

Avoidance of Adverse Weather Areas in Amsterdam Airport Schiphol Operations using Advanced Controller Support Tools

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Abstract—The Air Traffic Control - Trajectory Based Operations (ATC-TBO) project, a Single European Sky ATM Research (SESAR) initiative, aims to validate operational solutions for Trajectory Based Operations. As part of this project, the Royal Netherlands Aerospace Centre (NLR) developed a Conflict Detection and Resolution (CD&R) tool to indicate potential conflicts between aircraft and Adverse Weather Areas (AWA) to Air Traffic Controllers (ATCOs) working at Amsterdam Airport Schiphol (EHAM). The tool was validated through human-in-the-loop real-time simulations on the NLR ATM Research Simulator platform (NARSIM) together with assessment specialists from Deep Blue, showing promising results with potential benefits for operational safety. However, further development and refinement are needed to also address sequencing and separation issues. The CD&R tool is considered a solid basis for further research, aiming to enhance air traffic control operations and safety during adverse weather conditions.

Keywords—Trajectory Based Operations, Adverse Weather Areas, Conflict Detection and Resolution, NARSIM

I. INTRODUCTION

Within the Single European Sky ATM Research 3 (SESAR 3) Programme, the Air Traffic Control - Trajectory Based Operations (ATC-TBO) project aimed at a fundamental modernization of air traffic management in Europe, moving away from fragmented, reactive control toward a more predictive, data-driven and collaborative system approach.

At the core of this new approach lies the precise 4D aircraft trajectory as a central element of air traffic control. Instead of air traffic controllers (ATCOs) continuously intervening to resolve conflicts and adjust routes, all actors in the system, i.e. ATCOs, pilots, network managers, and airline operations centers will work from a shared and continuously updated trajectory. This is expected to create a common operational picture that allows decisions to be made earlier, with greater accuracy and less uncertainty.

A key objective of the ATC-TBO project was to embed trajectory-based operations into daily ATC practice, not just as a concept but as an operational reality. Therefore, a focus of the investigations was the tactical execution phase for en-route and Terminal Manoeuvring Area (TMA) operations.

This phase was validated by the project, thereby contributing to the vision expressed for the Deployment Phase of the Digital European Sky in the European ATM Master Plan [1].

The project activities involved developing and validating the tools, procedures, and system interfaces that allow ATCOs to manage traffic based on predicted trajectories rather than immediate surveillance observations alone. In this way, the project sought to enhance tactical ATC through trajectory-based management, enabling ATCOs to anticipate and manage traffic evolution while retaining the ability to intervene tactically whenever required.

Another important aim of ATC-TBO was to improve predictability and stability of flights across the network. By ensuring that all stakeholders use the same high-quality trajectory data, enabled by a digital information-sharing infrastructure, the system is expected to anticipate conflicts, congestion, and disruptions much earlier. This should allow for smoother traffic flows, fewer last-minute changes, and better use of available airspace capacity.

The project also focused on reducing workload and increasing efficiency. For ATCOs, this means that enhanced decision-support tools are added to the workplace that can automatically detect and propose solutions to conflicts based on trajectory data. For pilots and operators, it means fewer unexpected instructions and a closer alignment between planned and flown trajectories. Altogether, this must lead to more efficient flight operations, with benefits in terms of fuel consumption, delays, and environmental impact.

As part of the ATC-TBO project, NLR together with their partner in Human Factors assessment, Deep Blue, carried out a validation exercise that contributed to the operational validation of improved separation management processes and conflict resolution advisories with regard to so-called Adverse Weather Areas (AWAs). These are geographical regions of airspace where meteorological conditions are severe enough to negatively impact the safety, efficiency, or predictability of flight operations [2]. Validation occurred using observed locations and predicted movements of AWAs being integrated in the controller working positions (CWP) of both TMA and Amsterdam Area Control Centre (ACC) controllers (considered to be en-route controllers). To that end CD&R

software tooling was developed on NARSIM, the NLR ATC Research Simulator, a well-known, highly-realistic SESAR validation platform supporting executive ATCOs for ACC and TMA in a high-complexity environment, specifically the Amsterdam Airport Schiphol (EHAM) approach sectors. The exercise was based on earlier results of the SESAR 3 project PJ18 4D Skyways [3].

II. OPERATIONAL ENVIRONMENT

A. Characteristics

The operational environment that was chosen for carrying out the ATC-TBO validation activities of NLR and Deep Blue focused on the Eastern approaches towards Schiphol Airport. Since this airport and the surrounding airspace and traffic patterns are considered highly complex in a full operational configuration, involving many more controllers, it was decided to reduce the validation to a representative area that can operate independently without significant influence from surrounding operations.

Traffic flows on the Eastern side of Schiphol Airport were thus managed by ACC controllers in Sector 1 and 2 (Fig. 1) and arrival and departure traffic from and towards Sector 1 and 2 was managed by the TMA East controller (TOC) who had responsibility for the working area to the East of the highlighted dashed line in Fig. 2. All other traffic, including coordination with the arrival controller (ARR) and the departure controller (FDR/DCO) for the TMA, and coordination with adjacent centers for ACC (Langen ACC, Bremen ACC, Maastricht Upper Area Control Centre), was managed fully automatically by the simulator.

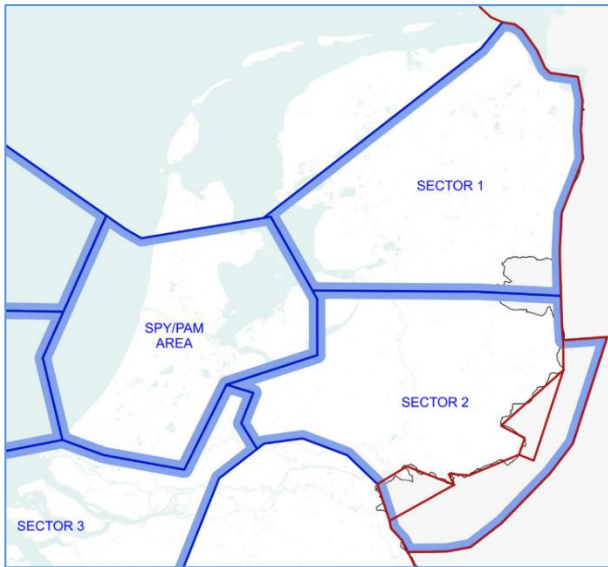


Fig. 1: ACC Working Environment in ATC-TBO.

For the operational solution developed in the validation environment, AWAs were shown to controllers with their observed location and predicted movement using nowcasts obtained from the Royal Dutch Meteorological Institute (KNMI). All controllers could use the menu structure of the touch-input devices on their working position to customize the visualization and set the desired look-ahead time for the nowcasts in incremental steps of five minutes. The nowcasts were shown in a different color from the AWAs in their observed location. Generally, the weather patterns were located inside the ACC, just outside the TMA East, and moved

along the TMA boundary from the southwest toward the northeast. This can be seen in Fig. 3 where the current observation is shown in blue and the nowcast in amber.

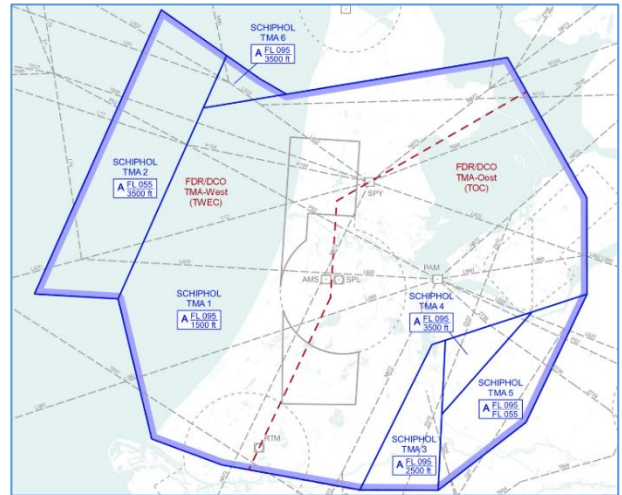


Fig. 2: TMA Working Environment in ATC-TBO.

On top of this new visualization of AWAs, ATCOs used additional tools as part of the developed TBO solution to detect and resolve conflicts between aircraft and AWAs. A closer look at these will be given in the next section.

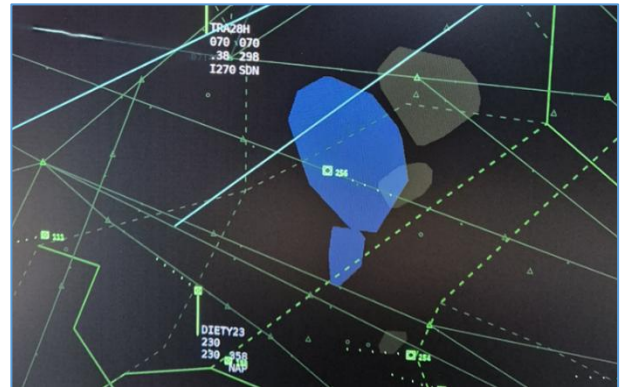


Fig. 3: AWA Visualization on Surveillance Displays (NARSIM).

The tools were implemented in a working environment that is highly realistic and that all participating ATCOs were very familiar with. It contained all relevant features that their current environment provides with the exception of short-term conflict alerting (STCA). This service was removed from the environment, as it did not fully represent the currently applied algorithm.

B. Actors and Service Provision

Three controller roles were considered in the simulations: two Amsterdam ACC controllers working the traffic towards initial approach fix (IAF) ARTIP (Fig. 4) and the Amsterdam Approach (APP) controller for TMA East (TOC).

The ACC controllers provided air traffic services (ATS) within their area of responsibility. For Sector 1 and Sector 2 these are the areas Amsterdam CTA East 1 and 2, the Emmen Area and delegated areas over Germany. The TOC provided approach control services, area control services, flight information services and alerting services within the area of responsibility.

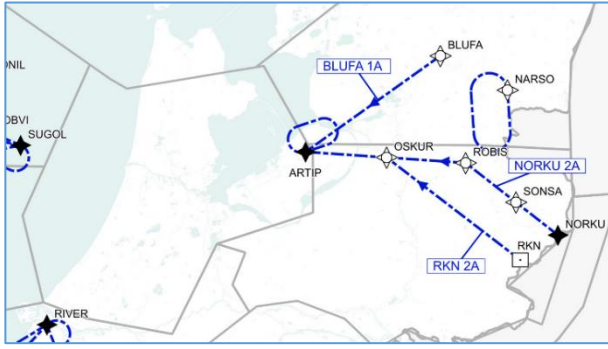


Fig. 4: Standard Arrival Routes (STAR) in Sectors 1 and 2.

Both ACC controllers and the TOC usually inform all involved pilots, ATCOs, units and centers about operational issues that are relevant for them and perform coordination activities with ATCOs from other ATS units. The other ATC units were automated in the simulation, though, so that coordination activities could only be carried out among the participating ATCOs.

Per radio-telephony (R/T) frequency, a pseudo-pilot controlled several aircraft simultaneously and communicated with the ATCOs via voice or a datalink (CPDLC). The latter was one of the additions for the developed TBO solution.

III. OPERATING METHOD

A. Procedural Baseline

As a procedural baseline, a reference scenario with the following characteristics was defined:

- Dutch airspace was simulated as mentioned above, in particular the Schiphol TMA and ACC Sectors 1 and 2 (north and east arrival and departure flows to/from Schiphol).
- Simulated traffic was based on recorded traffic from an operational day in 2023 with significant Cumulonimbus (CB) and AWA events. For the reference scenario that had to represent expected traffic levels in 2040, flights were added to increase the number of aircraft by 10%.
- Three controllers were involved in the simulation, as described earlier, one for the TMA and two for the ACC sectors. All other sectors and transfer conditions were automated. Pseudo-pilots controlled the flights in the simulation and communicated with the pilots via radio-telephony (R/T).
- AWAs with their observed location and a time resolution of 5 minutes were integrated into the Human-Machine Interface (HMI) of the CWP. However, no information on their predicted movement was available.
- The system did not detect conflicts between AWAs and aircraft and did not generate resolution proposals either.

B. Tools for Improved Task Execution

The scenarios defined for the developed TBO solution for AWAs used the same airspace, and the same actors described above worked in this operational environment. Furthermore, the used traffic samples for 2023 and 2040 were identical.

The following elements were changed for the developed TBO solution for AWAs:

- AWAs with their observed location and a time resolution of 5 minutes (blue areas in Fig. 3) as well as their predicted movements in 5-minute increments (amber areas in Fig. 3) were integrated into the HMI of the CWP. This information was obtained from KNMI for the chosen day of operation (in 2023).
- A detection tool for conflicts between aircraft and AWAs was available.
- A conflict resolution tool was available presenting several resolution proposals.

The first change has already been described above and is shown in Fig. 3. The amber AWAs could be presented at their expected future location (according to the nowcast information from KNMI) and the look-ahead time could be changed from the touch-input device (in the center of Fig. 5) on the CWP in increments of 5 minutes.



Fig. 5: Input Devices on the CWP (NARSIM).

The detection of a conflict between an aircraft and the AWAs, on the current route between the aircraft and IAF ARTIP (or an alternative waypoint inside the TMA if ARTIP was not available due to the AWA position), was shown to controllers in the aircraft label as a warning indication with an orange “W”. A conflict was defined as a case in which an aircraft was expected to pass within 3 NM of the predicted position of an AWA. The aircraft route was derived from a trajectory prediction based on the current position of the aircraft and its flight plan. When the current position deviated from the planned route, the prediction assumed a direct track to the next appropriate waypoint on the flight plan before continuing along the planned route. The calculation for prediction of the route was repeated every 30 seconds. An example is shown in Fig. 6, where the selected aircraft has a yellow label and the conflicting segment is highlighted.



Fig. 6: Detection of Aircraft-AWA Conflict.

The conflict resolution tool was implemented on the CWP with resolutions being shown on the surveillance display. In order to see them and toggle between different proposals for an aircraft, ATCOs had to use the menu structure of the touch-input device again. The proposals were based on a web of routes that was generated from the current position of the aircraft towards ARTIP or an alternative waypoint inside TMA East (SIDNI), along the edges of the AWAs. Again a safety buffer of 3 NM around the predicted AWAs was applied. An A* search algorithm [4] determined the shortest route within this web, also considering certain weights for the cost function at the beginning of the route, preventing excessive maneuvers to avoid the AWAs. This meant that the algorithm sometimes preferred a longer route around the opposite side of an AWA because it involved fewer sharp turns. The proposal resulted in 3D positions in lat/lon coordinates to navigate around the AWAs (Fig. 7). AWA altitude limits were not considered.



Fig. 7: Resolution Proposal for Aircraft-AWA Conflict.

If a resolution proposal was selected by the ATCO, it could be uplinked to the pseudo-pilot via a CPDLC message. The pseudo-pilot would accept the message with the changed route and the simulated aircraft would then automatically fly that route, unless instructed otherwise (Fig. 8).



Fig. 8: Pseudo-pilot Working Position with CPDLC Display

It should be noted that the tools described here were available for all ATCOs. Yet only the ACC controllers would experience AWAs in their sectors and use the CD&R tool frequently. The TMA controller used the tools as well, but less frequently, focusing on the necessary coordination with ACC controllers regarding transfer conditions rather than applying alternative route proposals.

IV. VALIDATION METHODOLOGY

Validation methodology employed a real-time simulation (RTS) using a human-in-the-loop (HITL) approach. Various data collection techniques were used to collect both quantitative and qualitative results, such as data logs, observations by technical specialists, post-run and end of day questionnaires (using Likert and Frequency scales) and debriefs with both ATCOs and pseudo-pilots.

A. Human Performance Assessment Planning

One of the aims of the concept validation was to determine the impact on the Human Performance (HP) of end-users, which are the ATCOs, when enhanced automation support with integrated AWAs is implemented. Based on the user needs, it was found that the following HP aspects are most likely to be significantly impacted and need to be assessed:

- Roles and procedures
- Workload and Situational Awareness
- Automation Trust and HMI Usability

The assessment should consider both new or updated procedures coming from the use case, and the enhanced tools.

B. Safety Assessment Planning

Safety, as the primary objective of the success of the operational concept, was validated by ensuring that the new concept does not increase the number of conflicts or potential encounters, and by assessing its performance across varying traffic levels, including high-traffic scenarios.

C. Simulation Environment

The validation platform used for assessment of the developed TBO solution for AWAs was NARSIM, the NLR ATC Research Simulator (Fig. 9). NARSIM is a high-fidelity, human-in-the-loop simulation platform which has decades of proven reliability and has been used in many SESAR projects before. The NARSIM Radar software replicates key ATM functions, including realistic surveillance data, aircraft behavior, and interfaces familiar to ATCOs. It is also used by ATC The Netherlands (LVNL) for training exercises and as part of their current efforts in airspace redesign, which means that it is highly representative of the current system (Amsterdam Advanced ATC System, AAA).



Fig. 9: NARSIM Validation Platform in ATC-TBO Configuration.

Relevant system data could easily be extracted from NARSIM while, at the same time, HP related data was collected through questionnaires as well as debriefing and interview sessions. In addition, workload was assessed using an instantaneous self-assessment (ISA) method implemented to be minimally intrusive (small rating scale on voice communication display).

D. Experiment Set-up

The study involved four air traffic controllers and a group of experienced commercial airline pilots acting as pseudo-pilots. Simulations were conducted on NARSIM, replicating the Dutch airspace with a focus on the earlier mentioned ACC and TMA sectors where ATCOs handled North and East arrival and departure flows to and from Schiphol Airport.

Three controllers operated simultaneously per run, one per sector, while upstream traffic feeds were automated. Weather data consisted of real adverse weather area (AWA) observations from a single historically challenging day, provided by KNMI at five-minute intervals. Traffic scenarios were derived from real recorded traffic data and adjusted in consultation with participating controllers to reflect realistic flow and capacity conditions under severe weather.

Two traffic load conditions were employed: one representative of 2023 operations, and one extrapolated to 2040 levels through a 10% traffic increase.

Four simulation scenarios were assessed, combining the two traffic loads with and without the CD&R tool active, yielding two reference and two solution conditions. The four scenarios were carried out twice, i.e. once on each of the two simulation days, and with different ACC ATCO teams. All scenarios addressed abnormal weather conditions exclusively; nominal and faulted conditions were outside the scope of the study.

V. RESULTS

Results of the real-time simulations were organized around four areas: operational and technical feasibility, human performance, safety, and controller–pilot interaction, drawing on both quantitative simulation logs and qualitative evidence from post-run questionnaires, workload assessments, and structured debriefing sessions.

A. Operational and Technical Feasibility

The simulation confirmed the technical feasibility of integrating AWA information into a ground-based CD&R tool, within the scope of abnormal weather conditions. Implemented on the validation platform, the detection component successfully triggered conflict alerts as soon as aircraft appeared on the radar display, and the timeliness of detection function was considered adequate. The resolution tool succeeded in generating conflict-free lateral routes based on weather nowcasts provided by KNMI at five-minute intervals.

However, the system capability to calculate resolutions varied by context. For outbound TMA traffic, controllers resolved future AWA conflicts with minimal interaction effort; however, for inbound ACC traffic the tool was substantially less effective due to the complete absence of sequencing logic, resulting in proposals that were geometrically valid but operationally incompatible with established arrival flows. A critical technical defect was identified whereby the "W" conflict indicator persisted in the aircraft label after a resolution had been issued, attributed to an insufficiently tuned route algorithm that developed routes exactly on the AWA boundary without an additional detection buffer compensating for round-off errors in coordinate calculations for the route waypoints. The five-minute weather data update interval caused abrupt positional shifts in displayed AWAs, disrupting controllers' planning horizon and forcing the CD&R system to recalculate resolutions abruptly.

From an operational standpoint, the tool did not alter the formal allocation of controller roles and responsibilities, with the controller remaining the sole decision-maker for separation management, and was found to be compatible with current working methods in principle. However, its operational benefit proved highly context-dependent: in environments where sequencing and arrival flow management

were dominant, controllers were required to manually adapt or disregard proposals, substantially reducing the practical utility of the automation.

Collectively, these limitations define the boundary conditions within which the current implementation can be considered operationally viable, and identify the primary development priorities for subsequent iterations.

B. Human Performance

The human performance assessment was evaluated across the different dimensions mentioned above. While controllers demonstrated adequate understanding of roles and procedures, with End-of-Day Likert scores ranging between 3.0 and 4.0, the current implementation of the tool faced challenges across the remaining dimensions, particularly under high-complexity, high-traffic conditions (Fig. 10).

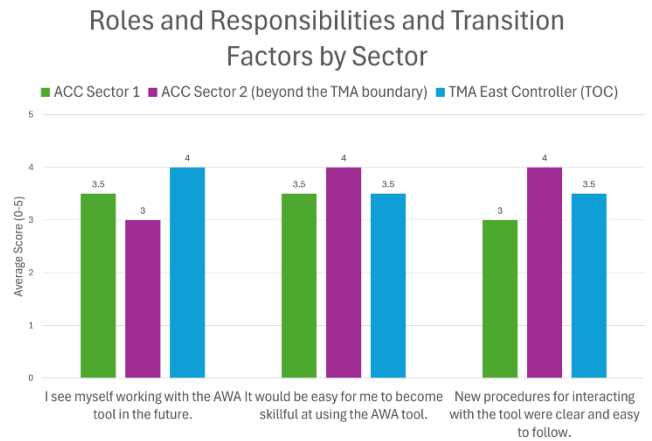


Fig. 10: Roles and Responsibilities and Transition Factors by Role/Position (End of Day Questionnaire).

Workload was manageable under lower traffic conditions but increased under the 2040 scenario, with ACC Sector 1 Bedford scores reaching 6.5 in the high-traffic solution condition; rather than alleviating effort, the tool introduced additional cognitive overhead due to persistent "W" indications and the absence of sequencing logic, which required controllers to manually intervene.

When looking at Fig. 11 for the Bedford workload scores, it should be noted that higher scores indicate reduced spare cognitive capacity. ACC Sector 1 recorded the highest workload in Solution Run 2 (score = 6.5).

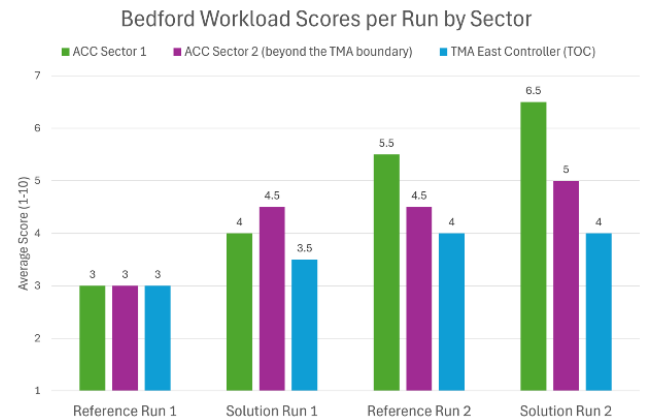


Fig. 11: Mean Bedford Workload Scale Scores by Operational Role across Reference and Solution Runs.

In Fig. 12 the ISA scale ranges from 0 to 5, capturing momentarily perceived workload during task execution. A progressive increase in scores across runs is observed for ACC Sector 1 on both simulation days, consistent with increasing workload under the high-traffic solution condition.

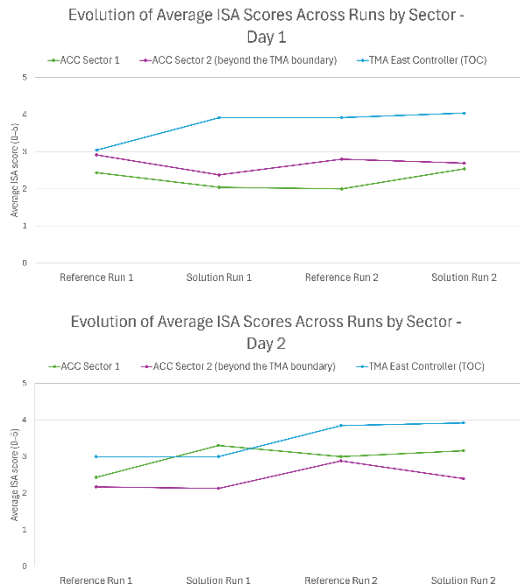


Fig. 12: Evolution of Mean Instantaneous Self-Assessment (ISA) Workload Scores by Operational Role across Simulation Runs.

A slight decline in situational awareness was observed in solution runs compared to reference runs, with SASHA (Situational Awareness for SHAPE [5]) scores for ACC Sector 1 dropping from 4.7 to 3.6 in the first solution run; inconsistent alert updates and difficulty in tracking aircraft whose 2D routes had changed were identified as the primary contributing factors, with controllers scoring 2.0 on the item regarding awareness of rerouted aircraft.

In Fig. 13, scores are reported on a 0–6 frequency scale. A decline in ACC Sector 1 scores between Reference Run 1 and Solution Run 1 reflects reduced situational awareness associated with initial tool exposure.

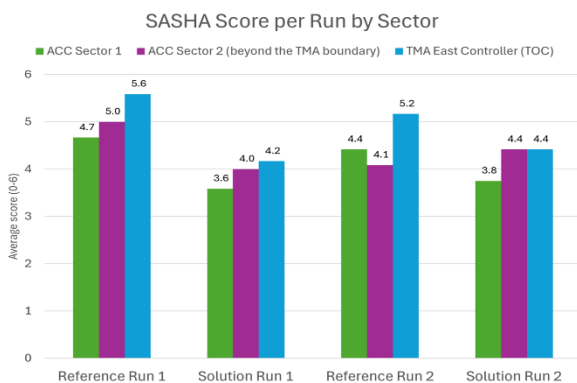


Fig. 13: Mean SASHA Scores by Operational Role across Reference and Solution Runs.

Trust in automation was consistently lower in solution runs than in reference runs, specifically regarding rapidly changing route proposals. Persistent or absent weather conflict indications undermined controller confidence, with one controller ceasing tool use entirely during the first solution run.

Trust results in Fig. 14 are reported on a 0–6 frequency scale. A consistent reduction in trust scores is observed in solution runs relative to reference runs across all participants.

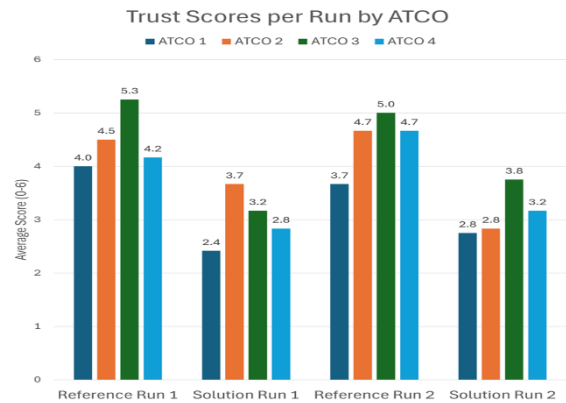


Fig. 14: Post-run Trust Scores by Individual ATCO across Reference and Solution Simulation Runs.

While the visual design of the HMI was praised for clarity and lack of clutter, usability was compromised by the infrequent weather update rate, which caused predicted AWA boundaries and solution routes to shift abruptly, making it difficult for controllers to maintain a stable mental picture; SUS (System Usability Scale [6]) scores ranged from 53.75 to 71.25, reflecting moderate overall usability (Fig. 15). In that regard it should be noted that SUS scores in this figure are normalized to a 0–100 scale, with scores below 68 conventionally interpreted as below average usability. Individual scores thus ranged from 53.75 to 71.25.

Taken together, these findings indicate that human performance benefits are conditional on resolving the tool's current behavioral instabilities. The tool demonstrated potential, particularly for strategic conflict detection in lower complexity situations; however, future development must prioritize technical stability, operational logic integrating sequencing constraints, and HMI improvements to ensure it supports rather than distracts the operator.

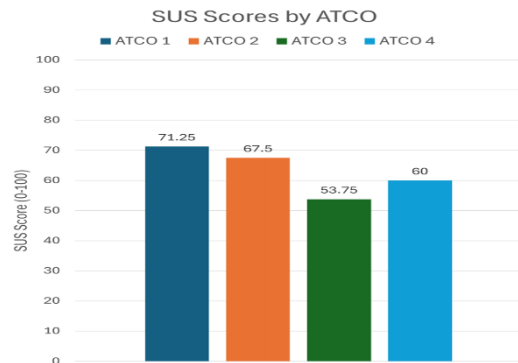


Fig. 15: SUS Scores by Individual ATCO.

C. Safety

No widespread safety hazards were reported, and the findings suggest that the introduction of the CD&R tool did not significantly degrade overall safety. These results, however, derive from a small-scale exercise, and should be read as indicative rather than statistically conclusive. Quantitative analysis of simulation logs recorded a reduction in the count of en-route separation infringements in the solution condition compared to the reference baseline,

decreasing from four total infringements to one. Given the small counts involved, this difference can be interpreted as a tendency rather than a statistically significant safety improvement. Qualitative data, however, provided important context: while system logs recorded one infringement in the first solution run, controllers reported an additional event resolved manually just before it became eligible for logging. This incident, occurring at IAF ARTIP during a sector handover, was attributed to degraded situational awareness caused by persistent "W" label indications rather than to the tool's concept itself. Short-term conflict alerts decreased from 13 to 4 under the 2023 traffic load and from 19 to 2 under the 2040 load, based on system logs, as HMI-level alerts were deactivated after the first simulation day due to excessive sensitivity. In fact, the STCAs were turned off on the HMI level as filtering was applied with buffers that were too broad and caused displaying STCAs to ATCOs that would not be operationally considered as STCAs. This limits the weight that can be placed on the infringements observed and the alert counts.

Fig. 16 shows that a 67% reduction in total infringements is observed between the 2040 reference condition and the 2040 solution condition. This pattern was not consistent across conditions: under the 2023 traffic load the solution condition recorded more infringements than the reference (four versus three). This increase is plausibly associated with an adaptation or first-exposure effect; however, learning effects cannot be excluded as a contributing factor to the apparent improvement at the higher traffic load either. The short exposure to the tool does not allow to separate the tool effect from the learning effect, so no casual safety benefit can be firmly attributed to the tool on the basis of these results alone.

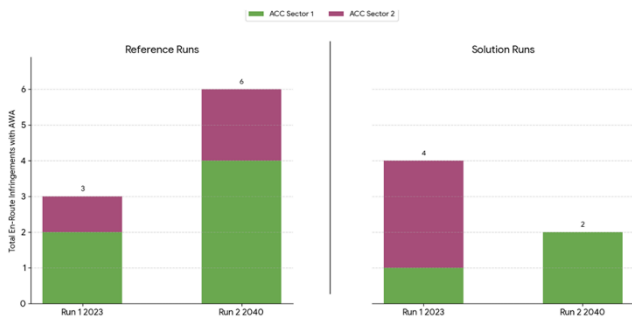


Fig. 16: En-route Aircraft-AWA Infringements per Run by Sector.

Furthermore, qualitative feedback indicates that trust in the tool diminished when proposals were perceived as insufficient or inapplicable to the evolving traffic situation, particularly when high traffic volumes required complex sequencing that the tool did not support. Controllers were observed to revert to manual control when decision times were short, so tool usage was not constant across the solution runs. The reduced infringements recorded may therefore reflect, at least in part, the controllers' own vigilance rather than automation support. Zero separation infringements were recorded in the TMA across all runs and traffic loads, noting that no AWA were present within the TMA itself during the study.

The ratings in Fig. 17 are reported on a 0–6 frequency scale, where higher scores denote a higher number of perceived safety-impacting events. ACC Sector 1 recorded elevated scores in both solution runs, consistent with observed

increases in conflict-management workload and cross sector coordination demands. This also indicates that subjective experience of safety did not improve, and in some cases deteriorated with the active tool.

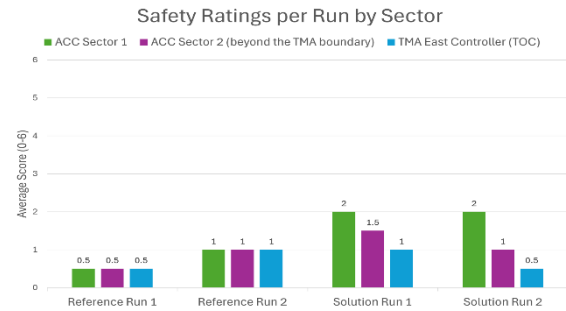


Fig. 17: Mean Perceived Safety Ratings by Operational Role across Reference and Solution Simulation Runs.

These findings indicate that while the aggregate infringement and alert counts moved in a favorable direction, this was not always matched by results concerning perceived safety. Moreover, interface stability and handover coordination represent residual risk vectors not fully captured by infringement counts alone, and proper training on the tool and its procedures may be a necessary mitigation to increase operator trust and reduce reliance on constant manual monitoring.

D. Impact on Pilots

Pilot impact was assessed through qualitative feedback from pseudo-pilots, the majority of whom were experienced commercial airline pilots. A recurring observation was that aircraft did not consistently comply with uplinked resolution routes, with some maintaining original trajectories despite having received a datalink clearance; both controllers and pseudo-pilots acknowledged that working with pilots from diverse airline cultures would be expected to produce additional negotiations and variability in compliance.

The tool transforms bilateral controller-pilot weather negotiation into a unilateral datalink instruction, reducing voice communication effort but removing the pilot's contextual contribution; pseudo-pilots and controllers agreed this would generate clarification requests, particularly where deviation angles appeared excessive from the cockpit perspective. Conservative safety buffers applied around AWAs were larger than pilot-preferred margins, with efficiency-conscious pilots expected to contest proposals while more risk-averse pilots might request even larger deviations; both groups agreed that no single buffer value would be universally acceptable.

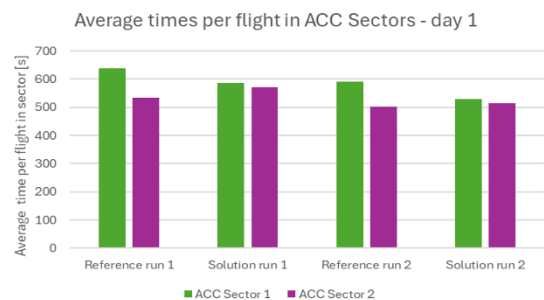


Fig. 18: Mean Flight Duration per Aircraft in ACC Sectors 1 and 2 across Reference and Solution Simulation Runs (Day 1).

Fig. 18 shows that increased flight times in solution runs are consistent with the application of conservative safety buffers around AWAs in the resolution algorithm. Results in Fig. 19 are broadly consistent with the findings for Day 1, with solution runs generally producing comparable or longer average flight times relative to reference conditions.

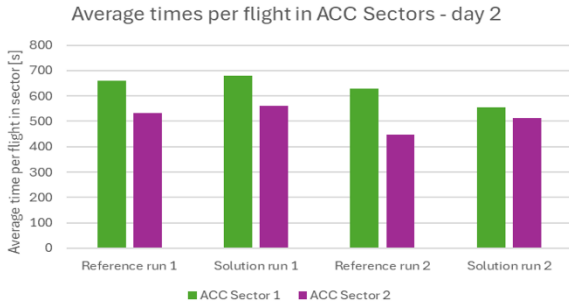


Fig. 19: Mean Flight Duration per Aircraft in ACC Sectors 1 and 2 across Reference and Solution Simulation Runs (Day 2).

Participants consistently identified the absence of binding controller-pilot interaction procedures as a critical gap, specifically regarding when pilots should comply without voice negotiation and when contestation is permissible. Resolving these ambiguities is considered a prerequisite for meaningful assessment of the tool's communication efficiency benefits in future studies.

VI. DISCUSSION

A. Operational and Technical Feasibility

The simulation showed that integrating AWA data into a ground-based CD&R tool is technically feasible, enabling timely conflict detection and successful weather-avoiding route generation under abnormal conditions. However, performance was context-dependent: it worked well for outbound traffic but not inbound traffic due to missing sequencing logic, and was further limited by issues such as persistent conflict indicators and unstable route updates caused by five-minute weather refresh intervals.

Operationally, the tool fit existing ATCO roles but offered limited practical benefit in complex arrival environments, highlighting key limitations and priorities for further development.

B. Operational Efficiency

When looking at the objectives mentioned in the project validation plan, one of the assumptions was that applying the AWA and CD&R tools would lead to operational efficiency improvements [7]. This, however, could not be confirmed. While the tool generated conflict-free trajectories, it did not optimize them for efficiency or predictability compared to manual operations, despite potential ATCO HMI benefit.

Fuel efficiency did not improve, as conservative safety buffers around AWAs led to longer routes than manual vectoring, where tighter margins may be accepted. As a result, fuel consumption remained similar. Flight times also showed no reduction, with routes being robust but not time-optimized, often matching or slightly exceeding current operations. Predictability was negatively affected by technical limitations. The five-minute weather update interval caused abrupt shifts in AWA positions, triggering sudden trajectory recalculations and disrupting planning. In addition, the absence of

sequencing logic led to variable arrival times at sector boundaries, requiring manual intervention to maintain traffic flow stability.

C. Safety

The validation results indicate that the concept generally maintains safety levels compatible with current operations, with favorable tendencies towards a safer environment, though critical robustness issues were identified under saturation conditions. Overall, ATCOs were able to spot potential encounters ahead of time in most cases and react accordingly, prior to the reduction of the separation. Specific tool behaviors, such as infrequent weather updates causing abrupt trajectory changes and inconsistent conflict detection indications, were found to introduce potential risks to Situational Awareness, particularly when traffic complexity prevented controllers from cross-checking automated proposals manually.

The TBO solution demonstrated a favorable tendency towards a safety improvement regarding the avoidance of AWAs in ACC sectors. In high-traffic 2040 scenarios, the ratio of cloud infringements decreased (by 67%). Moreover, there was a 0% separation infringement rate. However, a critical safety degradation was observed regarding the severity of conflicts between aircraft during the high traffic scenario; while the total number of STCA alerts decreased, the system recorded a cluster of alerts where separation minima dropped below 1.0 NM. This could indicate that the tool's logic becomes volatile under extreme sequencing pressure when traffic complexity exceeds the tool's capabilities. However, it was also found that ATCOs would stop using the CD&R tool, as shorter times for decision-making would require instant communication loops with the pilots.

The TMA environment remained stable, without any separation infringements being recorded. The negligible cloud infringements (<0.15 NM) recorded in the system logs were identified as technical boundary interactions during the handover phase rather than operational separation failures. It must be noted that there were no AWAs present within the Schiphol TMA itself. Consequently, the TMA controller's role in avoiding AWAs was limited to selecting solution routes for outbound traffic that avoided AWAs located in the adjacent ACC sectors. The tool successfully supported this proactive management of outbound flows.

These safety results must be interpreted with caution, though, and are to be considered as preliminary. The evidence base is small, and this precludes statistical inference and limits generalizability. Adaptation and first-exposure effects cannot be separated from any genuine effect over such short exposure. Automation trust degraded during the runs, driven by unstable HMI behavior, and controllers intermittently stopped using the tool and reverted to manual control. Thus, recorded outcomes cannot be attributed to the automation itself. The STCA safety net was deactivated at the CWP for most runs meaning that the results understate the real exposure. Finally, perceived safety among ACC controllers did not improve and in several solution runs decreased relative to the reference. Altogether, these factors mean that the observed reductions in infringement and alert counts should be interpreted as an encouraging but preliminary indication.

D. Human Performance

Human Performance was evaluated through quantitative and qualitative evidence (questionnaires, ISA/Bedford

workload measures, observations, and debrief feedback). The underlying concept was understood, but the current implementation introduced constraints in workload support, situational awareness, automation trust, and system usability, particularly under conditions with high-traffic levels.

- ATCOs reported a generally positive understanding of their roles, responsibilities, and the transition factors, confirming the concept's operational feasibility.
- The tool failed to positively support workload in high-traffic scenarios. Instead, it introduced additional cognitive overhead due to persistent aircraft-AWA conflict indications in the labels that were perceived as nuisance, and due to a lack of traffic sequencing logic, which required a manual replanning of the arrival sequence.
- A slight decline in situational awareness was observed. Factors such as inconsistent alert updates and the difficulty in tracking aircraft with changed 2D routes contributed to this decline.
- Trust levels decreased, mainly due to the unpredictability of route proposals which changed abruptly due to an insufficient weather update rate.
- The HMI was praised for clarity and lack of clutter, but usability was compromised by the low update frequency of weather data, which caused predicted areas to shift abruptly, disrupting the controllers' mental model.

E. Capacity

The CD&R tool in its current state was not effective in increasing traffic throughput in the TMA or ACC environments. Although the experiment was conducted with limited traffic levels, the analysis of throughput and perceived workload did not indicate a potential for capacity enhancement when compared with the reference scenario.

In the TMA, traffic throughput remained similar. However, perceived workload was typically higher when using the CD&R tool. Since the TMA controller already operates at high workload levels, the tool in its current form appears to negatively impact capacity rather than increase it.

In the ACC sectors, throughput decreased when using the CD&R tool. This confirms ATCO feedback that the tool is currently unworkable in high-density sectors due to the absence of sequencing logic. Additionally, the conservative safety buffers used around AWAs extended sector transit times. Consequently, the validation did not demonstrate a successful increase in capacity.

VII. CONCLUSIONS

A. Concept Conclusions

The validation exercise confirmed that ATCO roles remain unchanged: controllers retain full responsibility for separation, while the solution supports earlier conflict detection and more proactive planning without altering core responsibilities for the safety of aircraft within the sector.

While no role changes were introduced, the exercise showed a shift toward more proactive planning. Increased automation and AWA conflict information enable earlier detection of potential conflicts and allow to advise pilots early

regarding resolution strategies, while separation responsibilities remain unchanged.

The solution does not fundamentally change current operations. Controllers continue established processes, but interaction with the enhanced CD&R functionalities introduces additional monitoring and verification activities, particularly when weather data updates lead to changes in predicted conflict areas or proposed resolutions. These aspects highlight the need for clearly defined operating guidance addressing tool behavior, alert persistence, and resolution stability.

Task performance may improve through earlier, better information supporting decision-making and reduced time pressure. However, benefits are context-dependent and limited in environments where traffic sequencing and flow constraints are dominant. There, automated resolutions are not fully suitable and require manual adjustment or rejection, thus reducing the practical benefit of automation.

Operational feasibility is confirmed in principle and largely compatible with current ATC operations, except for sequencing constraints. Effectiveness in very high complexity environments depends on stable outputs, appropriate alerting, and alignment with operational constraints, such as sequencing and downstream traffic management. The tool prioritizes safety via conservative buffers rather than trajectory optimization, so that operational efficiency criteria were not met.

B. Technical Conclusions

1) Aircraft-AWA conflict detection

The tool successfully identified conflicts between 4D trajectories and 3D AWA polygons, triggering timely alerts (orange "W") as soon as aircraft entered the considered areas of responsibility. Detection was early enough to support tactical planning, confirming the feasibility of the approach.

2) Aircraft-AWA conflict resolution

The tool generated conflict-free lateral routes that avoided AWA geometry, performing well for outbound TMA traffic. However, it was less effective for inbound ACC traffic due to the absence of traffic sequencing logic, often producing operationally unsuitable routes. While calculations were timely, the interface caused inefficiencies, as controllers had to toggle between route options instead of viewing them simultaneously.

3) HMI

The integration of AWA alerting into the CWP was technically feasible. The system successfully displayed:

- The "W" status indicator in the aircraft label to signal an AWA conflict.
- A visual rendering of the proposed resolution routes directly on the radar screen.

Participants confirmed that the visual integration was clear, legible, and did not create excessive clutter, validating the technical maturity of the display logic.

4) Technical issues

The exercise revealed a number of technical shortcomings impacting the performance and usability of the CD&R tool:

- A significant technical limitation concerned the update frequency of the weather data (currently 5 minutes).

This latency caused sudden positional shifts in the predicted AWA positions, forcing the CD&R system to recalculate resolutions abruptly.

- The validation revealed a technical defect due to rounding errors in distance calculations between aircraft trajectories and AWAs. Consequently, the conflict detection symbol sometimes persisted in the label even after a resolution was chosen by the ATCO.
- While the resolution tool calculated paths to avoid weather, it lacked logic based on traffic flows.
- Technically, the system provided multiple resolution options, but the mechanism for toggling between them on the touch-input was inefficient.

VIII. RECOMMENDATIONS AND FUTURE WORK

Addressing the current limitations of the CD&R tool should be the basis for future research, as unresolved issues may affect further developments. The event-processing logic must ensure that conflict detection alerts are cleared immediately after selecting a resolution and do not reappear unintentionally. Using larger buffers for resolution than for detection may help prevent re-triggering. The route-generation algorithm also requires refinement: certain traffic-AWA geometries produced excessive turning angles, and some routes, while rule-compliant, were not operationally realistic (e.g. turning routes preferred over safe direct options). Resolving these issues would provide a solid baseline for future work.

Future iterations must also support higher-frequency weather updates. The current five-minute interval was insufficient, causing abrupt changes that affected usability. As update frequency depends on the data provider (KNMI), interpolation methods may be needed to smooth AWA movement and reduce disruption to the CD&R tool and HMI. A key priority is integrating traffic interaction into the routing algorithm. This includes incorporating flow constraints, identifying feasible traffic corridors for a more consistent operation, and accounting for sequencing in inbound ACC traffic toward TMA entry points. ATCO feedback confirmed these are essential for operational use. Moreover, the HMI should be optimized to improve efficiency. Toggling between route options is time-consuming and limits situational awareness; improvements could include displaying multiple options simultaneously or filtering out non-viable ones. Further ATCO input is needed to define the best approach.

Summarizing, the research produced valuable insights into many aspects of the AWA CD&R tool, but the experimental set-up was not suited to assess operational efficiency and cost-effectiveness. Future studies should therefore adopt a revised design including a wider range of traffic levels.

Operational use of the tool also requires further investigation. The current study indicated that large AWA buffers can increase flight times, yet selecting an appropriate buffer is challenging: smaller buffers may be rejected by safety-oriented pilots, while larger ones may be seen as inefficient. Identifying a balanced approach is essential before accurately assessing operational impact. Future experiments should also define procedures for ATCOs and pilots that contain clear rules on when route proposals can be discussed or when they must be followed without initiating additional

communication. These procedures should be validated with operational stakeholders and refined iteratively.

Finally, the impact of weather uncertainty must be examined. Real-world operations involve uncertainty in nowcasts, which was not considered in this study. Understanding how such uncertainty affects tool performance is essential for assessing its operational applicability.

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