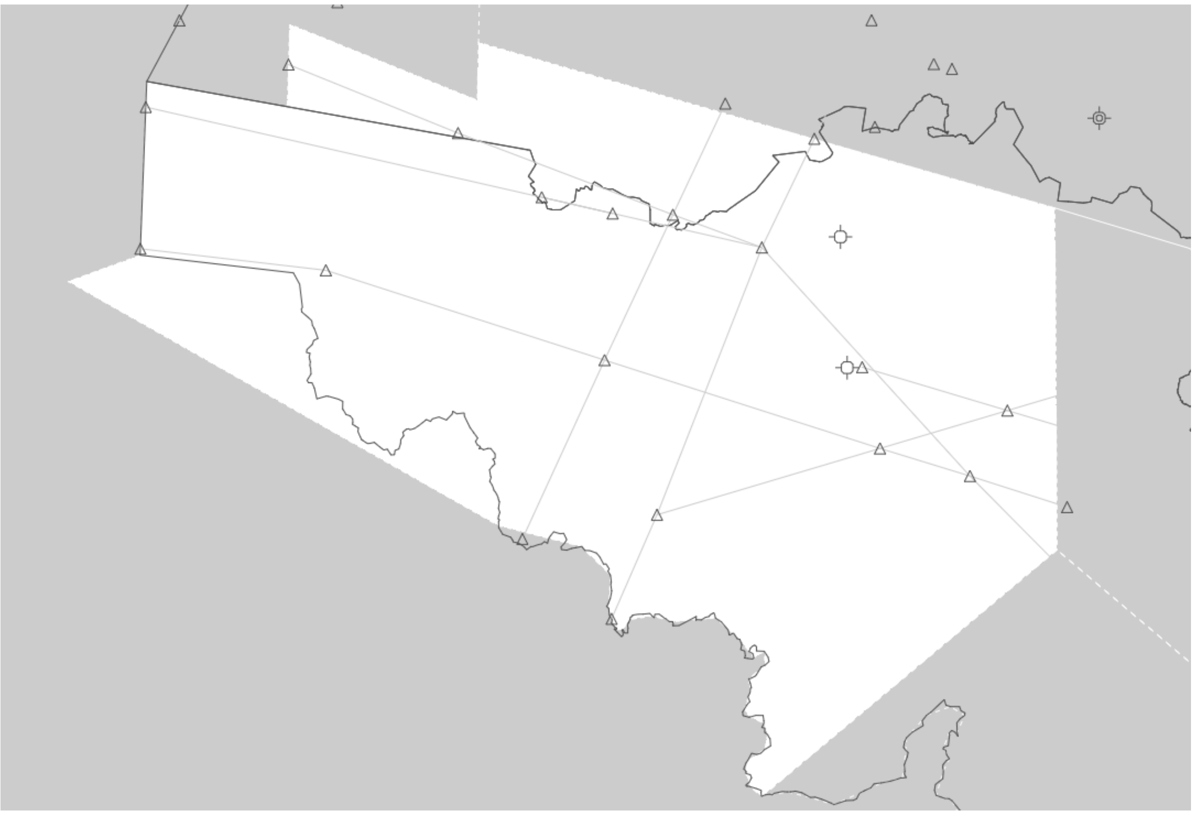
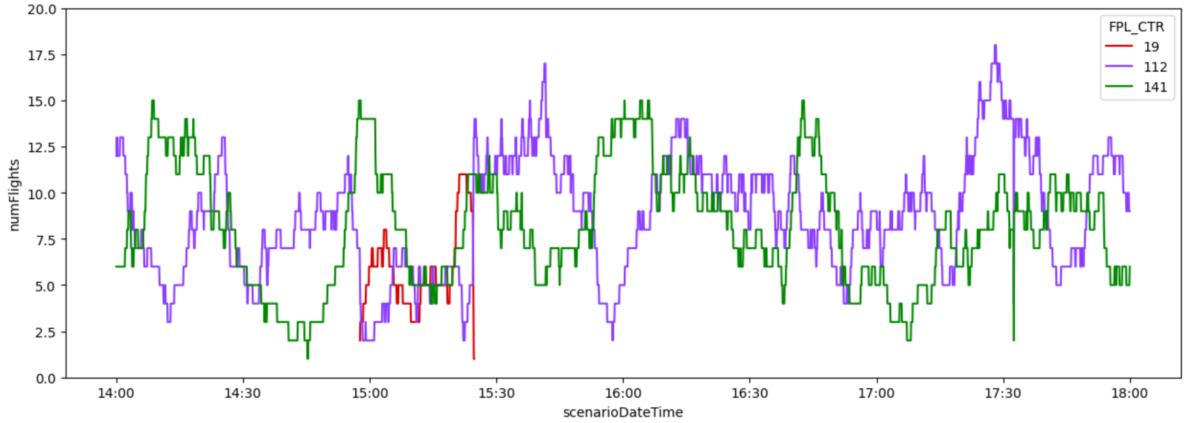
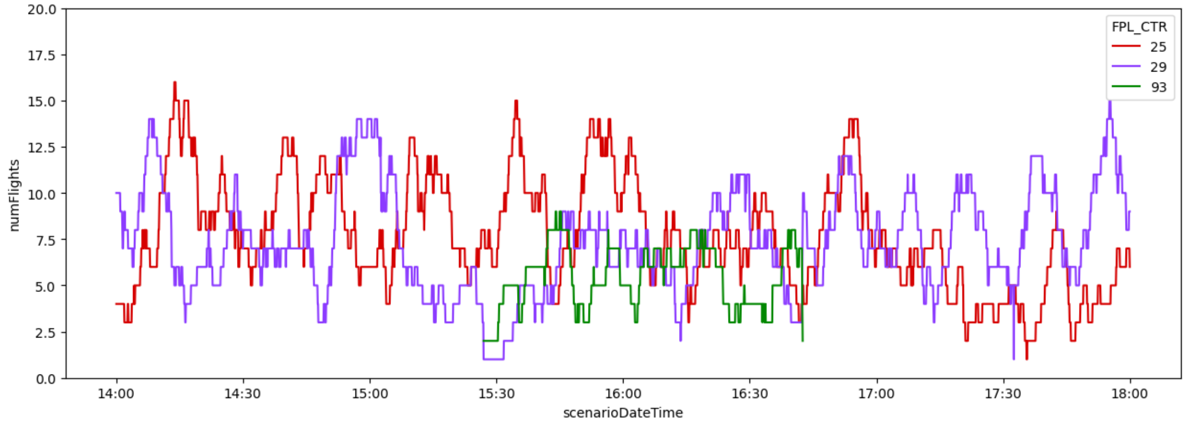


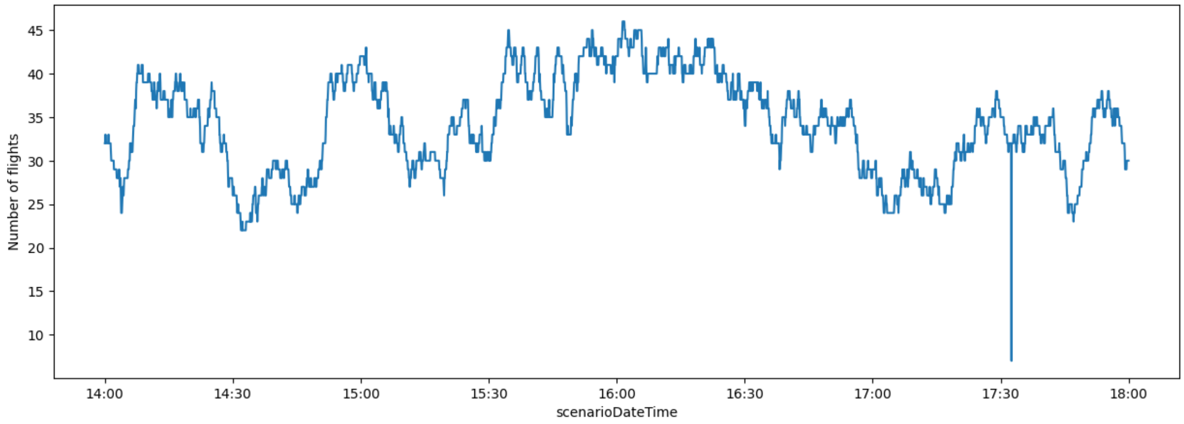
Figure C.1: Screenshot of the Brussels sector



(a) Brussels west airspace



(b) Brussels east airspace



(c) Brussels complete (east and west joined)

Figure C.2: The number of flights under control within Brussels airspace recorded on 02-September-2023 from 14:00 to 18:00 UTC; each color represents one ATCO

C.1. Practise Runs Design

Following are the sector, waypoints, and structured routes used for no-filtering scenario in the practice run.

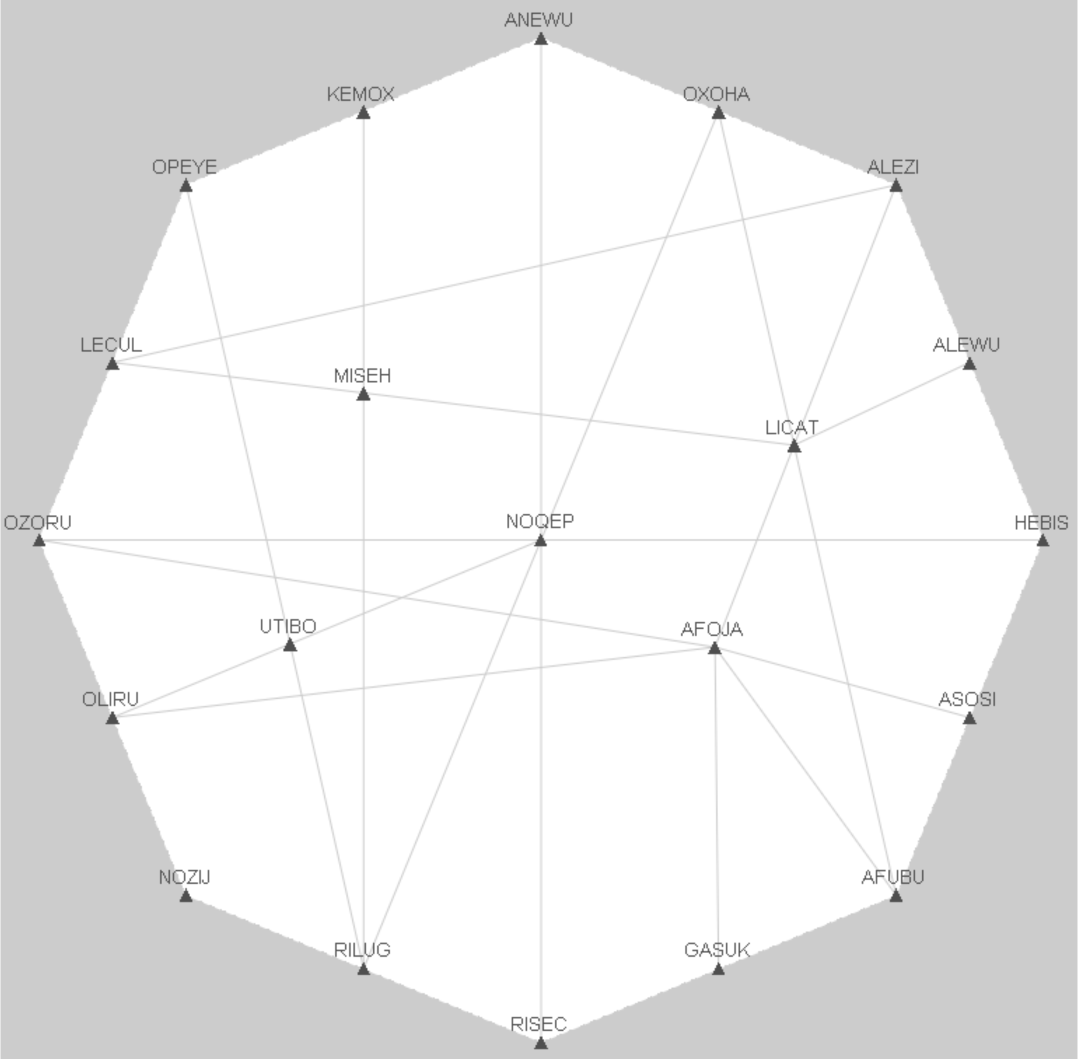


Figure C.3: Sector design for no-filtering scenario in practice run

Route 01	OPEYE	UTIBO	RILUG	
Route 02	RISEC	NOQEP	OXOHA	
Route 03	AFUBU	LICAT	OXOHA	
Route 04	HEBIS	NOQEP	UTIBO	OLIRU
Route 05	HEBIS	NOQEP	OZORU	
Route 06	ASOSI	AFOJA	OLIRU	
Route 07	ANEWU	NOQEP	RILUG	
Route 08	GASUK	AFOJA	LICAT	ALEZI
Route 09	AFUBU	AFOJA	OZORU	
Route 10	LECUL	MISEH	LICAT	ALEWU
Route 11	KEMOX	MISEH	RILUG	
Route 12	LECUL	ALEZI		

Table C.1: Structured routes for no-filtering scenario in practice run

Following are the sector, waypoints, and structured routes used for filtering scenario in the practice run. The scenario has distinct waypoint names and 90° view rotation to no-filtering scenario.

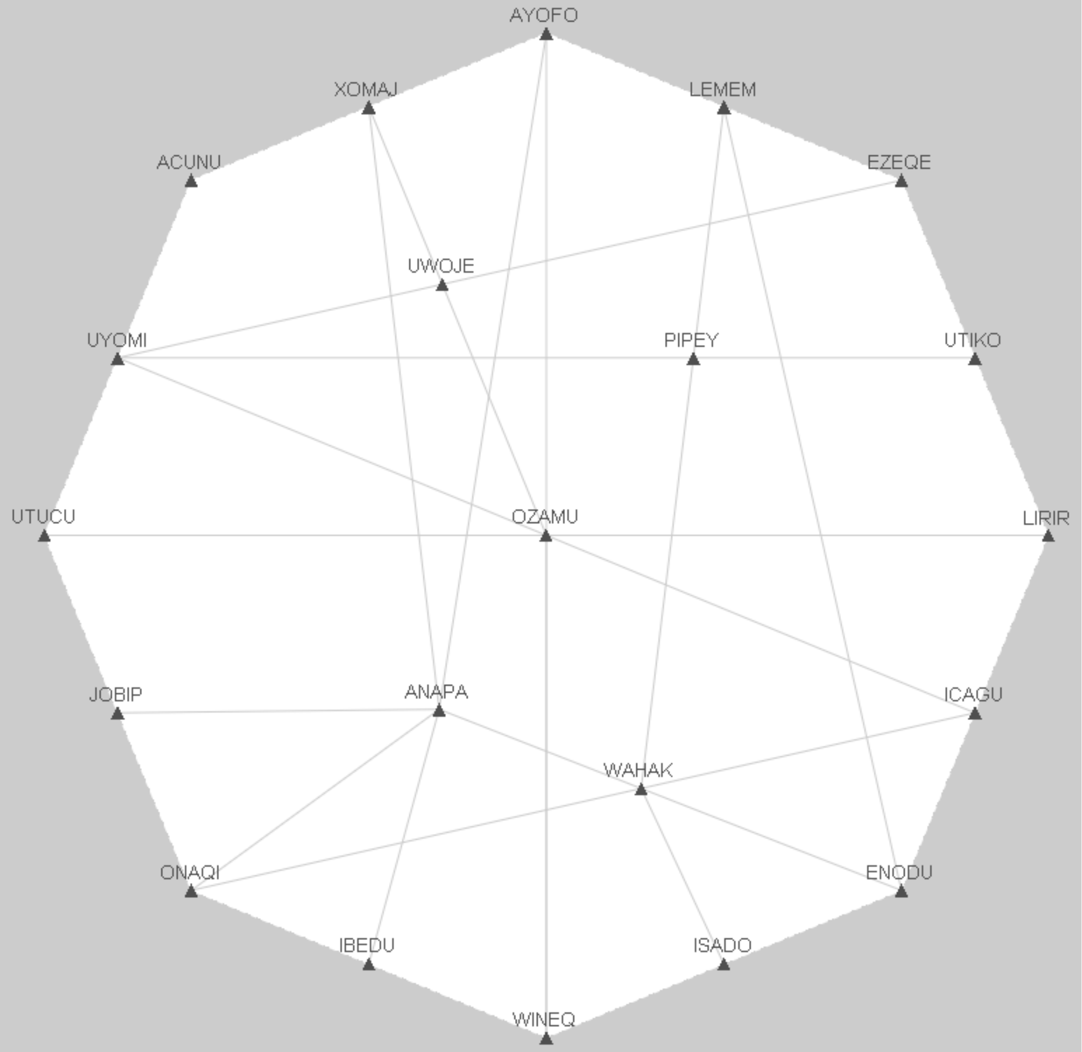


Figure C.4: Sector design for filtering scenario in practice run

Route 01	EZEQE	UWOJE	UYOMI	
Route 02	UTUCU	OZAMU	ICAGU	
Route 03	ONAQI	WAHAK	ICAGU	
Route 04	WINEQ	OZAMU	UWOJE	XOMAJ
Route 05	WINEQ	OZAMU	AYOFO	
Route 06	IBEDU	ANAPA	XOMAJ	
Route 07	LIRIR	OZAMU	UYOMI	
Route 08	JOBIP	ANAPA	WAHAK	ENODU
Route 09	ONAQI	ANAPA	AYOFO	
Route 10	LEMEM	PIPEY	WAHAK	ISADO
Route 11	UTIKO	PIPEY	UYOMI	
Route 12	LEMEM	ENODU		

Table C.2: Structured routes for filtering scenario in practice run

Bunch	Radar Appear [s]	No-filtering Callsign	Filtering Callsign	ICAO Flight Type	Current FL [ft]	Transfer FL [ft]	Assigned Route	Speed [kts]
Bunch 0	0	FUR33	WEH75	A320	38000	35000	10	255
	0	CUZ48	TIV27	A20N	37000	37000	9	263
	0	BIR45	DON15	B789	39000	34000	2	269
	0	CAL02	JER19	B737	38000	38000	12	256
	0	XUZ78	YAJ47	A333	36000	36000	3	283
	0	XOW23	FAC83	A332	36000	39000	4	266
	0	QOC93	XOZ20	B735	37000	37000	1	260
	0	LIH09	CIV51	B737	33000	39000	7	278
Bunch 1	60	WEZ71	HOW66	B788	37000	37000	2	290
	75	VEH85	PAM13	A320	37000	37000	7	265
	130	TAR54	HOR00	A332	34000	39000	6	273
	160	PUS74	QIP65	A318	36000	30000	3	264
	180	HAN69	NOY55	A333	36000	36000	8	258
	180	KET82	WIL60	B789	38000	38000	5	282
	220	NUN88	CUM60	B737	39000	35000	10	250
	260	WID99	JOC86	B738	32000	38000	11	273
Bunch 2	620	FIL59	MOX80	B737	33000	38000	7	288
	650	TED31	XAH25	B772	37000	40000	9	278
	705	HEN48	WAH10	A332	36000	36000	11	272
	735	CEJ07	QEV15	B772	36000	36000	2	290
	800	QOB24	RED87	B788	40000	34000	10	257
	870	HEL12	RUW39	A319	35000	35000	3	276

Table C.3: Traffic characteristics for no-filtering and filtering scenarios with distinct callsigns in practice runs

Figure C.5 shows the traffic distribution in the practice run. One head-on conflict was planned at the center of the sector, occurring around 480th second. Directing either one or both flights to their sector exits resolves planned conflicts through horizontal maneuver because these clearances lead to them diverging. The conflicting flights were following routes 2 and 7 of Bunch 1 traffic.

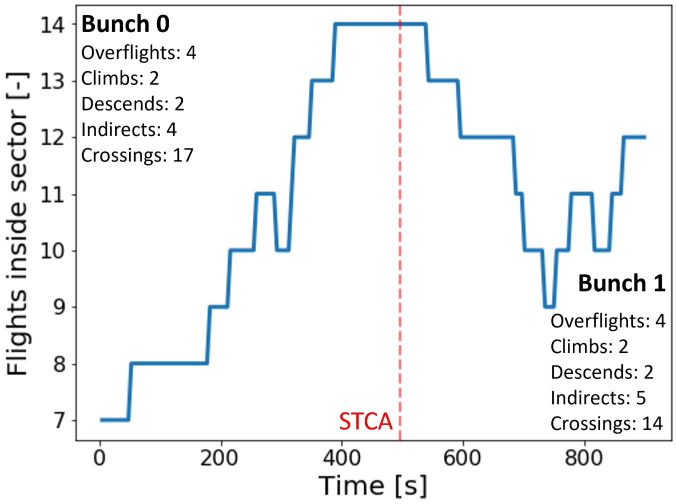


Figure C.5: Traffic distribution of flights entering the sector in the practice phase. The red dashed line indicates the timestamps of planned safety violation if no clearances were issued.

C.2. Measurement Runs Design

Following are the sector, waypoints, and structured routes used for no-filtering scenario in the measurement run.

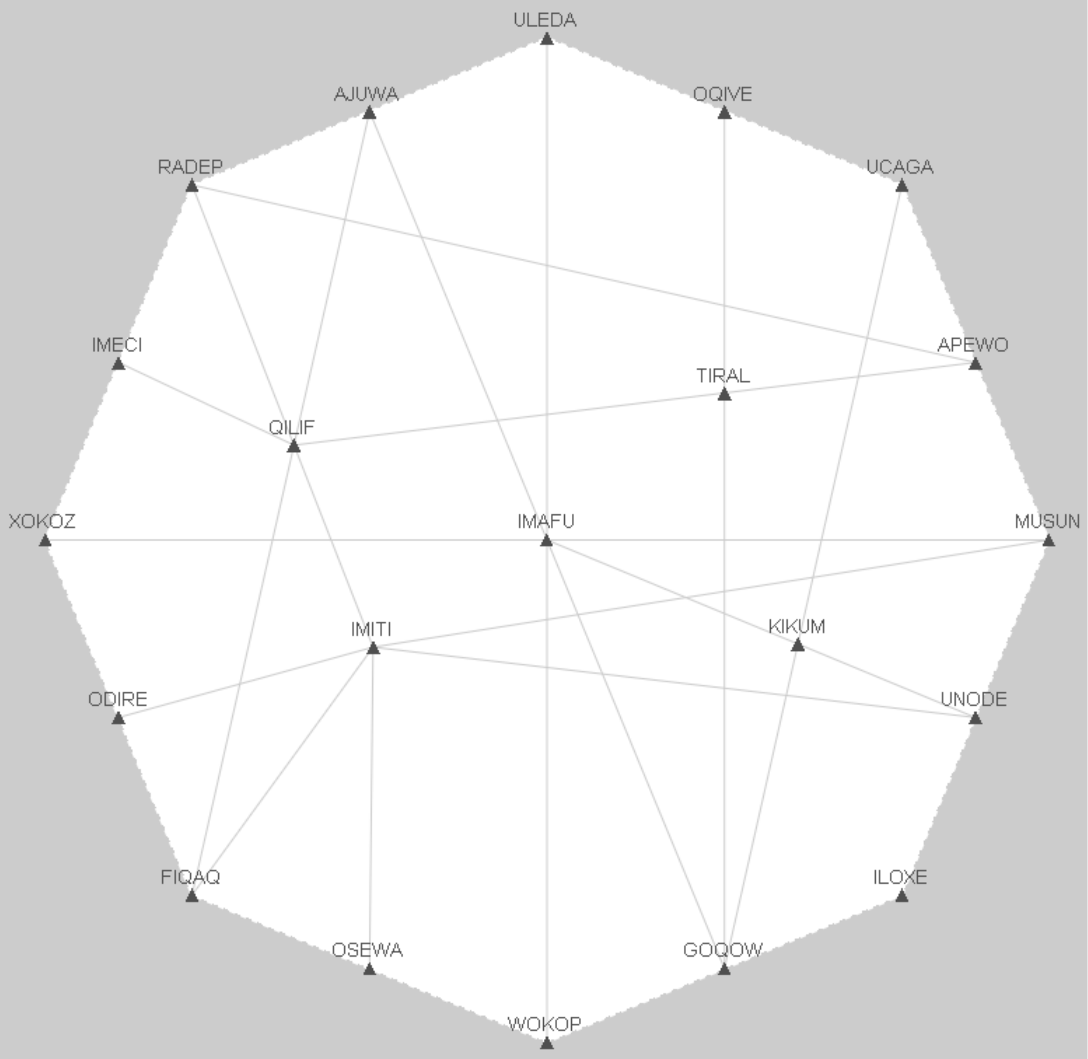


Figure C.6: Sector design for no-filtering scenario in measurement run

Route 01	UCAGA	KIKUM	GOQOW	
Route 02	WOKOP	IMAFU	AJUWA	
Route 03	FIQAQ	QILIF	AJUWA	
Route 04	XOKOZ	IMAFU	KIKUM	UNODE
Route 05	XOKOZ	IMAFU	MUSUN	
Route 06	ODIRE	IMITI	UNODE	
Route 07	ULEDA	IMAFU	GOQOW	
Route 08	OSEWA	IMITI	QILIF	RADEP
Route 09	FIQAQ	IMITI	MUSUN	
Route 10	APEWO	TIRAL	QILIF	IMECI
Route 11	OQIVE	TIRAL	GOQOW	
Route 12	APEWO	RADEP		

Table C.4: Structured routes for no-filtering scenario in measurement run

Following are the sector, waypoints, and structured routes used for filtering scenario in the measurement run. The scenario has distinct waypoint names and 90° view rotation to no-filtering scenario.

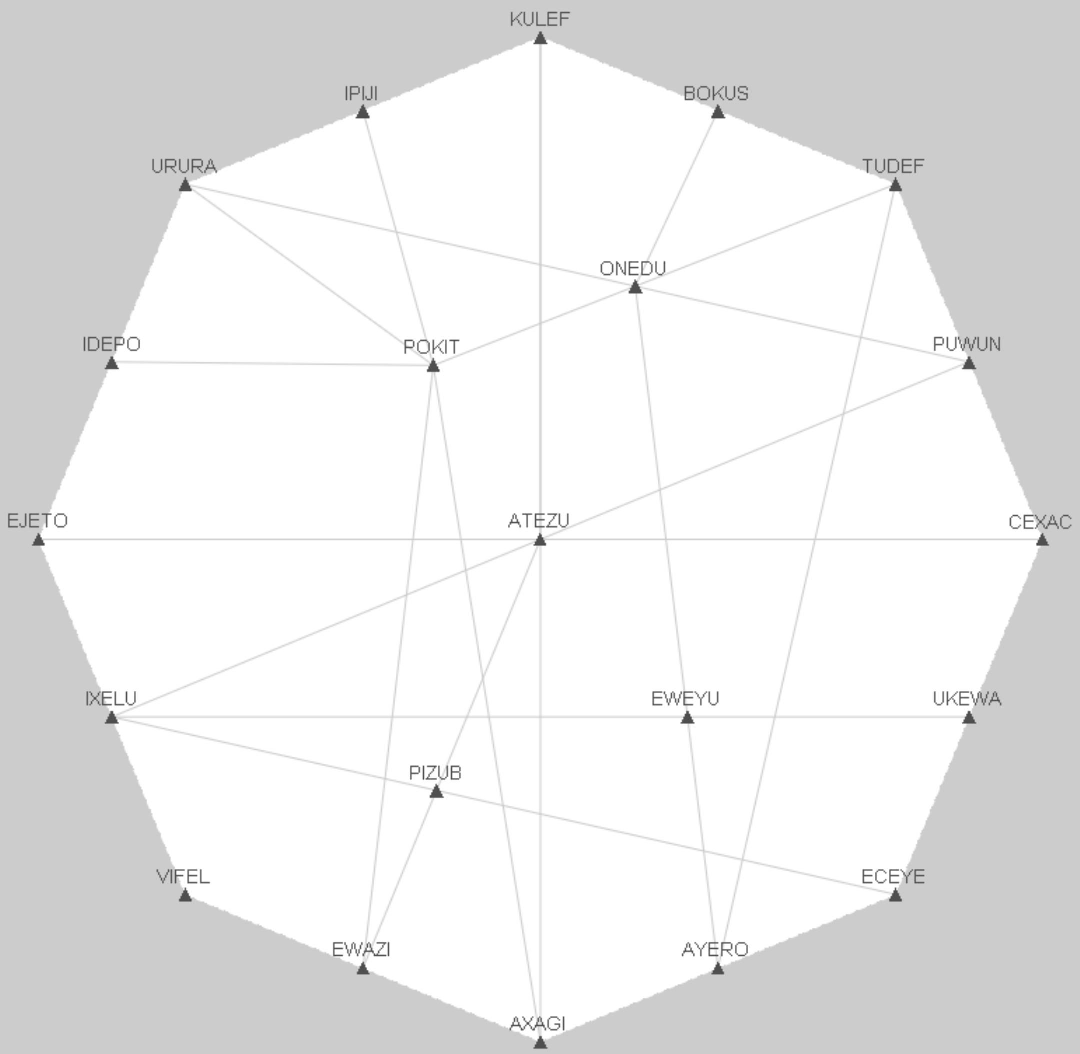


Figure C.7: Sector design for filtering scenario in measurement run

Route 01	ECEYE	PIZUB	IXELU	
Route 02	EJETO	ATEZU	PUWUN	
Route 03	URURA	ONEDU	PUWUN	
Route 04	KULEF	ATEZU	PIZUB	EWAZI
Route 05	KULEF	ATEZU	AXAGI	
Route 06	IPIJI	POKIT	EWAZI	
Route 07	CEXAC	ATEZU	IXELU	
Route 08	IDEPO	POKIT	ONEDU	TUDEF
Route 09	URURA	POKIT	AXAGI	
Route 10	AYERO	EWEYU	ONEDU	BOKUS
Route 11	UKEWA	EWEYU	IXELU	
Route 12	AYERO	TUDEF		

Table C.5: Structured routes for filtering scenario in measurement run

Bunch	Radar Appear [s]	No-filtering Callsign	Filtering Callsign	ICAO Flight Type	Current FL [ft]	Transfer FL [ft]	Assigned Route	Speed [kts]
Bunch 0	0	VAL72	LUM12	A333	38000	32000	8	270
	0	FOR65	NUM46	A320	37000	37000	3	261
	0	ZOF14	FUF65	A319	39000	35000	2	250
	0	NEP01	SUT79	B788	40000	35000	10	259
	0	ZUD45	FUP14	A20N	33000	37000	7	284
	0	MIQ63	ZAH77	B738	36000	38000	6	260
	0	XAY45	YIT26	B737	36000	36000	1	258
	0	ROX76	WAV81	A333	34000	36000	4	297
Bunch 1	80	WEX37	VIN75	A332	36000	36000	5	273
	120	KOX90	DEZ39	A332	40000	35000	2	235
	135	PEC56	TUP31	B733	37000	30000	8	259
	165	YIF16	PAN28	B731	33000	38000	4	285
	215	RUZ05	MOC12	A333	38000	38000	10	275
	210	WEJ20	JIQ47	B737	38000	38000	7	260
	270	ROL67	BUV74	A318	39000	39000	6	248
	290	KAQ55	VER72	A20N	34000	40000	11	243
	310	QUB66	HOB81	B789	37000	37000	1	281
	330	TUK94	PIF12	B788	39000	39000	3	265
Bunch 2	620	XEK56	KUX56	B737	33000	38000	7	288
	650	NUP97	ZOX61	B772	37000	40000	9	278
	700	JOB19	RAT35	A320	36000	36000	4	250
	705	LUP81	GUR56	A332	36000	36000	11	272
	735	BOL23	JUH94	B772	36000	36000	2	290
	800	MUC01	PIM17	B788	40000	34000	10	257
	850	BIK57	ROZ21	A321	33000	37000	6	268
	870	BUP41	LUK41	A319	35000	30000	3	276
	880	YIB67	VEG56	A333	35000	35000	1	269
	950	ROW43	VIV14	B734	34000	34000	12	285
Bunch 3	1260	WEN50	MOJ35	B788	37000	37000	2	290
	1275	MEJ81	VIT65	A320	37000	37000	7	265
	1330	HAV09	LUH03	A332	34000	39000	6	273
	1380	KEL47	GAR19	B789	38000	38000	5	282
	1420	MAN70	LIW73	B737	39000	35000	10	250
	1460	SIG74	MUZ59	B738	32000	38000	11	273

Table C.6: Traffic characteristics for no-filtering and filtering scenarios with distinct callsigns in measurement runs

Figure 8 in the scientific paper shows the traffic distribution for the measurement run. Two crossing conflicts were planned, occurring around 540th and 1140th second. The conflict is resolved by directing only one flight to their sector exit through horizontal maneuver. The first conflicting flights were following routes 7 and 10 in Bunch 1 traffic, whereas the second conflicting flights were following routes 2 and 4 in Bunch 2 traffic.

Note: During experiment sessions, waypoints were not filled, and their names would only be displayed if the mouse cursor was hovered over that particular waypoint.

D

Post-Experiment Survey

Post-Experiment Questionnaire

Participant ID:

Age:

Job Position:

Q1. Please indicate your ratings for 'baseline (no filtering)' on the following dimensions:

Managing your workload	☐ Very Poor	☐ Poor	☐ Average	☐ Good	☐ Excellent
Maintaining your Situation Awareness	☐ Very Poor	☐ Poor	☐ Average	☐ Good	☐ Excellent
Timely detecting and solving conflicts	☐ Very Poor	☐ Poor	☐ Average	☐ Good	☐ Excellent
Efficiently expediting traffic through the sector	☐ Very Poor	☐ Poor	☐ Average	☐ Good	☐ Excellent

Q2. Please indicate your ratings for 'flight filtering' on the following dimensions:

Managing your workload	☐ Very Poor	☐ Poor	☐ Average	☐ Good	☐ Excellent
Maintaining your Situation Awareness	☐ Very Poor	☐ Poor	☐ Average	☐ Good	☐ Excellent
Timely detecting and solving conflicts	☐ Very Poor	☐ Poor	☐ Average	☐ Good	☐ Excellent
Efficiently expediting traffic through the sector	☐ Very Poor	☐ Poor	☐ Average	☐ Good	☐ Excellent

Q3. How much did you **rely** on the 'flight filtering' in controlling traffic?

☐ Not at all ☐ Slightly ☐ Moderately ☐ Very ☐ Extremely

Q4. Briefly explain your rating.

Q5. How much did you **trust** on the ‘flight filtering’ in controlling traffic?

☐ Not at all ☐ Slightly ☐ Moderately ☐ Very ☐ Extremely

Q6. Briefly explain your rating.

Q7. How much did the filtered results match your expectations?

☐ Not at all ☐ Slightly ☐ Moderately ☐ Very ☐ Extremely

Q8. How much did you agree with the filtered results in terms of relevant/highlighted flights?

☐ Not at all ☐ Slightly ☐ Moderately ☐ Very ☐ Extremely

Q9. How much did you agree with fading all non-relevant flights?

☐ Not at all ☐ Slightly ☐ Moderately ☐ Very ☐ Extremely

Q10. Please briefly explain your ratings for the expectations and agreeableness of the fading/highlighting of the non-relevant/relevant flights.

Q11. How often did you make use of ‘flight filtering’ in detecting conflicts?

☐ Not at all ☐ Slightly ☐ Moderately ☐ Very ☐ Extremely

Q12. How often did you make use of ‘flight filtering’ in previewing clearances before executing them?

☐ Not at all ☐ Slightly ☐ Moderately ☐ Very ☐ Extremely

Q13. Please describe briefly how you used ‘flight filtering’ in your control strategy to safely and efficiently expedite the flow of traffic.

Q14. Do you have any other comment and/or suggestions on how to improve flight filtering?

E

Briefing Manual

Participant Briefing and Training Manual

By Ajay Kumbhar Vijay Kumbhar

1. Introduction

Enroute Air Traffic Controllers (ATCos) determine the best course of action by scanning the radar display, selecting a flight of interest requiring a maneuver, and evaluating the impact of potential control action on the safety and efficiency of the airspace sector while controlling it. Selecting a flight to provide a maneuver can be motivated by several reasons, including expediting the flow, ensuring minimum separation between flights, and clearing the flights to their target states. Several flight parameters, such as flight directions, current, and target altitudes displayed on the flight labels, are compared visually before deciding and implementing a maneuver to the selected flight of interest, avoiding possible safety infringements in the future. The predicted increase in air traffic will make it difficult for ATCos to visualize and compare the flight parameters displayed on the flight labels in the radar display while controlling the flight safely and efficiently in their airspace sector.

The scope of the experiment is to research whether guiding ATCo's attention towards the relevant flights relative to the potential control action for the selected flight of interest assists ATCos in implementing better decisions while expediting the flow in the sector. Flights having no possible interaction relative to the potential control action or the target states for the selected flight of interest are deemed irrelevant and lose their luminance while controlling the flight. The participants will be exposed to both with and without visual attention guidance support tools relative to the potential control action for the selected flight of interest while manually expediting the air traffic safely and efficiently in their airspace sector.

2. Briefing ATC Simulator

SectorX is a Java-based ATC simulator developed within the Control and Simulation department in the Faculty of Aerospace Engineering at TU Delft. This section describes the information formulated from the radar display, control inputs provided by the ATCo to expedite the air traffic, and the proposed visual attention guidance tool relative to the potential control action for the selected flight of interest.

2.1. Plan View Display

SectorX adapts to mimic the latest plan view display design of a controller working position found at the Maastricht Upper Area Control (MUAC). It displays the sector geometry, flight position as blips, and their label information. Figure 1 shows the latest plan view display as implemented in SectorX. SectorX utilizes minimized MUAC toolsets that are considered critical in supporting ATC tasks as follows:

(a) **Verification of Separation and Resolution Advisory (VERA) tool:** inspecting the current and future separation properties (distance and time to the closest point of approach (CPA)) between flight pairs.

(b) **Short term conflict alert (STCA) table:** Conflict information regarding the current distance and the distance CPA between conflicting pairs based on urgency.

(c) **Flight label:** gathering flight information such as flight position, callsign, altitude, heading, and target states.

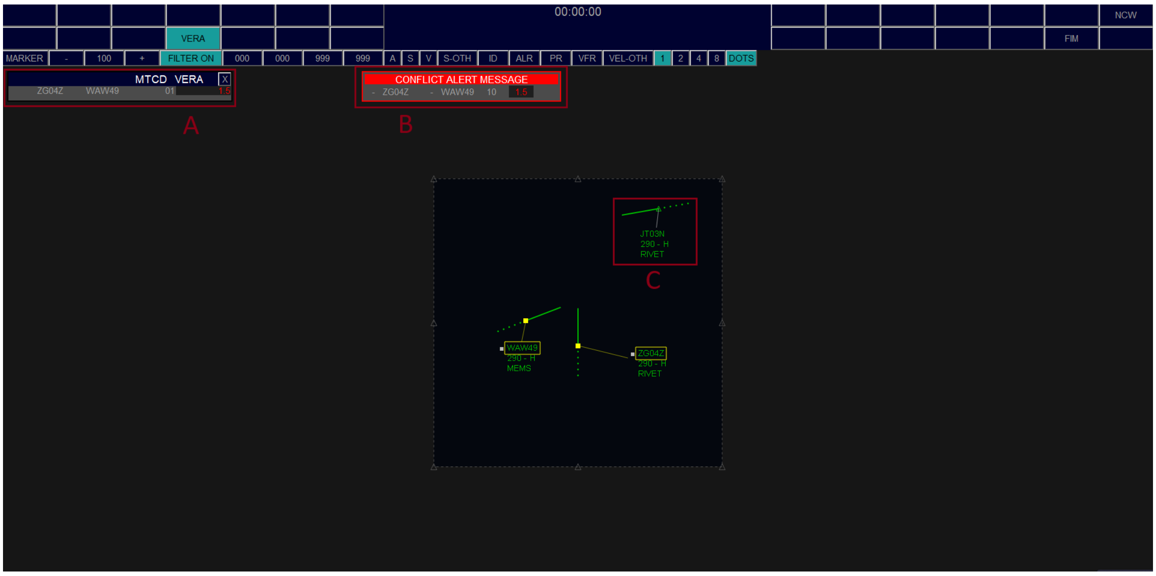


Figure 1: State-of-the-Art Plan view display implemented in SectorX

The flight location is depicted and represented in the guise of blips on the radar display, where each blip corresponds to the position of an individual aircraft in the airspace, providing valuable real-time information to ATCos, triggering the control action for effective operations, as shown in Figure 2.

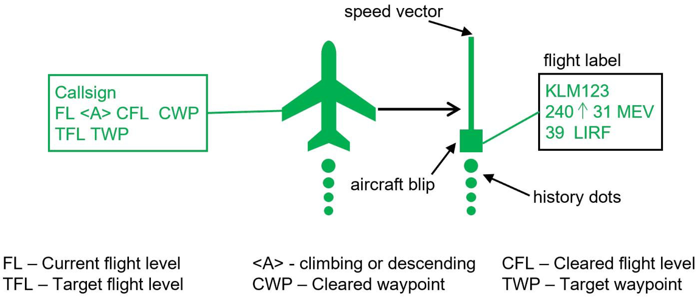
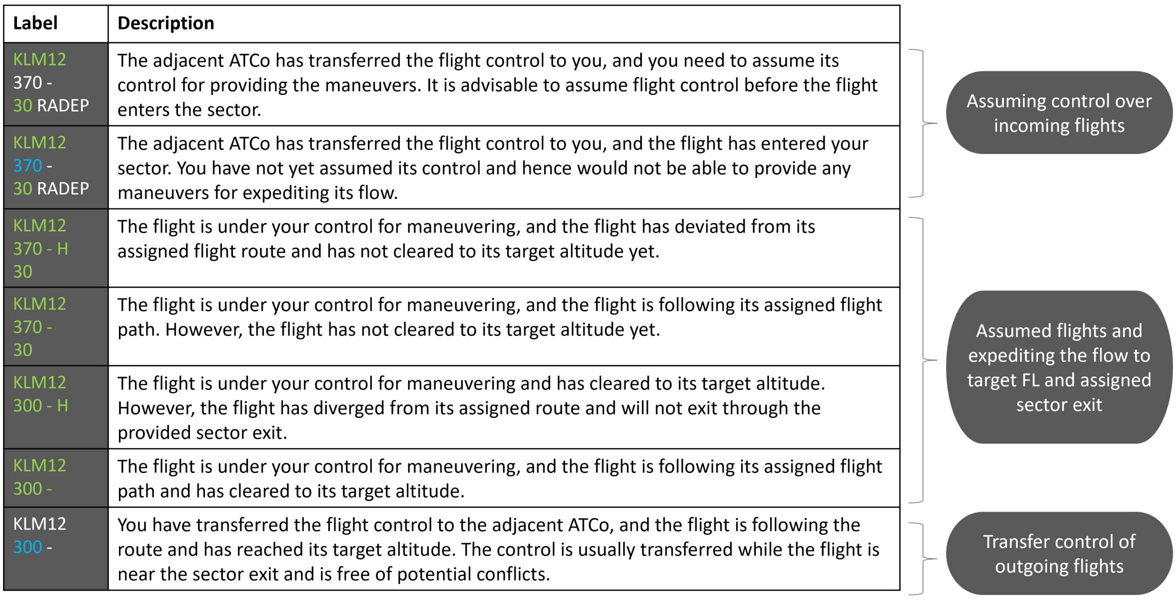


Figure 2: Flight label description with parameters

Enroute ATCos provides services to flights at their responsible upper airspace called a sector. The responsible ATCo assumes control over incoming flights from the adjacent sector, expedites their flow safely and efficiently through the sector, and transfers its control to the other adjacent ATCo. They are responsible for flights leaving the sector according to their assigned flight plan and reaching their target states (flight level and sector exit).

The flight labels displayed on the radar display vary accordingly to grab the attention of the ATCos over the control of flight and its expedition through the sector. The flight labels are displayed concisely to support the ATCo's cognitive skills and manage their workload while expediting the traffic through the sector. The detailed flight label information (with target states) for a blip appears when the mouse cursor hovers over the particular flight label, the flight has not achieved its target flight level, or the flight diverges from its assigned trajectory accordingly. Figure 3 displays the possible flight labels ATCos encounter while expediting the flow through the sector before providing a control input.



Label	Description
KLM12 370 - 30 RADEP	The adjacent ATCo has transferred the flight control to you, and you need to assume its control for providing the maneuvers. It is advisable to assume flight control before the flight enters the sector.
KLM12 370 - 30 RADEP	The adjacent ATCo has transferred the flight control to you, and the flight has entered your sector. You have not yet assumed its control and hence would not be able to provide any maneuvers for expediting its flow.
KLM12 370 - H 30	The flight is under your control for maneuvering, and the flight has deviated from its assigned flight route and has not cleared to its target altitude yet.
KLM12 370 - 30	The flight is under your control for maneuvering, and the flight is following its assigned flight path. However, the flight has not cleared to its target altitude yet.
KLM12 300 - H	The flight is under your control for maneuvering and has cleared to its target altitude. However, the flight has diverged from its assigned route and will not exit through the provided sector exit.
KLM12 300 -	The flight is under your control for maneuvering, and the flight is following its assigned flight path and has cleared to its target altitude.
KLM12 300 -	You have transferred the flight control to the adjacent ATCo, and the flight is following the route and has reached its target altitude. The control is usually transferred while the flight is near the sector exit and is free of potential conflicts.

Assuming control over incoming flights

Assumed flights and expediting the flow to target FL and assigned sector exit

Transfer control of outgoing flights

Figure 3: Flight labels and their significance for attention in expediting their flow

When an ATCo provides a control input, such as a flight level change to a flight for reaching its target value, an arrow is introduced (climb or descent) along with the cleared flight level in the flight label.

2.2. Control Inputs

ATCos meet defined goals by scanning the radar display to find a flight requiring attention and provide a control action. Clearing a flight to its target states, preserving the separation minima, or providing an efficient trajectory are criteria for assigning attention to a flight and providing a control action accordingly.

Control inputs are accessible by clicking the interactive items on the flight label and opening the clearance menus, as shown in Figure 4. The clearance menu is accessed by the specific label item that is clicked, as follows:

1. **Callsign:** allows ATCo to assume control over incoming flights from the adjacent sector or transfer outgoing flights' control to the adjacent sector. The clearance menu also allows ATCo to initiate the VERA tool starting from that flight.
2. **Cleared Flight Level (CFL):** opens the flight level menu, allowing ATCo to initiate altitude change, and if the target flight level deviates from the current cleared level, the mouse cursor will automatically snap to it.
3. **Heading (HDG):** opens the heading clearance menu, allowing ATCo to input either an absolute heading or a relative heading (e.g., adjusting the flight a certain number of degrees to the left or right from the current heading).

4. **Heading (DCT):** opens the Direct-To (DCT) menu, allowing ATCo to adjust the current route by removing the intermediate waypoints while expediting its flow towards sector exit.

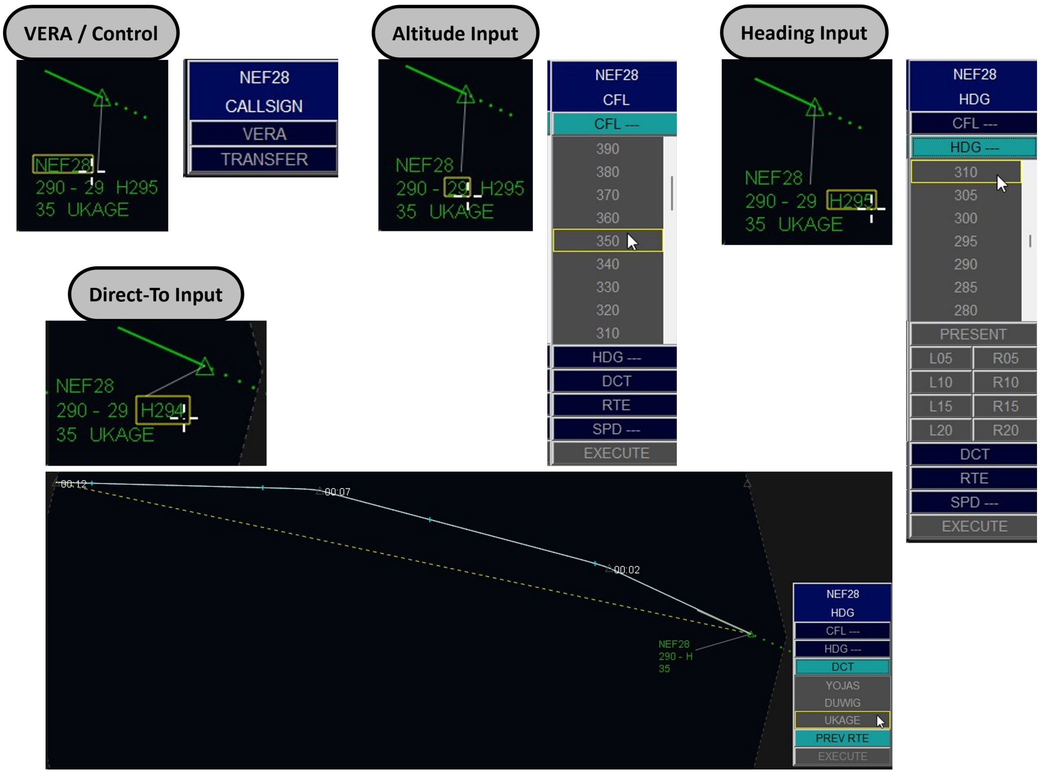


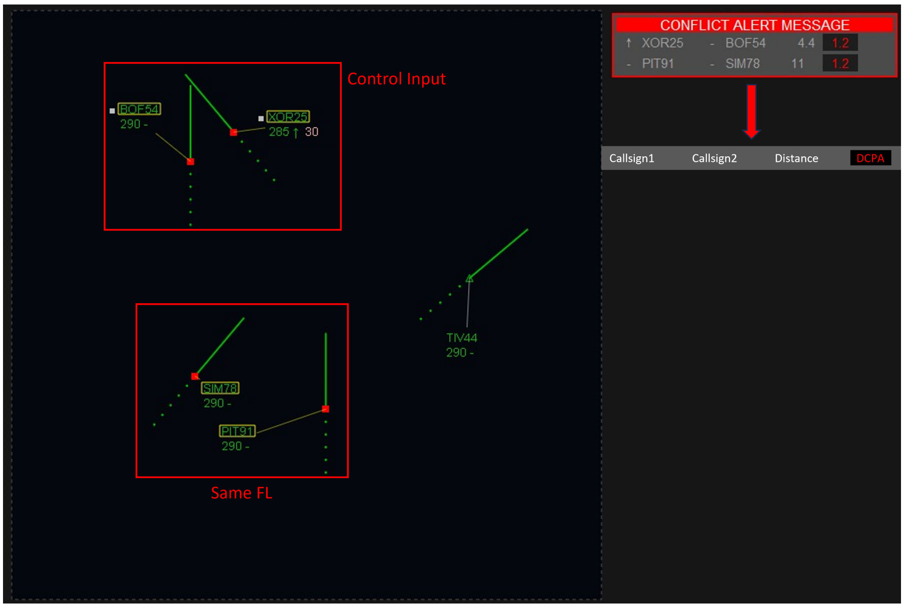
Figure 4: Means to execute the ATC control tasks to expedite the flow

After selecting the preferred clearance action, ATCo has to click the ***EXECUTE*** in the clearance menu to execute the command. The ATCo can provide maneuvers to only flights under their control (assumed flights) and has no authority over other flights.

2.3. Expediting the Air Traffic

ATCo is responsible for the safe and expedient flow of air traffic in their sector. Flights should be separated at least 5 NM horizontally or 10 FL vertically to maintain safety in the upper airspace. A Loss of Separation (LOS) occurs in the sector if the ATCo fails to maintain horizontal and vertical separation simultaneously between a flight pair. A conflict is called a prediction of LOS and is a key parameter for the overall safety of the airspace.

ATCo uses a look-ahead time strategy to foresee the possibility of conflicts based on the current situation and choice of maneuver to implement. MUAC utilizes STCA, a safety alert tool warning ATCo of immediate LOS situations within a short look-ahead time of 2 minutes based on the radar data or ATCo input, assuming they remain on the current track. The STCA tool displays the callsigns, current separation distance, and distance CPA for conflicting flights based on their urgency. Figure 5 shows an example of STCA for two pairs; Flight SIM78 and Flight PIT91 have conflict while flying at the same flight level, and Flight BOF54 and Flight XOR25 have conflict based on an ATCo input of a level change for Flight XOR25.


CONFLICT ALERT MESSAGE

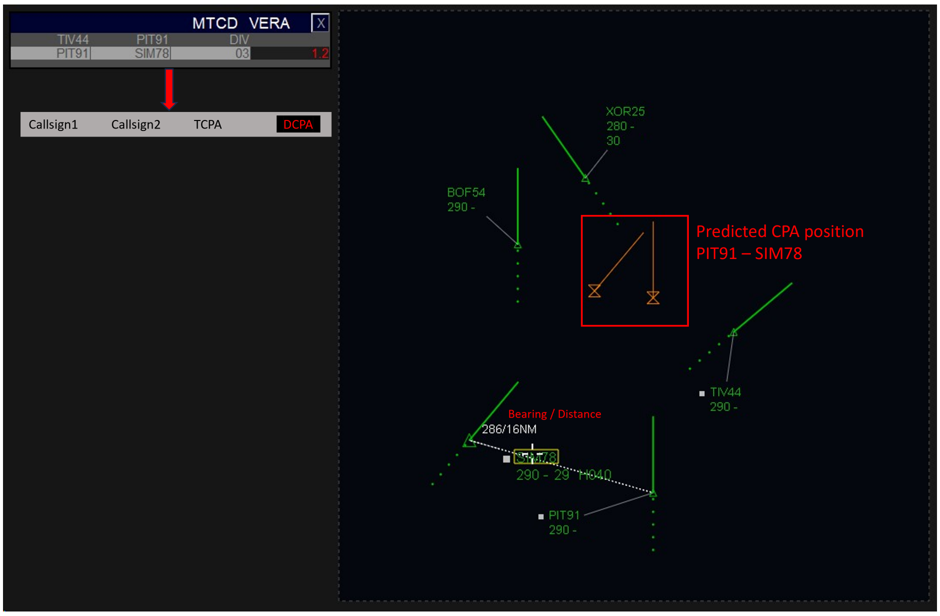
↑ XOR25 - BOF54 4.4 1.2

\- PIT91 - SIM78 11 1.2

Callsign1 Callsign2 Distance DCPA

Figure 5: STCA table and its significance

Ideally, ATCos should expedite air traffic safely and efficiently in the sector without triggering alerts from the STCA tool. For this, ATCos at MUAC uses the VERA tool to determine the relative distance, bearing angle, time CPA, and distance CPA of flight pairs. The VERA tool extrapolates and predicts future flight positions based on the surveillance data by considering their current headings and not flight intent, as shown in Figure 6. Once the flight pair has reached their possible minimum separation based on the current heading, the VERA tool shows the diverging message in the VERA table. VERA tool allows the ATCo to monitor multiple flight pairs and delete the flight pair (not requiring any more attention) from the VERA table with a single right mouse click for that flight pair in the VERA table.


MTCD VERA

TIV44 PIT91 DIV

PIT91 SIM78 03 1.2

Callsign1 Callsign2 TCPA DCPA

Figure 6: VERA table and its significance

SectorX allows the inspection of the current route of the flight by a single long left mouse click of the heading parameter in the flight label, as shown in Figure 7. If the flight diverges from its assigned trajectory, inspecting the route is still possible and can be directed toward its exit waypoint by clicking the **HDG** label item and opening **DCT** clearance menu.

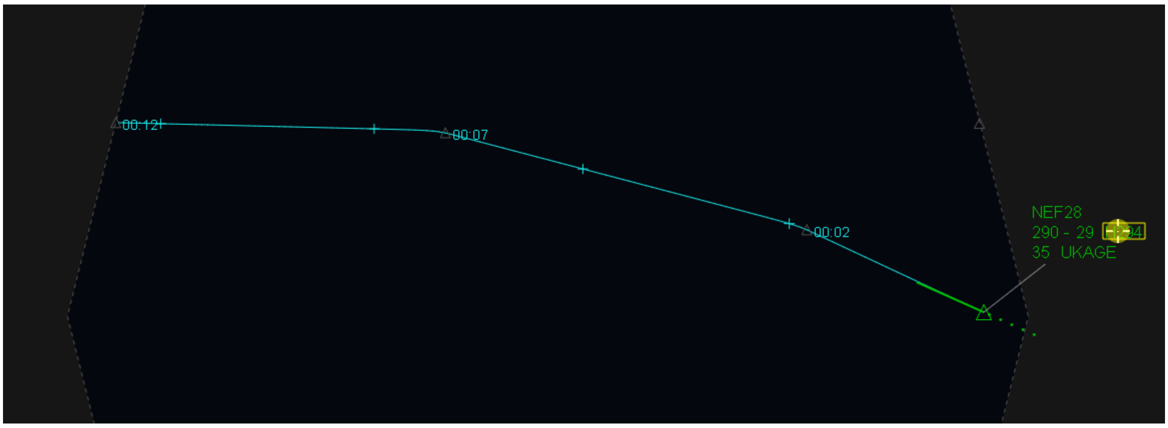


Figure 7: Inspecting the flight route

2.4. Visual Guidance Tool

ATCos provide command to the flights by scanning the radar display, selecting a flight of interest requiring attention, and evaluating the impact of potential control action on the sector safety and efficiency. The last two steps involve comparing several flight parameters displayed on the flight labels to examine whether the potential control action for the selected flight of interest does not introduce any additional conflicts to the surrounding traffic.

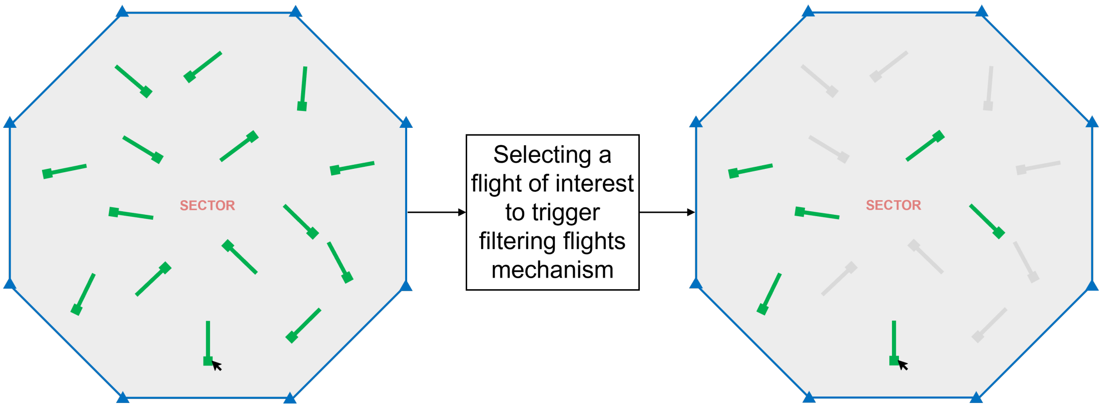
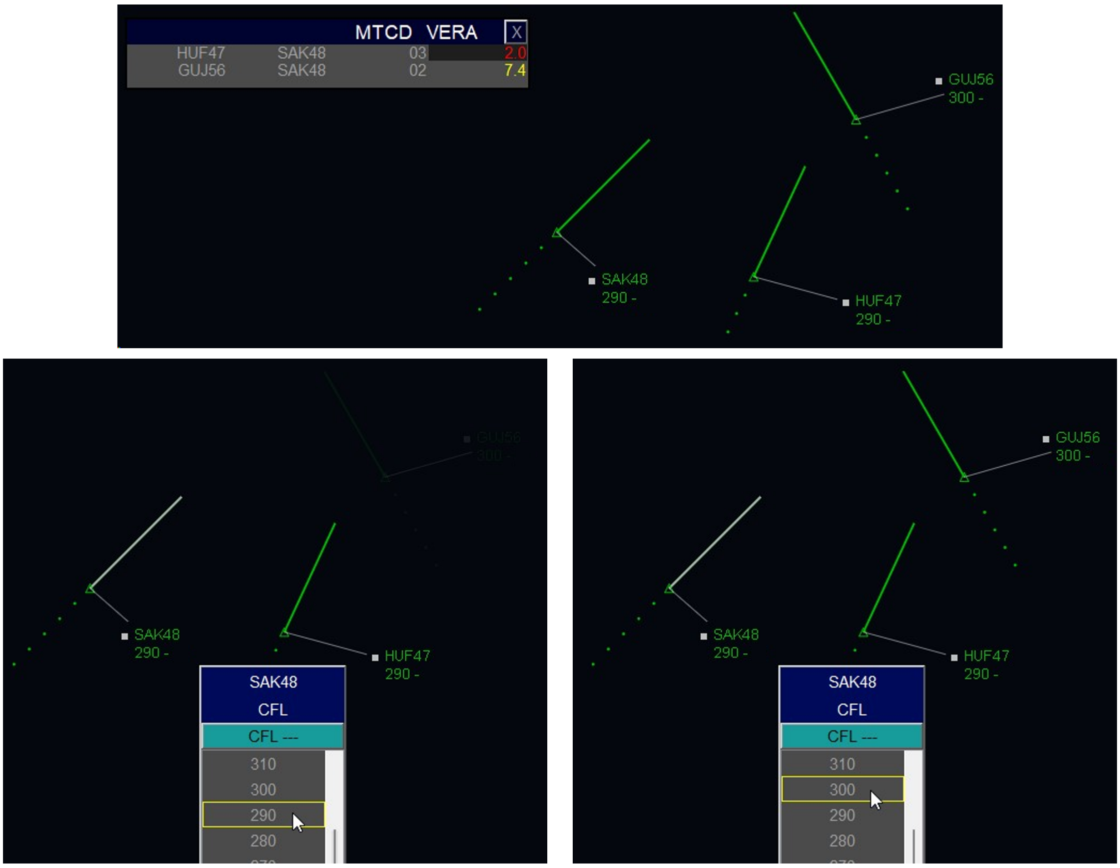


Figure 8: Visual attention guidance relative to potential control action for selected flight of interest

ATCo provides a heading, altitude, or direct-to clearance to a flight to expedite the flow safely and efficiently through the sector while attaining the target states. ATCos predict and provide maneuvers to flights in the sector before triggering alerts from the STCA table to achieve safety. To improve efficiency, ATCos clears the flight directly towards its sector exit rather than making it fly a structured route, thus reducing the additional flown distance for that flight. The provided maneuver may be safe and efficient for that time instance but may later threaten the sector's safety.

The proposed visual attention guidance tool will display flights that may impact the selected flight of interest based on the potential control action before executing it while expediting through the sector. The flights deemed irrelevant relative to the probable control action or the target states for the selected flight of interest lose their luminance and fade in the background, as shown in Figure 8.

Figure 9 provides a scenario between two flights (Flight SAK48 and Flight HUF47) that would experience an LOS situation as deducted using the VERA tool. Changing the heading, altitude, or route of the conflicting flights can resolve the conflict. Depending on the potential resolution maneuver, the flights deemed irrelevant or potentially not threatening the safety of selected flight of interest lose their luminance based on the maneuver choice. The ATCos could choose the best control action for the selected flight of interest based on the previewing of the number of flights getting affected through the probable control action for the selected flight of interest.



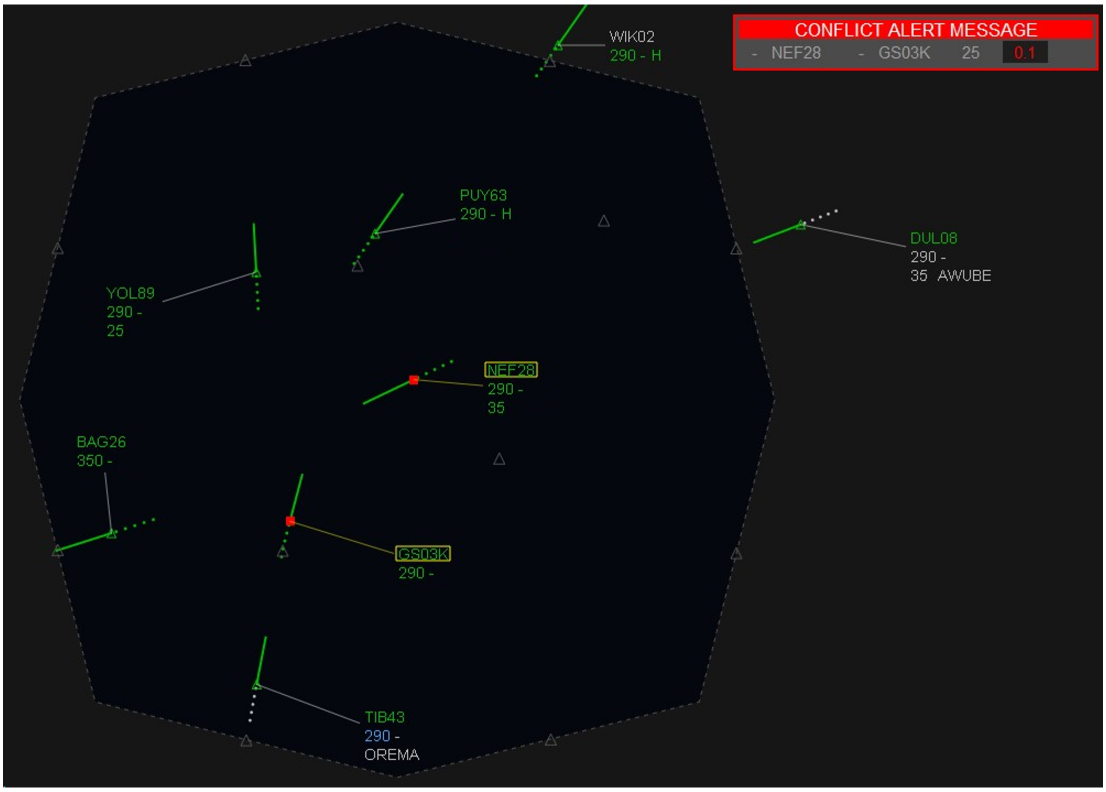
MTCD	VERA		
HUF47	SAK48	03	2.0
GUJ56	SAK48	02	7.4

Figure 9: Visual attention guidance while providing altitude change to Flight SAK48 to solve a conflict

The flights deemed relevant relative to the probable control action for the selected flight of interest indicate the closer proximity rather than guaranteeing the LOS situation with the selected flight of interest. For example, providing a flight level change to Flight SAK48 introduces the relevant Flight GUJ56 in the sector, even though the DCPA between these two flights is 7.4 NM, as indicated in the VERA tool. The ATCos should judge the relevant flights relative to the potential control action more promptly and provide the maneuver accordingly.

3. Experiment Setup and Goals

The following section presents the phases of the experiment and the tasks participants need to complete. The experiment session will last up to 2.5 to 3 hours. The first phase of the experiment is the training phase, where the participant will be instructed and trained in all the aspects of using the SectorX simulator for approximately 65 minutes, followed by a 10-minute break. The second phase of the experiment is the measuring phase, where the participants have to expedite the air traffic safely and efficiently through the sector for about 60 minutes (including a 10-minute break). The third phase of the experiment is the questionnaire for 20 minutes, where the participants are encouraged to provide feedback related to human factors concerning the experiment.



CONFLICT ALERT MESSAGE

- NEF28 - GS03K 25 0.1

Figure 10: Instances of assigning attention to a flight

In the measuring phase, the participants expedite the air traffic safely and efficiently through the sector. The participants assume control over incoming flights, monitor their flow through the assigned flight plan, clear them to their target altitudes, and transfer their control to the adjacent ATCo while the flights leave the sector. The participants are provided with the VERA tool, assisting them in predicting the current and future separation characteristics between flights in the simulation. The ATCos have to observe scenarios and provide control inputs while avoiding alerts from the STCA table. Following are the instances that could require attention while providing the control inputs and expediting the flow safely and efficiently through the sector, as shown in Figure 10:

(a) **Conflict Alert:** The flights will experience a LOS situation, violating horizontal (5 NM) and vertical (10 FL) separation simultaneously within 2 minutes based on radar data/participant input (Flight NEF28 and Flight GS03K).

(b) **Deviating from the route:** The flight is not following the assigned route and will deviate from its sector exit (Flight PUY63).

(c) **Not cleared to its target flight level:** The flight has not cleared to its target flight level yet, which is required while exiting the sector (Flight NEF28K and Flight YOL89).

Other instances for assigning attention to a flight include assuming the incoming flight late (after entering the sector - Flight TIB43) and not transferring the flight control to the adjacent ATCos while leaving the sector (Flight BAG26). The participant can provide maneuvers to only flights under their control (assumed flights) and not other flights.

The participants experience both scenarios with and without visual attention guidance support tools relative to the potential control action for the selected flight of interest. Each scenario consists of 25 minutes, tallying up to 50 minutes for the measuring phase, and the scenario order might vary among participants. The sector used during the experiment is presented in Figure 11.

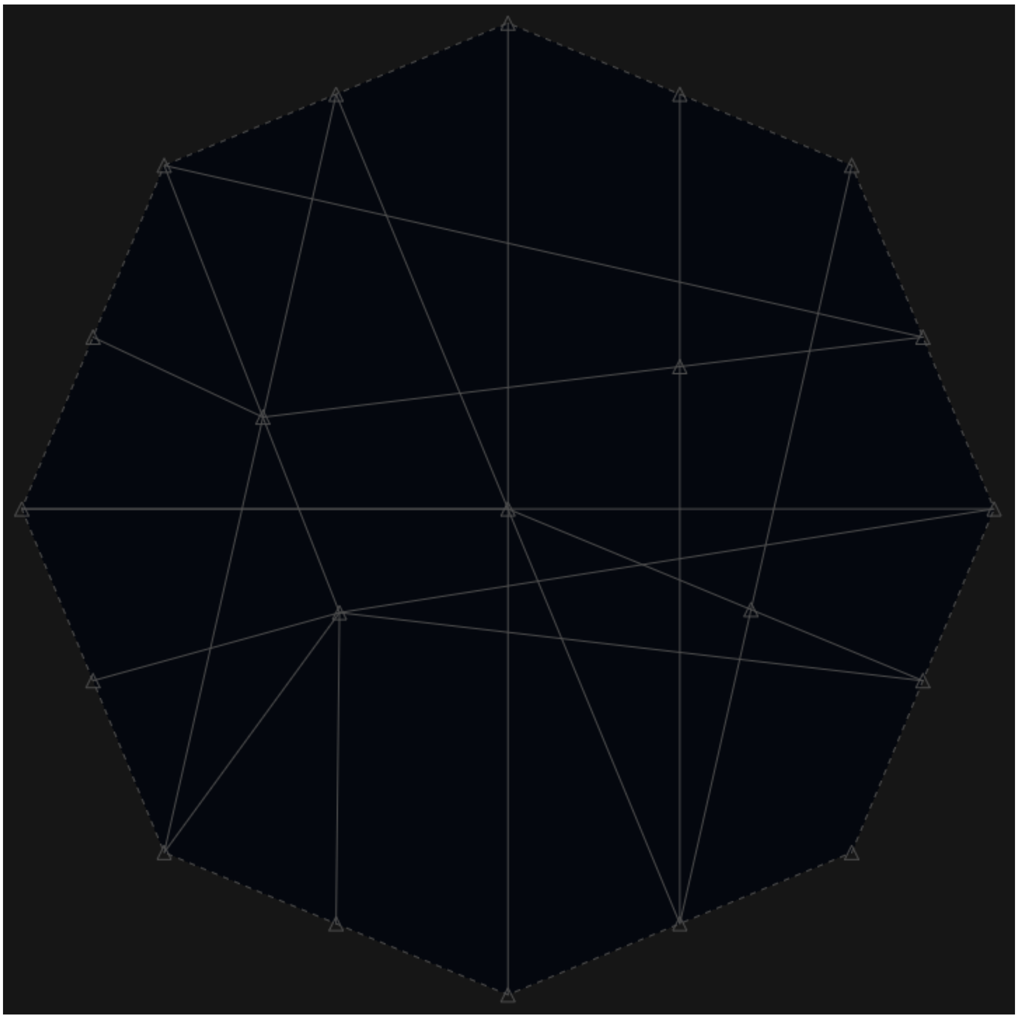


Figure 11: Sector design to be used in the experiment

4. Best Practices and Tips

The following section provides you with some tips and tricks that you should use during the experiment.

- Assume control over incoming flights before they enter the sector and check their route and target flight level initially to account for possible crossings with other flights while expediting its flow.
- Maintaining sufficient vertical separation between a flight pair would guarantee safety even if they encounter closer proximity in the horizontal plane.
- In case of a possible conflict, it is better to solve it sooner and more precautionary than later. Solving the conflict belated limits the number of resolution maneuver choices.
- For flights sharing the same flight level and with a possibility of conflict, provide a horizontal maneuver to a flight arriving at the crossing point late using the VERA tool. As shown in Figure 12, providing a maneuver to Flight MAQ02 (reaching the crossing point late) solves the conflict early and efficiently with less heading deviation. It supports ATCo's strategies of steering a flight behind another.

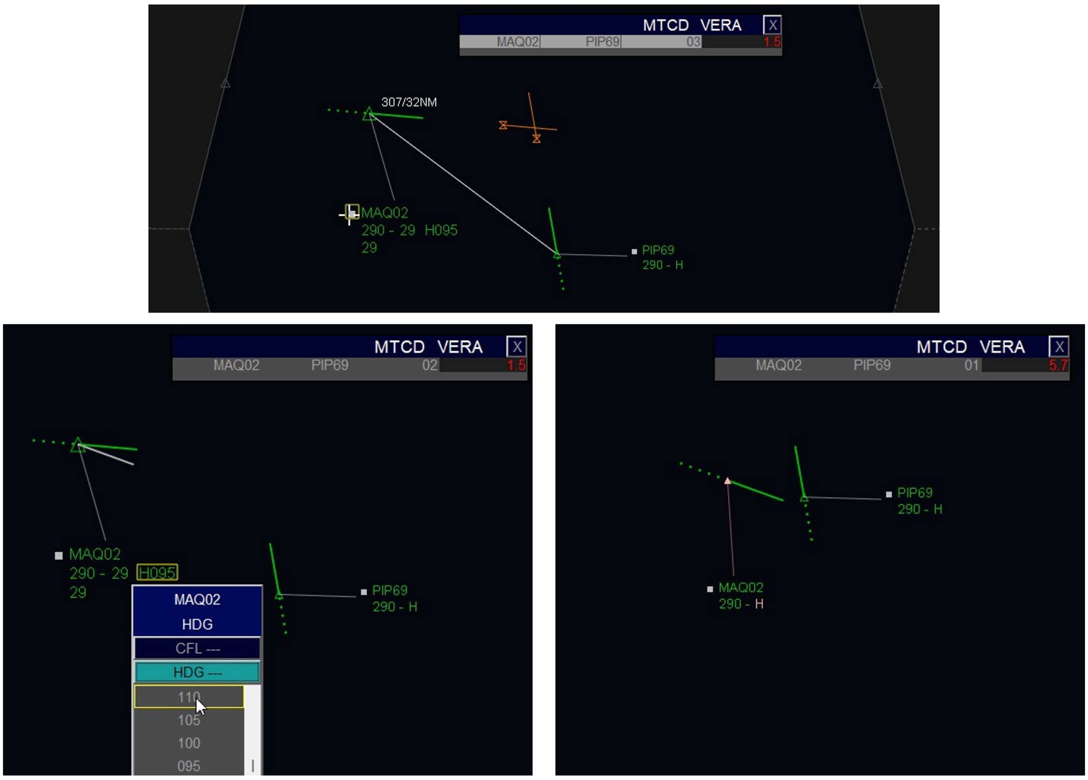
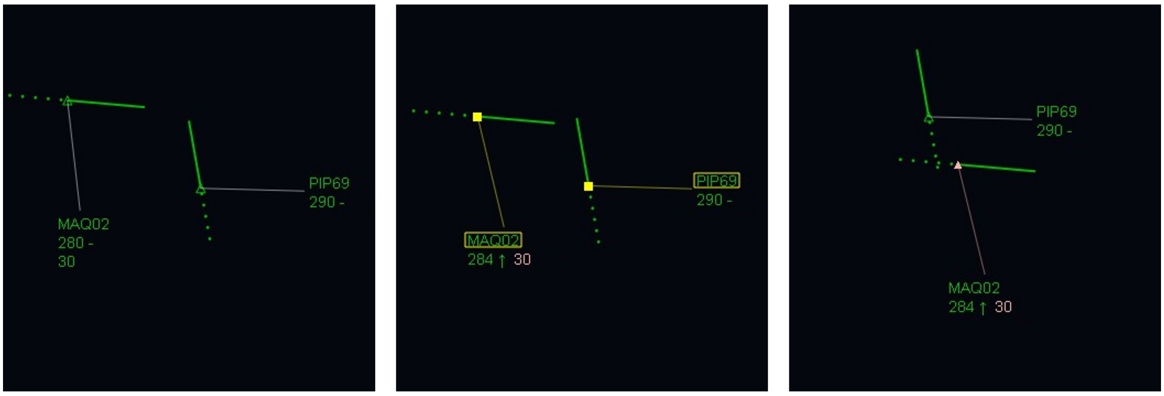


Figure 12: A simple way to provide a horizontal maneuver using the VERA tool

- The horizontal maneuver occurs through **HDG** or **DCT** clearance menus. Selecting an **HDG** item and providing a heading change might solve the conflict, along with diverging the flight from the assigned flight plan. The participant can notice it through the flight label, and they have to reroute the flight toward its sector exit using the **DCT** clearance menu.

- For flights requiring a vertical transition, initiate a step-wise approach (10 FL or 20 FL) rather than clearing it directly to the target level, especially for climbing flights because they take a longer time to reach cleared flight level compared to descending flights and have a higher chance of getting a conflict during the transition.
- For flights with closer horizontal proximity, provide a vertical maneuver to flight once diverging through the horizontal plane to avoid conflict with other flights during the transition while reaching the cleared / target flight level, as shown in Figure 13.



(a) Scenario (b) Before convergence – STCA alert possible (c) After convergence – safer solution

Figure 13: Providing a vertical maneuver to a flight to reach a cleared flight level during convergence

- Flights flying at higher altitudes are more efficient because they fly faster and leave the sector sooner than at lower altitudes.
- Transfer the flights once the flights are near the sector exit and if you are sure that there will not be any conflict near the sector exit.
- Try to use the VERA tool for necessary flights only (converging flights with overlapping altitudes) and find a solution minimizing the number of commands in total to keep workload low and improve overall efficiency.
- Safety and flights exiting through assigned sector exit have priority over efficiency and achieving target altitudes. The participant should trust their judgment in expediting the flow efficiently and maneuvering flights to their target flight level without triggering alerts from the STCA table. The flight routes might be structured to avoid potential conflicts, and skipping the intermediate waypoints (clearing directly towards the sector exit) does not always guarantee safety.

Note: The flights introduced (relevant) relative to the potential control action for the selected flight of interest might have a closer proximity rather than guaranteeing LOS.

F

Additional Results

F.1. Practice Run Plots

This section analyses the objective measures recorded during practice runs for both filtering and no-filtering conditions, with participants experiencing filtering on the second simulation run.

F.1.1. Safety

Figure F.1 shows the timing of clearances issued to resolve planned safety violations. Negative data points indicate proactive conflict resolution before STCA activation. The Wilcoxon signed-rank test revealed a significant difference in response time for planned conflict between conditions with and without filtering (p = 0.05). Proactive conflict resolutions involved participants issuing direct-to-exit clearances to either one or both conflicting flights. There was just one STCA for the planned safety violation in both experiment conditions. No-filtering condition induced the STCA duration of 52.89 seconds, whereas filtering had 24.07 seconds for the planned conflict.

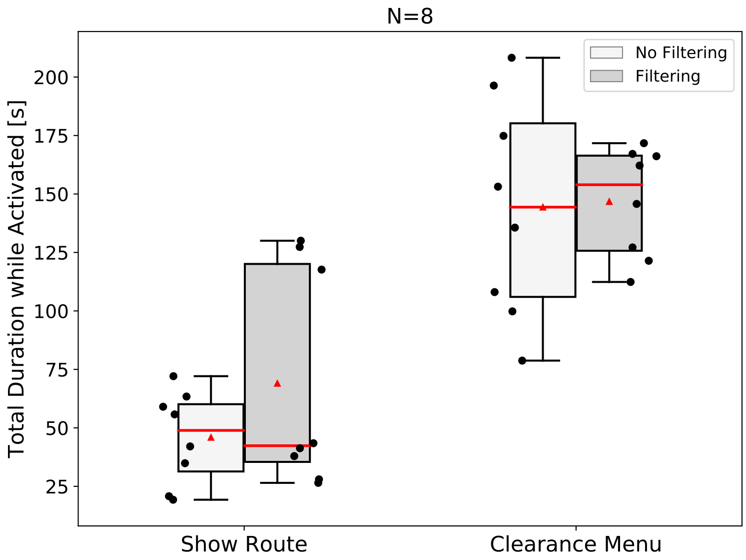


Figure F.1: Response time for planned STCA in practice runs.

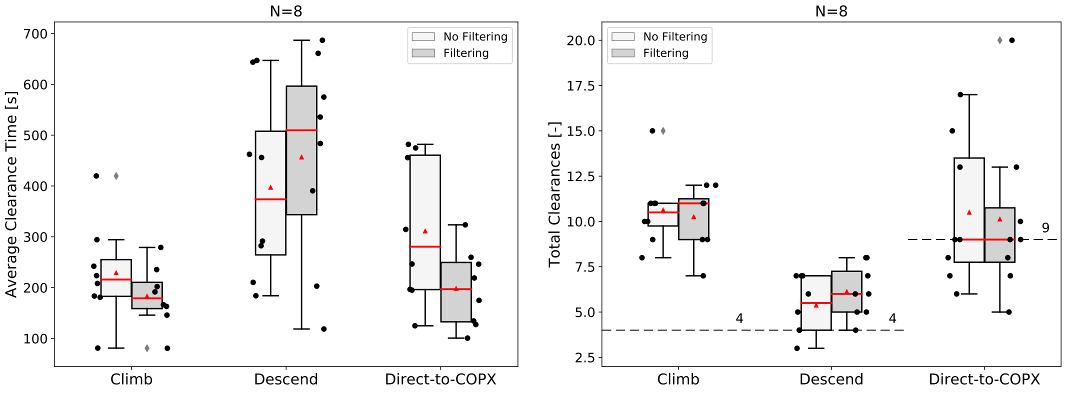
The no-filtering condition had no secondary STCAs, whereas the filtering condition had a participant generating an STCA while clearing a flight for the climb, creating an STCA duration of 14.44 seconds during the transition. This concludes that even though filtering may support resolving conflicts early, operator's clearances play a primal role in maintaining sector safety.

F.1.2. Control Performance

The average time taken by participants to issue the first clearance for climbing, descending, and indirect flights to meet operational demands is shown in Figure F.2a, comparing filtering and no-filtering conditions. The Wilcoxon-signed rank test did not reveal significant differences in the average clearance time for climbs and descents between the experimental conditions. However, the Wilcoxon signed-rank test revealed significant differences (p = 0.036) for average time for issuing a direct-to-exit clearance.

Figure F.2b shows the total number of clearances participants issued, with black dotted lines indicating the minimum clearances required to meet operational demands within a simulation trial. The mean and median for total climbs, descends, and direct-to-exit clearances issued are similar for both experiment conditions. A total of four heading clearances were issued in the no-filtering condition, whereas filtering had one heading clearance.

Analyzing deviations from task requirements revealed discrepancies in achieving the designated transfer flight levels for climbing flights. In the no-filtering conditions, three participants fell short of the transfer flight levels by a combined 40 FLs, while under filtering conditions, one participant underachieved for a deviation of 20 FLs. For descending flights, four participants failed to reach the transfer flight levels by a cumulative deviation of 90 FLs. Conversely, with filtering conditions, three participants demonstrated a shortfall with a total deviation of 60 FLs. All flights exited through their assigned sector exit for both experiment conditions. This substantial discrepancy suggests that filtering enabled participants to meet operational demands relatively better than the no-filtering condition.



(a) Average time to issue first clearance for climbing, descending and indirect flights considering operational efficiency.

(b) total altitude and direct-to-exit clearances issued with black dotted lines indicating the number of flights requiring clearance.

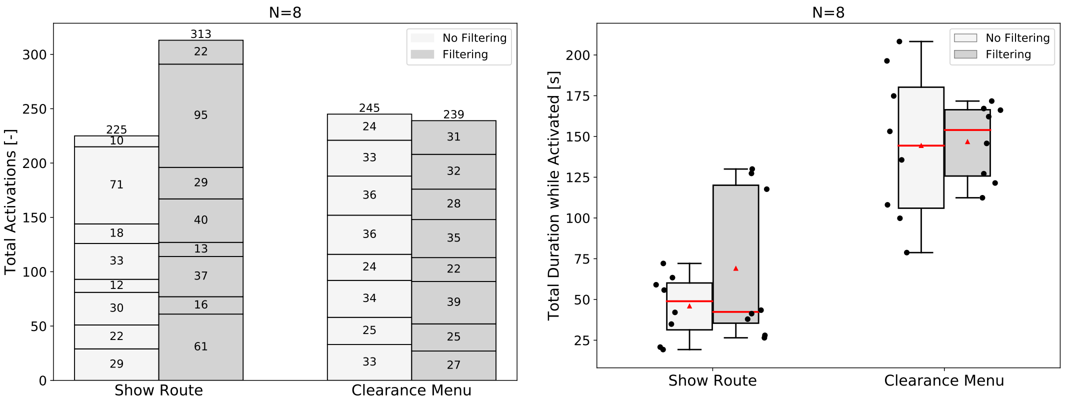
Figure F.2: Procedural compliance results while controlling the traffic in practice runs

Even though participants performed better in issuing efficient clearances during filtering condition, keeping flights at higher flight levels by issuing climb promptly and delay descends during filtering condition, the Wilcoxon-signed rank test confirmed no significant differences between the experiment conditions. Participants issued sector exit clearances sooner with filtering support, confirmed through the Wilcoxon-signed rank test. Participants with filtering support met operational demand with almost the same number of clearances as no-filtering condition. This concludes that filtering does not necessarily improve procedural compliance while controlling traffic.

F.1.3. Control Effort and Perceived Workload

Relevant flights are not highlighted unless the participant triggers filtering by inspecting their route or during clearance issuance. Figure F.3 shows the comparisons between conditions with and without filtering among participants relying on these activities. Participants during the filtering condition inspected flight routes more frequently and had a significant difference (p = 0.025) confirmed through the Wilcoxon-signed rank test. The data spread for the total duration participants perceive the filtered results are extensive, indicating few participants inspected routes for longer duration, which can be because of more frequent route inspections. However, no differences were observed in the total duration of participants perceiving filtered results through route inspections.

While issuing clearances, no significant differences were observed between conditions with and without filtering. The data points recorded during clearance issuance take into account the duration the clearance menu remained open and the participants' browsing through different clearances. This indicates that filtering did not have much effect while previewing the impact of various clearances on surrounding traffic.



(a) total activations for inspecting the route and opening clearance menu.

(b) total duration while inspecting the route and browsing through clearance menu.

Figure F.3: Control effort by participants while controlling the traffic in practice runs.

Figure F.4 shows the total number of VERA checks performed by participants in both filtering and no-filtering conditions. Although the Wilcoxon signed-rank test revealed no significant differences in VERA usage, filtering had more VERA initiations than no-filtering, contradicting the initial expectations. The possible explanation is that with filtering, few participants were proactive in monitoring multiple flight pairs to issue efficient clearances.

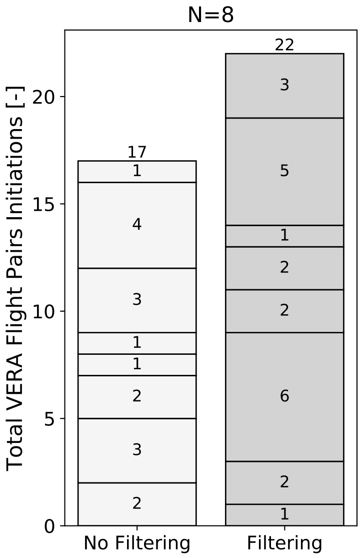
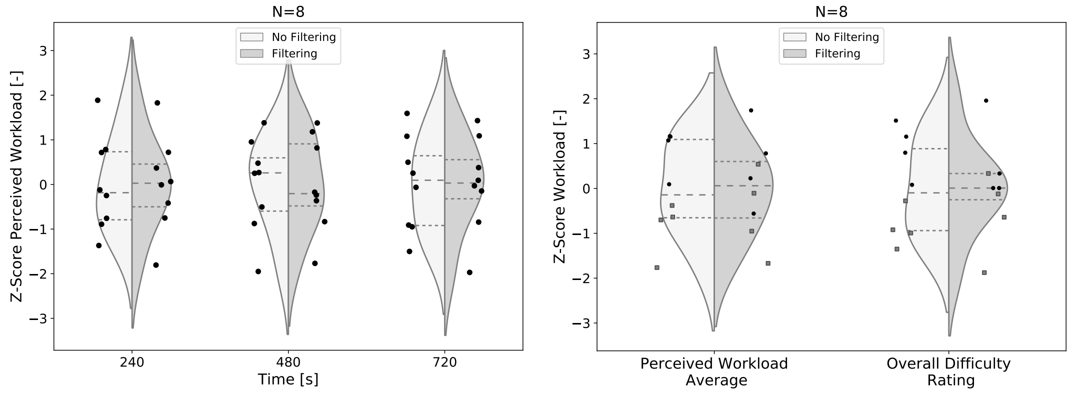


Figure F.4: Total VERA activations of unique flight pairs in practice runs.

Figure F.5 shows the Z-scores of perceived workload over time and the overall difficulty rating experienced by participants while controlling the traffic. The Wilcoxon-signed rank test confirmed no significant differences in perceived workload between conditions with and without filtering.



(a) perceived workload rating over time.

(b) average perceived workload and overall difficulty ratings

Figure F.5: Z-scores of perceived workload and overall difficulty rating while controlling traffic in practice runs.

Filtering plays a minor role in alleviating the cognitive efforts required for comparing flight parameters during conflict detection and issuing clearances. Filtering remains inactive during general traffic monitoring and is activated only during route inspections or previewing preferred clearances. Participants are likely to have a strong understanding of the traffic situation before activating filtering, which may result in only a modest reduction in their workload. Moreover, participants might misuse filtering by unnecessarily triggering it to explore its inner workings, resulting in no reduction in workload, as evidenced by frequent route inspections.

F.2. Experiment Survey Results

Following are the responses of participants while answering the subjective responses and open feedback questions related to the flight filtering concept:

1. **Please indicate your ratings for 'baseline (no filtering)' on the following dimensions:**

	Very Poor	Poor	Average	Good	Excellent
Mananging your workload		P01, P04,	P02, P03, P05, P06, P07	P08	
Maintaining your situation awareness		P04	P01, P02, P03, P05, P06, P07	P08	
Timely detecting and solving conflicts		P01, P04, P05, P07	P02, P03, P06, P08,		
Efficiently expediting traffic through sector		P01	P04, P05, P07, P08,	P02, P03, P06	

2. **Please indicate your ratings for 'flight filtering' on the following dimensions:**

	Very Poor	Poor	Average	Good	Excellent
Mananging your workload		P04	P02, P05, P06, P07	P01, P03, P08	
Maintaining your situation awareness		P04	P01	P02, P03, P05, P06, P07, P08	
Timely detecting and solving conflicts			P04, P07, P08	P01, P02, P03, P05, P06	
Efficiently expediting traffic through sector			P04, P05, P08	P02, P03, P06, P07	P01

3. **How much did you rely on the ‘flight filtering’ in controlling traffic?**

Not at all	Slightly	Moderately	Very	Extremely
P08	P02, P04	P01, P05, P06, P07	P03	

4. **Briefly explain your rating.**

- **P01:** When i use filtering, i could easily issue DCT command without hesitation, but could not rely that much with altitude overlap case (even though i want).
- **P02:** The measurement runs were higher workload than the practice runs, so the use of the flight filtering was lower in the measurement run than the practice run. In the practice run I used the filtering a couple of time and it was useful. In the measurement run I was often overwhelmed and didn’t have time to use the feature.
- **P03:** I did not check for potential issues with flights that did not show up in the filtering as much as I would’ve done if there was no filtering available.
- **P04:** flight filtering useful when giving direct
- **P05:** to check potential conflicts
- **P06:** Workload was quite high (for me), so I used the filtering opportunity to some extent. When workload would be less I think I’d have more time to search for options provided by the filtering.
- **P07:** The scenario was quite busy. Although it was automatically activated when showing the route, I did not have enough time to fully digest the filtering results.
- **P08:** It was not really part of my scanning pattern / workflow

5. **How much did you trust on the ‘flight filtering’ in controlling traffic?**

- **Slightly:** P02
- **Very:** P01, P03, P04, P05, P06, P07, P08

6. **Briefly explain your rating.**

- **P01:** sometimes it also provides me with the aircraft which is not that relevant in my opinions, so i believe it save itself with quiet sufficient buffer, which make me feel trustworthy.
- **P02:** When I used it (mainly during practice), it was useful in a broad sense, but I did not trust it to prevent future conflicts. I can imagine that by working with the system, more trust can be gained, e.g. by seeing how it handles future or expected changes in the flight paths.
- **P03:** I did re-check for potential issues further down the route, for example flights that may become a problem if I were to give clearances to those flights to solve another issue. I don’t think the filtering took that into account (i.e., carry-over effects from solving one conflict that may in turn impact another flight)
- **P04:** Filtering looked reasonable, not enough experience to know whether incorrect filtering applied
- **P05:** it is very clear for filtering out non relevant aircraft
- **P06:** Overall it was showing the scenario/traffic in the way I expected, that is, it left out the a/c which I also expected to play no role. This helped me build trust in the filtering,
- **P07:** In my opinion, the filtering was trustworthy, although sometimes I though it was quite ’conservative.’ In some cases, I had the impression that even diverging flights were highlighted.
- **P08:** I have no reason to doubt it

7. **How much did the filtered results match your expectations?**

- **Moderately:** P01, P04
- **Very:** P02, P03, P05, P06, P07, P08

8. **How much did you agree with the filtered results in terms of relevant/highlighted flights?**

- **Moderately:** P01
- **Very:** P02, P03, P04, P05, P06, P07, P08

9. **How much did you agree with fading all non-relevant flights?**
   - **Moderately:** P04, P06
   - **Very:** P01, P02, P03, P05, P07, P08
10. **Please briefly explain your ratings for the expectations and agreeableness of the fading/highlighting of the non-relevant/relevant flights.**
    - **P01:** Like question 9, i think there are even more flights should be faded away, especially when i do the computation about altitude, i hope there could be less targets that i need to focus on. While for the aircraft group that have already be faded away, i feel satisfied.
    - **P02:** I was never caught out by any flights that were deemed irrelevant, or presented with flights I wouldn't have kept an eye on myself.
    - **P03:** I think I saw a couple of flights that were not faded, even tough they were irrelevant in my opinion, because they were "behind" the selected flight, e.g., on diverging trajectories.
    - **P04:** fading maybe a bit too much, greying OK, but keep faded flights a bit more visible
    - **P05:** the ones that are filtered are correct in my opinion
    - **P06:** I would fade the non-relevant flights a little less, now they almost disappeared.
    - **P07:** I felt I could trust the filtered results. I liked the fading of non-relevant flights, because it directly indicates how many potential interactions a flight of interest might have.
    - **P08:** Once you get used to using it I think it can be a practical addition to the HMI
11. **How often did you make use of 'flight filtering' in detecting conflicts?**

Not at all	Slightly	Moderately	Very	Extremely
P04, P05, P08	P02	P01, P07	P03, P06	

12. **How often did you make use of 'flight filtering' in previewing clearances before executing them?**

Not at all	Slightly	Moderately	Very	Extremely
P08	P01, P03, P06	P02, P04, P05	P07	

13. **Please briefly explain how you used 'flight filtering' in your control strategy to safely and efficiently expedite the flow of traffic.**
    - **P01:** For efficiency: I activated flight filtering to check if there is a relative large space for DCT command, and manually check the current alt information of each aircraft (filtering offers) involved in that area. For safety: i simply count on the check when there is a crossing geometry then check altitude, even the flight filtering can help me to exclude some irrelevant aircraft, but i wont pay attention to most of them without filtering. In other words, the number of aircraft in conflict that you need to check is indeed not that much, so filtering's bonus support is limited.
    - **P02:** Mostly during practice I tried to vertical separate the flights as much as possible, based on the filtering, before fine-tuning the horizontal separation.
    - **P03:** I used the filter (especially when previewing the route), to narrow down the flights that I had to check for potential conflicts. I also used it (the route preview with filtering) to see which flights I needed to check before executing a control action, but I don't think I used the filtering to actually preview those clearances, except for maybe a few cases. I did use the VERA preview a couple of times when I wanted to give a heading clearance, to see if it would provide sufficient separation.
    - **P04:** efficiently inspecting flights that would be relevant for direct / shortcut
    - **P05:** for conflict detection, the filtering requires several clicks, which I am not too familiar
    - **P06:** It helped to detect, but to resolve I mostly used VERA or my own intuition.
    - **P07:** I used filtering most frequently for seeing if a DCT was safe and if it was safe to TRANSFER an aircraft. For detecting conflicts, I needed to use VERA as a follow-up to the filtered results. I did miss a few conflicts though, which I did not spot even with filtering. Again, this might have been caused by some workload 'overload' due to complexity of the scenario.

- **P08:** I sometimes noticed it when selecting a command. In these cases it served as a confirmation

14. **Do you have any other comment and/or suggestions on how to improve 'flight filtering'?**

    - **P01:** For altitude case, there are still a lot of computation need to be done with my mind, but i have no idea that how much closer the distance between aircraft would get during altitude change, is there enough horizontal distance for the altitude change at this moment (e.g. before conflict alert come out, before the aircraft exit the sector) ?
    - **P02:** I found the measurement scenarios quite challenging, which reduced my spare mental capacity. I couldn't use the filtering as much as I wanted.
    - **P03:** - When giving a direct it would be nice to see the effect directly when hovering over a route point. - The fading might be slightly too much. Might be nice to still be able to see the faded flights a little bit better, to get a better overall overview of the airspace.
    - **P04:** NA
    - **P05:** showing filter with ctrl (e.g.) with mouse over
    - **P06:** Apart from the fading, no.
    - **P07:** It looks great. I wonder if professional ATCOs really need this filtering; I see it more as a potential training tool or as a supportive tool for less-experienced ATCOs.
    - **P08:** with more training it could be more useful / more used