AWARE Report on ATCO Support Tools

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Abstract

ATCO support tools form an integral part of the Artificial Situational Awareness (ASA) System, which supports ATCOs at both the advisory and execution levels, corresponding to automation levels 2A and 2B. Working in conjunction with other ASA system components, the tools assess the ATCO's situational awareness and dynamically adapt their functionalities to assist and complement ATCOs during task execution. The report outlines each tool's purpose, key features, performance, and limitations. It also details how the tools are integrated into the ATM system and describes the HMI approach adopted for each tool.

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[1] Representatives of the beneficiaries involved in the project.

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AWARE

Achieving Human-Machine Collaboration with Artificial Situational Awareness

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1. Executive Summary

This report presents a description of the ATCO support tools developed within the AWARE project as part of the Artificial Situational Awareness (ASA) system. These tools constitute a core element of the AI Assistant Application (AAA) and are designed to support en-route ATCOs by enhancing situational awareness, reducing workload, and enabling safer and more efficient decision-making.

The report focuses on the operational behaviour of the tools, including their data inputs, triggering mechanisms, internal logic, and output messages. It describes how flight, airspace, and system configuration data are integrated and processed through knowledge-based reasoning to identify relevant situations and generate appropriate support actions. Attention is given to the interaction and dependency between tools, highlighting how coordination, transfer, and conflict resolution functions are linked and jointly contribute to the overall ASA system functionalities.

The content of this report is aligned with the AWARE Concept of Operations and Functional Requirements. It translates the high-level concepts and requirements into concrete tool-level descriptions, thereby providing a clear link between system design principles and their practical realisation. By clarifying how ASA tools operate individually and in combination, this report supports a consistent understanding of the AWARE solution across design, development, and validation activities.

This report contributes to the maturation of the AWARE solution by providing a coherent and operationally grounded description of the ATCO support tools, serving as a reference for further validation within the project.

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2. Introduction

The AWARE project aims to advance human-machine collaboration in air traffic management (ATM) through the development of an ASA system. This system enhances the decision-making capabilities of ATCOs by providing timely, relevant support using artificial intelligence, enabling them to manage complex air traffic scenarios more effectively.

The purpose of this report is to describe the internal logic, data flows, and output structures of selected ASA support tools developed in the AWARE project. The report explains how these tools use and process data, apply reasoning mechanisms, interact with other ASA tools, and generate outputs that support ATCO in en-route ATC operations. In total, four tools are described: Conflict Detection and Resolution, Transfer, Coordination and Quality of Service tool. Together, these tools form a crucial part of the AI Assistant Application (AAA), providing real-time operational support to ATCOs via the HMI by enhancing decision-making processes through automation and data-driven insights. The position of these tools within the overall AWARE system architecture is illustrated in Figure 1.

As defined in the AWARE Concept of Operations (ConOps) [1], ASA support tools assist ATCOs either by supporting them during task execution or by autonomously executing tasks outside the ATCO's immediate focus of attention. This report clarifies the distinction between these two modes of support and describes how each tool operates across different levels of system support. It also explains how tool suggestions and actions are presented to ATCOs through the HMI, and identifies the expected outcomes, benefits, and limitations associated with each tool. Collectively, the tools contribute to achieving the expected Key Performance Area (KPA) performance outcomes of the AWARE solution [1].

The described tools are fully aligned with the Functional Requirements Document (FRD) [2]. They operate across different levels of automation and fulfil the functional requirements defined therein. Their suggestions and actions are rooted in explainable, knowledge-based representations, ensuring transparency and supporting ATCO trust in the system.

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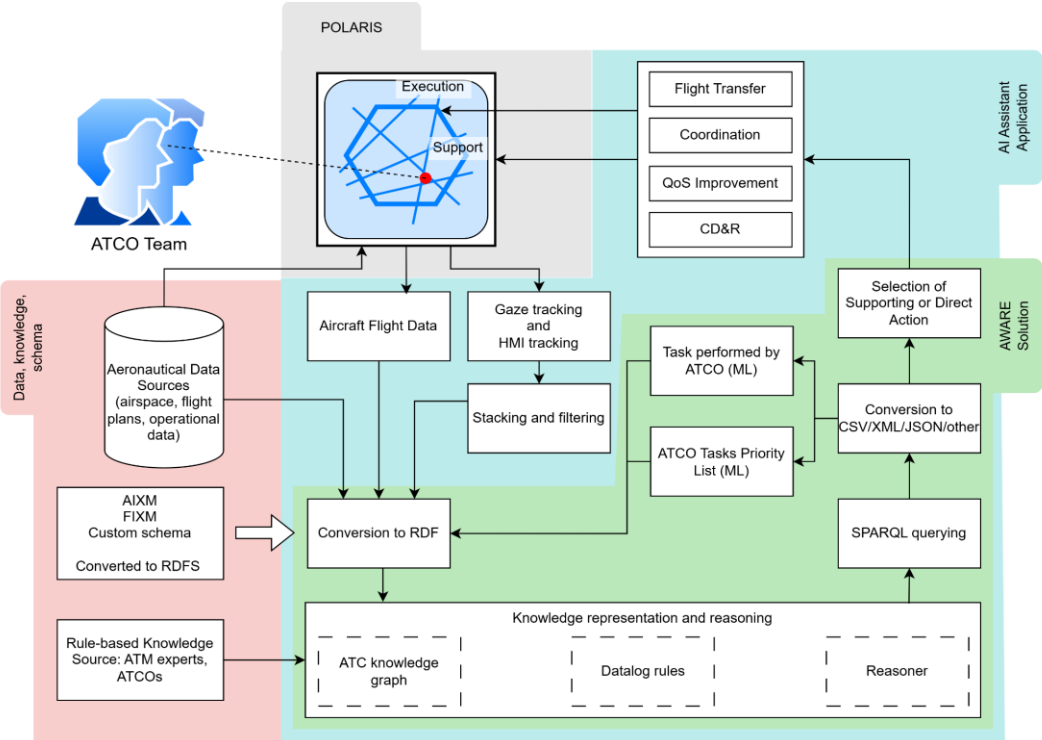

Figure 1. ASA system interaction identification [2]

The ATCO support tools are designed to form an adaptable and resilient system capable of operating under varying traffic conditions. They will be validated through medium, high, and future traffic scenarios, with functionalities tailored to different traffic volumes and complexity levels in order to assess the system's adaptability and performance [3]. A dedicated experimental plan will enable the analysis of how different levels of ASA support affect relevant KPIs. A detailed description of the validation scenarios is provided in Deliverable D2.14 [4].

This report will describe and assess the four core ATCO support, where each of these tools represents a critical component of the broader AI-based assistance application. The document is structured as follows:

- Section 3 describes the Conflict Detection and Resolution Tool, including its functionality, technical design, operational relevance, benefits, and limitations.
- Sections 4, 5 and 6 address the Transfer Tool, the Coordination Tool, and the Quality of Service Tool, following the same structured approach.
- Section 7 explains how the tools are integrated into the ATM system, covering both the HMI perspective and the backend system design and interfaces.
- Section 8 presents the conclusions, summarising the main contributions of the ATCO support tools.

3. Conflict Detection & Resolution tool

3.1 Purpose & Functionality

The Conflict Detection and Resolution (CD&R) Tool continuously analyses airspace, identifying potential conflicts between aircraft based on 4D predicted trajectories. It then proposes resolution strategies grounded in human-centric reasoning, taking into account factors such as time to minimum separation and flight characteristics that typically influence ATCO decision-making. It supports ATCOs at automation levels 2A (advisory) and 2B (execution), enhancing situational awareness, reducing workload during high-demand periods, and ensuring timely and safe decision-making. The tool adapts its behaviour based on the ASA system's assessment of ATCO intent ensuring that the human remains in the loop.

To achieve that performance, CD&R tool is composed of two modules:

1. Conflict Detection (CD): The conflict detection goal is to identify aircraft pairs in which the separation minima can be infringed on the basis of the conflict horizon calculation. Conflict metrics such as minimum separation, location of closest point of approach (CPA), time to CPA, etc., must be calculated by the Conflict Detection module.
2. Conflict Resolution (CR): Conflict Resolution goal is to propose aircraft manoeuvres that solve conflicts. This tool can generate different horizontal or vertical solutions that can be prioritised or not depending on the ASA needs.

Both modules operate in the short term and rely on the accuracy of 4D trajectory predictions. The system must avoid false or missed alerts, provide timely information, and ensure that resolution advisories do not introduce new conflicts.

3.2 Technical Description

3.2.1 Conflict Detection Module

The CD module uses 4D trajectory predictions and surveillance data (gathered from KG) for its calculation. The CD module works in a two-stage calculation process as follows:

1 CPA calculation
It calculates the evolution of the separation between an aircraft pair (new aircraft and any of the aircraft within the airspace) for the whole 4DT predictions. The CPA is identified as the position where the aircraft pair reaches the predicted minimum separation (Figure 2). CPA calculation begins when flight reaches CD calculation horizon (10 minutes).

2 CD metrics
Based on the CPA information and operational variables, the following CD metrics are calculated:

a. Aircraft pair: Identifiers of aircraft pairs involved in an SI (Situations of Interest) or conflict.
b. SI: Binary variable (1 or 0) if an aircraft pair satisfies the SI requirements

c. Conflict: Binary variable (1 or 0) if an aircraft pair matches Conflict requirements.
d. Closest Point of approach (CPA): Geographic coordinates of both aircraft (CPA1 and CPA2) at the expected minimum distance:
    i. Minimum Separation at CPA (MinSep): Expected minimum separation at CPA (combined longitudinal and vertical)
    ii. Time/Distance to CPA: Time (sec) or Distance (NM) from the current location to the CPA location.

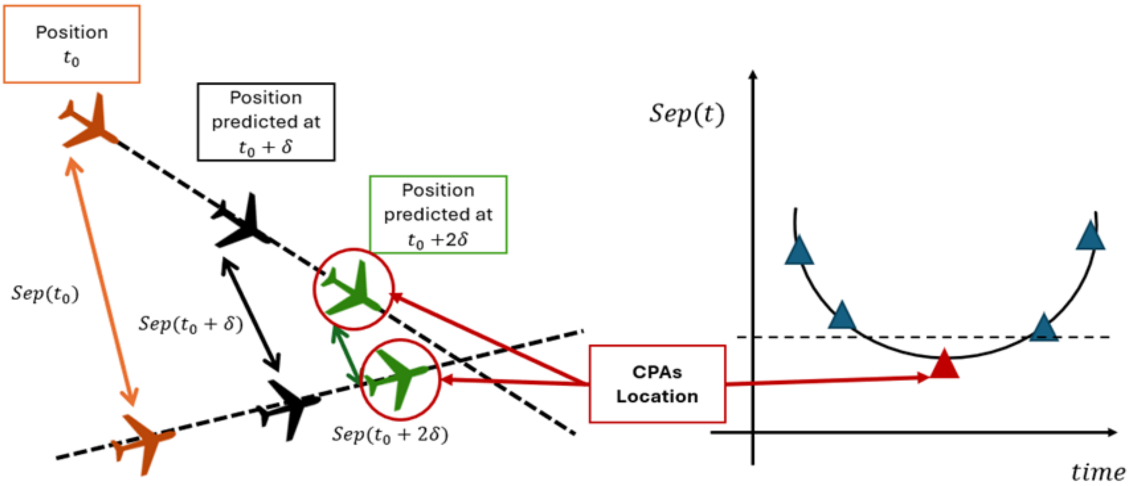

Figure 2. Representation of the CPA calculation.

Therefore, most CD metrics depend only on the calculation of the CD module based on the 4DT predictions used. That is, their values do not vary until the 4DT prediction is updated. However, the time to CPA and the distance to CPA vary throughout the evolution of the aircraft, and they present a time dependency. This issue is planned to be solved by introducing a function in the KG where it calculates every time period the evolution of both variables. In the case the solution selected for the CD is every X second, the CD provides these values at each calculation.

The CD module results in:

- Aircraft pairs in
- SI or conflict
- CPA locations
- Minimum separation
- Time/Distance to CPA
- SI/Conflict binary indicators

These outputs serve as inputs for the CR module. Details available in Section 2.4.1.

3.2.2 Conflict Resolution Module

CR is the next module that calculates resolution manoeuvres to solve a conflict between an aircraft pair. CR is triggered in the case a conflict is predicted between 2 flights and time to conflict is lower than the CR activation horizon. It can be considered a CR activation horizon different from the CD identification horizon.

Operational requirements for CR module are:

- The resolution advisory shall not create new conflicts;
- The resolution advisory shall inform ATCO timely of the conflict;
- The resolution execution shall only be performed as a last effort to ensure safety, similar to that of a safety net.
- The system shall provide feedback on executed tasks to keep ATCO in the loop

The following assumptions have been considered for the development of the CR module:

- CR is calculated once the time to conflict has reached the CR calculation horizon.
- CR provides a solution that is free of conflict between a conflicted aircraft pair and the rest of aircraft pairs considering the CD identification horizon.
- CR provides a solution that is free of Temporary Reserved Areas (TRA).
- It is assumed that once the CR proposes a manoeuvre, it must be applied within the next 30 seconds. This time validity refers to the validity of the proposed solution. The module evaluates solutions between 0 seconds to the next 30 seconds. The solution should be conflict free at t+15 and at t+30 seconds. Otherwise, the solution is not provided to the ATCO. In this assumption it is supposed that once the CR is provided to the ATCO it must be applied considering an expiry time of maximum 30 seconds, otherwise the CR does not validate the solution.
- A buffer value for validity reasons of CR manoeuvres is fixed on 30 seconds. It means that CR evaluates the proposed manoeuvres at different times from the local time to the next 30 seconds. It has been selected t+15 and t+30 when the CR evaluates the solution. In the case the three manoeuvres are free of conflict then the solution is considered free of conflict. This buffer works as an expiry time of the validity of the solution proposed.
- If the ATCO rejects all the solutions generated by the CR module, the tool won't be triggered again for the same conflict pair. The assumption is that ATCO will handle conflict without CR.

CR is separated into four modules:

1. Resolution Manoeuvre Generation Module. This module is responsible for generating various solutions considered in this work. The manoeuvres under consideration are:
    a. Adaptation of FL based on operational conditions. This function is considered the most efficient because it allows the controller to resolve a conflict locally without impacting

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other aircraft. It also positively affects the aircraft's efficiency. This function adjusts the aircraft's altitude to meet the operational needs of the environment:

i. Adaptation of actual FL to the corresponding XFL or CFL.
ii. Block of climb or descend when the aircraft are close to the CPA.

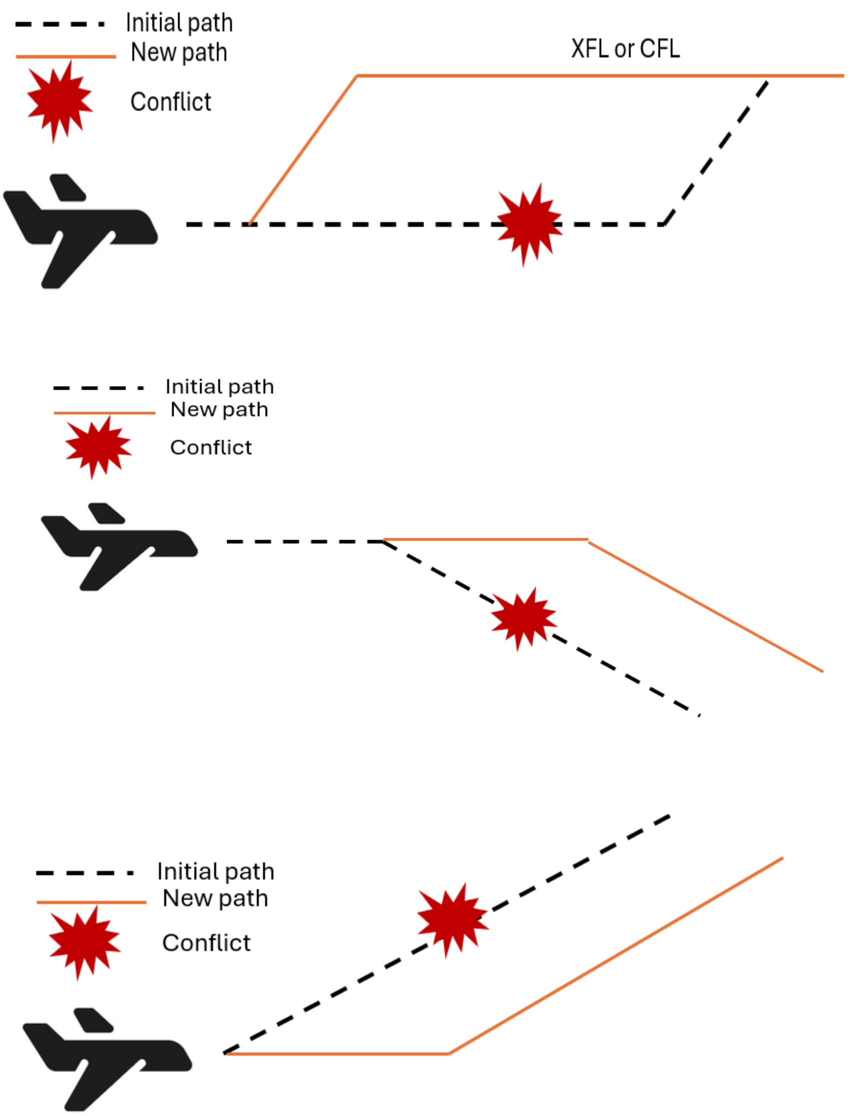

Figure 3. Conceptual examples of avoiding manoeuvres considering flight operational conditions.

a. Direct to a waypoint. This function modifies the current trajectory, enabling the aircraft to fly directly to a specified waypoint. While this solution positively impacts aircraft efficiency (reducing distance, time, and fuel consumption), it can negatively affect the overall network. Two possible solutions have been considered:
    1. Direct to the next second waypoint indicated in the FP.
    2. Direct to the next third waypoint indicated in the FP.

No direct-to waypoints beyond the AoR have been considered, as these waypoints can be deemed too far from the AoR, although this may vary depending on the operational scenario.

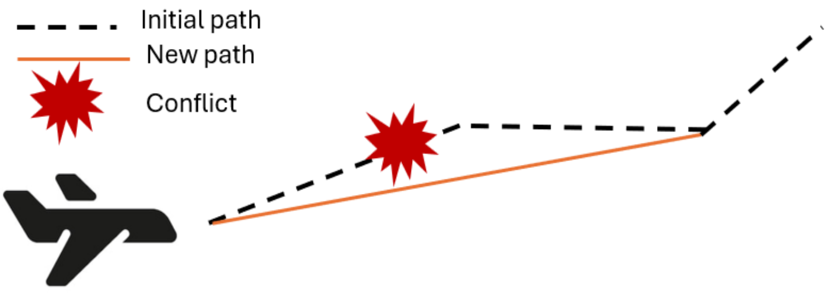

Figure 4. Conceptual example of Direct-to avoiding manoeuvres.

b. FL change. This manoeuvre is considered a last resort as it implies that none of the preceding manoeuvres are safe, necessitating an intervention on the aircraft to avoid conflict. Restrictions have been applied to these ascents and descents based on the distance covered by the aircraft, aiming to limit the negative impact on the aircraft. The following solutions have been considered:
   1. Climbs when aircraft has covered less than 75% of the FP:
      1. Climb 1000 ft
      2. Climb 2000 ft
   2. Descends when aircraft has covered more than 75€ of the FP:
      1. Descend 1000 ft
      2. Descend 2000 ft

One of the drawbacks of this manoeuvre is that while it changes an aircraft's actual FL to avoid a conflict, it also increases the controller's workload. This is because the controller may then need to return the aircraft to its original FL.

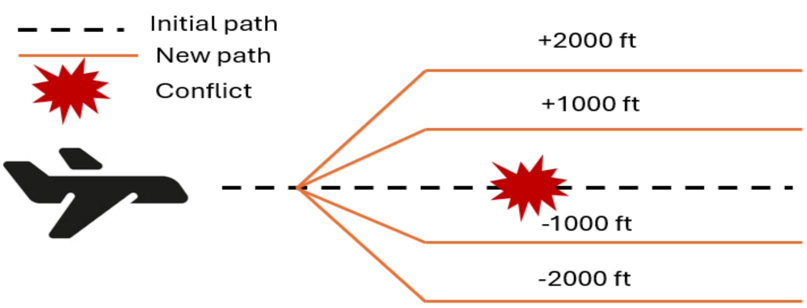

Figure 5. Conceptual example of FL change +-1000/2000 ft.

1. Modified Trajectory Generation Module. This module takes the selected resolution strategy and calculates the new trajectories resulting from the resolution manoeuvre. Additionally, it's

within this module that uncertainty regarding trajectory validity is incorporated. Evaluated resolution strategies can be provided to the ATCO as an information source in the case it is needed. Figure 6 shows an example of the possible outputs of the CR based on the modification of the current FL.

2. For each manoeuvre, two trajectories are generated:
    a. New nominal trajectory. This trajectory assumes the aircraft begins the manoeuvre 15 seconds later. For ascent rates, a nominal speed of 1500 ft/min is considered.
    b. New last trajectory. This trajectory represents the last and worst conditions for a trajectory modification and assumes the aircraft begins the manoeuvre 30 seconds later. For climbing rates, a nominal speed of 1000 ft/min is considered, and for descents, -1000 ft/min.

	Aircraft Pair	Aircraft to solve	FL + 100	FL + 200	FL - 100	FL - 200
0	(TAP822W, EJU9644)	TAP822W	Conflict with Aircraft EZS52LH	Valid Action	SI with Aircraft EJU9644	Valid Action
1	(TAP822W, EZS52LH)	TAP822W	Conflict with Aircraft EZS52LH	Valid Action	SI with aircraft EJU9644	Valid Action
2	(TAP822W, EJU9644)	EJU9644	SI with Aircraft TAP822W	Conflict with Aircraft EWG60HK	Conflict with Aircraft RYR9CJ	Conflict with Aircraft RYR9CJ
3	(TAP822W, EZS52LH)	EZS52LH	Valid Action	Conflict with Aircraft TAP822W	Conflict with Aircraft TAP822W	Conflict with Aircraft TAP822W

Figure 6. Example of vertical CR actions.

3. CD module. This module corresponds to the one described in Section CD tool and evaluates the new modified trajectories against the remaining predicted trajectories of aircraft operating in the environment. The objective is to determine whether this new trajectory maintains existing conflicts, generates new ones or SI. This information is stored to be available for the AI. Since each manoeuvre generates two new trajectories, a conflict or SI is considered to exist if any of the new trajectories generates an SI or a conflict.

4. Solution Prioritisation Module. This module implements a rule-based algorithm that identifies the best solution by following specific criteria for safety, operational efficiency, and ATCO workload.

CR manoeuvre types

CR is designed to evaluate different solutions in the horizontal and vertical planes for both aircrafts. The considered manoeuvres are:

- Adaptation of current altitude to flight-plan requested cruise level (vertical manoeuvre)
- Block of climb or descent until CPA in the case there is less than 3 minutes (vertical manoeuvre).
- Direct to the second or third next waypoint (horizontal manoeuvre). The first next waypoint is discarded because the aircraft is already flying to it.
- Modify current FL (by 1000 or 2000 ft).

Although the 4DT prediction calculation is performed by the POLARIS system, CR has its own 4DT prediction trajectory module based on the manoeuvres to be applied. The modified trajectory prediction is calculated internally because this tool is part of the ASA system and is not directly connected to the POLARIS system. In the future, it must be required to have the same 4DT prediction tool in the CD&R as in POLARIS. The reason is similar to what is explained in the CD module because the validity of the solution highly depends on the 4DT prediction accuracy.

Prioritisation algorithm

For each conflict pair, a maximum of 10 possible solutions can be obtained, whether conflict-free or not. Typically, more than one manoeuvre will resolve a conflict between a pair of aircraft. For this reason, it is necessary to develop a prioritisation algorithm to select the single best solution from the possible options.

To clarify, the most efficient manoeuvres are calculated starting from the CR activation horizon (also referred to as Resolution Activation Time – RAT).

Firstly, some resolutions are limited to the following time horizons:

- FL change manoeuvres are calculated for the short term $TimetoCPA < 5\ min$.
- Blocked climb or descent manoeuvres are calculated for a minor short term $TimetoCPA < 3\ min$.

Secondly, the prioritisation algorithm is based on logical rules. These logical rules form a decision tree where solutions are grouped based on defined conditions. To achieve this, three criteria have been considered for ordering the possible solutions:

1. Safety: This is the primary criterion. For a solution to be considered valid, it must be conflict-free $t_{CPA} < 10\ minutes$. This means that while some manoeuvres might initially appear valid, they could lead to a safety infringement (SI) or a conflict with $t_{CPA} > 10\ minutes$ on the new projected trajectories. Therefore, when comparing solutions at the same level, the prioritisation algorithm will first select those that do not generate any such events.
2. Operational efficiency: Operational efficiency evaluates the impact a manoeuvre has on aircraft performance. A manoeuvre can primarily have either a positive impact (e.g., the aircraft begins flying at higher flight levels earlier than predicted, or it reduces distance, time, or fuel by flying direct to a waypoint) or a negative impact (e.g., its FL is changed solely for conflict resolution purposes).
3. ATCO workload: When a conflict is identified, the ATCO must take necessary actions to prevent a loss of separation. Similar to operational efficiency, some solutions can minimise the impact on the workload:
    - Adjustment to an Operational FL: This resolution method involves a subsequent clearance from the ATCO to adjust the aircraft to an appropriate operational FL.

- Direct-to Waypoint: Resolving a manoeuvre by directing an aircraft to a waypoint means it spends less time in the current sector. However, this could have a negative impact on subsequent sectors due to an earlier estimated time of arrival.
- FL Change: This resolution type typically involves the highest workload. It requires diverting an aircraft from its current flight level and then, later, clearing it back to its original FL.

Finally, for the calculated set of solutions, the best solution for each conflict is obtained, as shown in Figure 7. The prioritisation algorithm provides five solutions, one per each conflict identified.

	Aircraft Pair	Aircraft to solve	Maneuver	Comments	tcpa	time_to_cpa_hms_1	time_to_cpa_hms_2	Valid until time	Validity	Post ATC CLR
0	(AFR459, EZS52LH)	EZS52LH	FL+10	Valid Action	2023-07-06 07:18:17	00:01:57	00:01:57	2023-07-06 07:16:50	YES	YES
1	(AFR459, RYR83HD)	RYR83HD	Direct to 2nd WP	Valid Action	2023-07-06 07:25:27	00:09:07	00:09:07	2023-07-06 07:16:50	YES	NO
2	(EWG60HK, EZS52LH)	EWG60HK	Direct to 2nd WP	Valid Action	2023-07-06 07:18:21	00:02:01	00:02:01	2023-07-06 07:16:50	YES	NO
3	(EZS52LH, TOM7JW)	TOM7JW	Direct to 2nd WP	Valid Action	2023-07-06 07:19:48	00:03:28	00:03:28	2023-07-06 07:16:50	YES	NO
4	(RAM1616, RYR83HD)	RYR83HD	Direct to 2nd WP	Valid Action	2023-07-06 07:34:06	00:17:46	00:17:46	2023-07-06 07:16:50	YES	NO

Figure 7. List of proposed manoeuvres for different conflicts based on prioritisation algorithm.

Furthermore, since only one aircraft should be chosen for action, if both aircraft have valid manoeuvres at the same level of safety, operational efficiency, or ATC workload, the algorithm prioritises acting on the aircraft farthest from the CPA ($max\ (DistoCPA_1, DistoCPA_2)$). This is a common practice among ATCOs, as the aircraft further away has more distance to complete the requested manoeuvre.

The CR module results in:

- Aircraft pair and aircraft selected to perform the manoeuvre
- Description of the manoeuvre
- Time to CPA and CPA timestamp
- Minimum separation
- Validity status
- Comments (e.g., “Valid action”, “Conflict with ACj”, “Valid although SI/conflict >10 min”)
- Validity expiry time
- Post-clearance requirement
- S Coordination requirement (if manoeuvre affects another AoR).

Details available in Section 2.4.2.

3.3 Operational description

According to the design of the ASA system, both tools receive the information directly processed from the KG and not from the surveillance system, since they are tools of the ASA system itself. Figure 8 shows the design of the CD&R data flow:

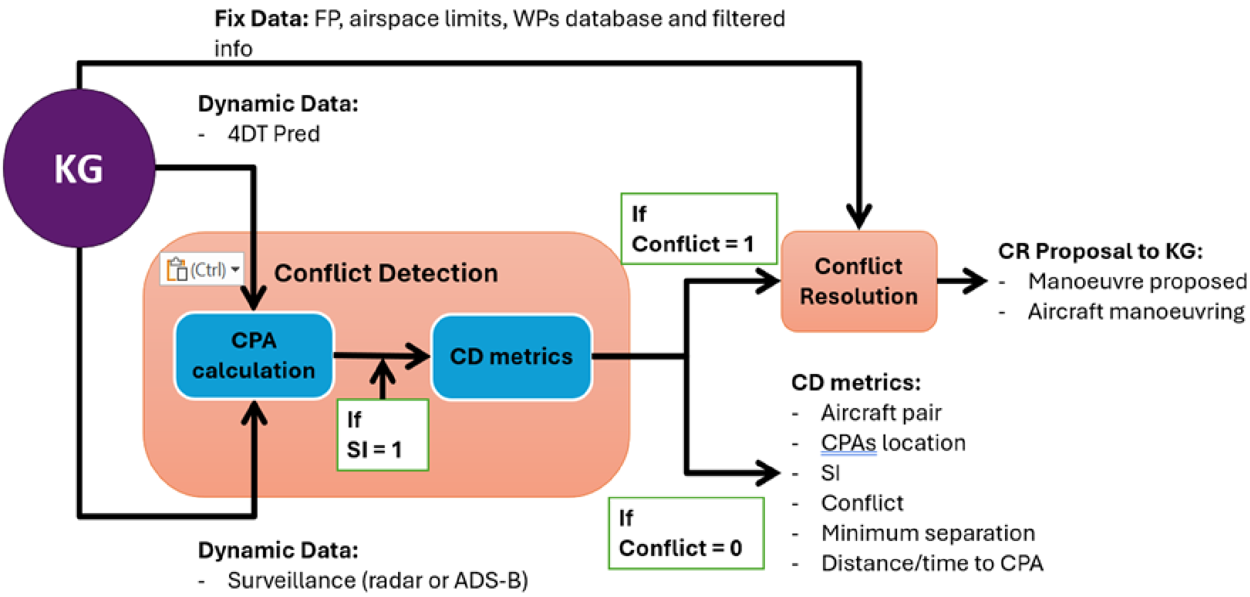

Figure 8. CD&R performance design.

Each module receives and provides different information. An example of data flow is as follows:

- The ASA system from the Knowledge Graph (KG) provides the information required for the CD&R. This implies that all the required data are filtered and provided by the KG and not from POLARIS.
- CD demands as input dynamic data from KG. 4DT predictions are provided by the system based on 4D format (position + time) and surveillance data (it can be radar or ADS-B, but it is required to use the position and operational variables such as ground speed, etc.).
- CD calculations Situation of interest (SI) and conflicts. Situations of Interest are defined as any aircraft pair that crosses infringing SI separation minima (10 NM and 1000 ft) and conflict as any aircraft pair that crosses infringing en-route separation standards (5 NM and 1000 ft).
- CD provides output related to CD metrics: Aircraft pair, CPAs location, SI, Conflict, Minimum separation, Distance and time to CPA.
- CR demands data from different sources: from the CD it needs 4DT predictions and calculated safety metrics, from the KG it demands info filtered from the flight plan (next available waypoints depending on the sector boundaries), geographical location of those waypoints, position and activation time of TRAs in the sector.
- CR provides output considering manoeuvre solutions and aircraft involved for this manoeuvre.
- The proposed manoeuvre of CR must be conflict-free and compared with the rest of aircraft flying in the airspace as well as with all active TRAs.

3.4 Requirements of data flow

3.4.1 CD module requirements

Input data for CD module is:

- 4DT prediction: each 4DT prediction is constituted by a list of vectors constituted by 4D positions longitude (lon), latitude (lat), altitude (h) for each timestamp $(t_0, t_1, \ldots)$
    - $Pred[(lon, lat, h, t_0), (lon, lat, h, t_1), \ldots]$
- Surveillance data: ADS-B or radar operational data for each aircraft at each timestamp considered for CD prediction. This data should include at least the following:
    - Position $\left(Pos(t)\right)$: longitude, latitude, altitude and time.

Control variable:

- Look-Ahead Time (LAT): this control variable represents the maximum time it is considered to evaluate the conflict search. LAT coincides with the conceptual value of the CD calculation horizon.

Output data from CD module:

- Aircraft pair $\left(Ac_i, Ac_j\right)$: Id of aircraft pair involved in the conflict detection.
- Position of CPA $\left(Pos_{CPA_i}, Pos_{CPA_j}, Pos_{CPA_{int}}\right)$ for aircraft pair considered based on longitude, latitude, altitude and time and the intermediate position of the CPA (CPA_{int}).
- $MinDis$: minimum distance (NM) expected to reach by each aircraft pair.
- SI (binary): situation of interest
- $Conflict$ (binary): expected loss of separation for an aircraft pair.
- $TimetoCPA$: difference of time between the current timestamp and when is calculated to reach the CPA
- $DistoCPA$: distance (NM) between the current location of each aircraft and the location of the CPA

3.4.2 CR module requirements

Input data for CR module is:

- CD outputs for each aircraft in conflict: 4DT predictions, DistoCPA, TimetoCPA, status_CPA, status_initial
- Flight plan: this variable provides the next waypoints (longitude and latitude) that must be flown by the aircraft.
- XFL: this variable includes information about the Exit Flight Level of the aircraft within the AoR.
- CFL: this variable refers to the Cruise Flight Level indicated in the Flight Plan.

- Aixm data: this variable provides information about the geographic coordinates of TRAs.

Control variable:

- Resolution-Activation Time (RAT): this control variable represents the maximum time it is considered to trigger the CR.

Output data from CD module:

- Aircraft pair (Ac_i, Ac_j): Id of aircraft pair involved in the conflict detection.
- Actosolve $(Ac_i\ or\ Ac_j)$: Id of aircraft that applies a resolution manoeuvre.
- Solution: Resolution manoeuvre evaluated. Syntax is as follows:
  - Adapt FL of Ac_i to $FLXXX$
  - Maintain FL until CPA+ buffer = 30s
  - Direct to 2nd WP or Direct to 3rd WP
  - FL+10, 20, -10, -20
- tcpa: date time format of time of CPA.
- Time to CPA: difference of time between the current timestamp and when is calculated to reach the CPA in hours, minute, seconds format.
- Comments: description of the analysis of the resolution manoeuvre. Syntax is as follows:
  - Valid action: conflict-free manoeuvre with nothing to remark.
  - Conflict with Ac_j: the resolution manoeuvre generates a conflict or SI
  - Valid action although SI/conflict with Ac_j in X minutes: the resolution manoeuvre generates a SI or a conflict in more than 10 minutes and it is shown the time of the conflict (>10 minutes)
- If there are multiple separation issues, it is shown all of the different SI or conflicts identified.
- tvalidity: date time format of validity time of the resolution manoeuvre.
- Validity (binary): it specifies whether the resolution manoeuvre is valid (free of conflict until LAT) or not
- PostCLR: this variable specifies if the resolution manoeuvre demands a post clearance by ATC to return Ac_i to its original path.
- Coordination (binary): it specifies whether the resolution manoeuvre demands coordination with other airspace because the aircraft is not currently flying on the AoR. It implies that the ATCO must ask for a resolution manoeuvre by coordinating it.

The CD&R tool generates clearance suggestions in the form of CD&R messages. Each message may include information from the CD module and/or the CR module, as described below.

CD message content:

- Callsigns: Identifiers of the conflicting flight pair
- Time to CPA: Time remaining until the CPA
- Time to LOS: Time remaining until the separation infringement
- CPA Location: Positions of both flights at the CPA
- Minimum Separation: Predicted minimum separation at the CPA

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- Aircraft status at the CPA: Status (climb, descent or cruise) of the aircraft at the CPA based on the predicted trajectory

CR message content:

- Callsign: Identifier of the flight that should receive the resolution manoeuvre
- Clearance Type: Type of resolution clearance to be applied, such as:
    - Direct (DCT): Waypoint designator to be issued
    - Flight Level (FL): Cleared FL
    - Block Climb/Descent Until: End time of the block clearance, provided in HH:MM:SS format
- Coordination Field: Included when coordination with an external sector is required

3.5 Operational Use

This Section will describe how the CD&R tool will be presented to ATCOs and in which way they will interact with it. The ASA system supports the CD&R tool in both advisory and execution mode. Mode of operation is dependent on several factors: ATCO intent, active ATCO task list, ATCO task prioritisation list, temporal condition and hard-coded limitations. Later deliverables (D2.19 and D2.20) are dedicated to explanation of this topic.

The CD&R tool uses the output from the CD&R module to provide output. Initial variables the tool checks are:

- Position of the flights
- Position of the CPA
- Position of the LOS
- Time to CPA
- Time to LOS

Detailed variables are presented in the Table 1

Variable	Description
Position of the flight	If the flight is in the AoR of considered sector and if flight is less than 20 NM from sector boundary, CD&R will check for conflicts
Position of the CPA	If the CPA is positioned in the AoR of considered sector or 20 NM from the sector boundary, CD&R will send output.
Time to CPA	For advisory mode: If the time to CPA is less than 10 minutes, CD&R will send output. For execution mode: If the time to CPA is less than 5 minutes, CD&R will send output.

Table 1. Initial variables that trigger the activation of CD&R

Based on the position of flight and CPA, three possible types of conflicts are considered:

- In sector conflict: flights are in the same sector with less than 5 NM or 1000 ft separation.

- Exit conflict: for flights approaching exit point and with less than 5 NM or 1000 ft.
- Entry conflict: for flights approaching entry point and with less than 5 NM or 1000 ft.
- Outside of the sector conflict: Flights outside but within 20 NM of the sector boundary, with less than 5 NM or 1000 ft separation, and previously under the control of the considered sector.

The operation of the CR tool depends on the current (local) time and the time to the CPA. The objective of considering the time to CPA ($TimetoCPA$) is twofold: on one hand, it aims to reduce computational cost by decreasing the number of maneuvers to be calculated, and on the other hand, to provide maneuvers that are operationally meaningful and have an impact on operational efficiency consistent with these margins. Figure 9 shows time horizons considered for interaction between CD and CR.

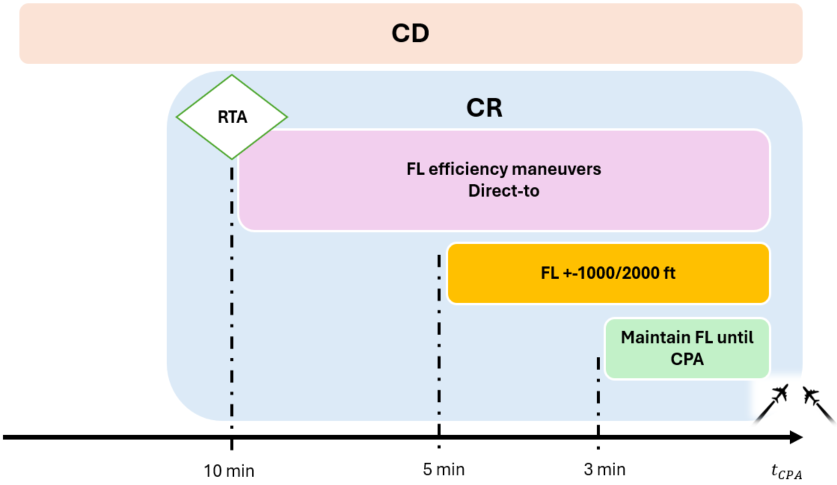

Figure 9. Time horizons for CD and CR

CD&R tool functionality in advisory and execution mode

Detailed comparison of tool functionality in both operational modes is presented in Table 2. Values in the table are founded in SME opinions.

	Advisory mode	Execution mode
Action execution responsibility	The CD&R tool in the advisory mode will send an output to the ATCO once conflict is detected. ATCO will be responsible to execute conflict resolution. A conflict resolution message is sent to the pilot via CPDLC.	The CD&R tool in the execution mode will send an output to the ATCO once flight is detected to be in the conflict. The tool will inform the ATCO about the resolution action it wants to execute and give ATCO enough time to validate that action and interfere if needed. ATCO can accept the tool's output or reject it. If there is no interference from ATCO, the tool will execute the conflict resolution action. A CR

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		message is sent to the pilot via CPDLC.
Activation of the tool	The tool will check for conflicts for all the flights that are 20 NM horizontally or 30 FL vertically from the sector boundary. Also the tool continuously checks for conflict pairs for flights within sector ESMM23.	The tool will check for conflicts for all the flights that are 20 NM horizontally or 30 FL vertically from the sector boundary. Also the tool continuously checks for conflict pairs for flights within sector ESMM23.
Time out of the tool's output	CD&R tool times-out after 30 seconds OR earlier if resolution is no longer valid	CD&R tool times-out after 30 seconds OR earlier if resolution is no longer valid.
Protocol after the time-out	After the time-out, the system will send another message if the time to CPA is less than 3 minutes.	After the time-out of the tool output and if ATCO didn't interfere with it, **the system will execute CR action**.
Protocol after the rejection of the tool's output	After the rejection of tool output, the system will send another resolution to the ATCO until there are no more options, or until there is no longer conflict.	After the rejection of tool output, the system will send another resolution to the ATCO until there are no more options, or until there is no longer conflict.
Summary	Conflict pairs are checked from 20 NM before the sector boundary but only when **CPA is less than 10 minutes,** resolution will be sent to the ATCO.	Conflict pairs are checked from 20 NM before the sector boundary but only if **CPA is less than 5 minutes**, resolution will be sent to the ATCO.

Table 2. CD&R tool -comparison of advisory and execution mode

3.6 Expected Benefits

The main purpose of a Conflict Detection and Resolution (CDR) tool is to enhance the safety of air operations and provide air traffic controllers with conflict-free solutions. The primary influence on safety is that the CDR acts as a safety barrier by informing ACTOs of future losses of separation and providing operational information about these conflicts and other situations of interest. In addition, it improves safety since the tool's calculations are more precise and have a lower error rate than the mental calculations performed by the ATCOa.

Regarding workload, this tool can indirectly increase capacity by reducing the ATCO's workload. It does this by decreasing the time needed to spend on conflict detection and resolution tasks. At this point, it's important to highlight that improvements in this area are related to the ATCO's trust in the CDR tool.

Efficiency can be analysed based on two areas:

- Considering efficiency as the ability to improve the aircraft trajectory performance, the CR module was developed to analyse potential solutions and find the most efficient, conflict-free manoeuvre for each individual aircraft. For example, the CR algorithm prioritises selecting a direct-to over a FL change.
- Considering efficiency from the ANSP, if the CDR tool is able to increase safety and capacity up to some point, then the cost of service for each aircraft will diminish.

3.7 Limitations / Challenges

As with any tool developed without direct user involvement, a number of limitations or challenges have been identified and must be analysed after its implementation in the planned experiments:

Regarding the tool and its developed functionalities:

- The functionality for conflict resolution based on vectoring has not been implemented.
- Ground Speed (GS) is used as the velocity item for the CR although wind has not been considered in the scope of the AWARE project. Speed is assumed to be constant at the current GS for the various manoeuvres.
- A prioritising algorithm has been developed for the CR module to find the best solution balancing their impact on aircraft trajectory performance and ATCO workload. This algorithm has been developed based on expert judgement and not on quantitative assessment.
- The trajectory prediction module developed for CR was based on typical aircraft performance limitations. It might be beneficial in future developments to implement specific aircraft models from BADA (Base of Aircraft Data) or other sources to improve trajectory prediction, as well as to develop a unique trajectory predictor for the AAA system.
- This CR provides head-to-head solutions only and does not directly resolve multi-aircraft conflicts. However, a solution for one aircraft pair might also resolve a conflict involving another aircraft.
- FL change manoeuvres have been limited to ±1000/2000 ft, depending on the aircraft's distance from its origin and destination airports. This aims to provide efficient solutions based on the aircraft's travelled distance and to avoid negatively impacting aircraft operations. Therefore, climbing is allowed for aircraft that are less than 75% of the distance from the ADEP. Resolution manoeuvres involving descents are only considered if the aircraft is more than 75% of the distance from the ADEP.
- The validity period for a proposed manoeuvre is calculated up to the next 30 seconds from the moment the conflict is identified, and the CR is executed. This period is referred to as validity time and defines how long the proposed solution remains valid. Besides, this value is customised for this project and can be adapted.

- The time horizon for which a CR tool provides a solution is less than 10 minutes. This value can be adjusted and has been established as a trigger to limit the tool's use for longer time horizons based on the scope of the project.
- Maintain FL solutions until the CPA is only applied if the is less than 3 minutes. This hypothesis was considered to limit the impact on aircraft performance of maintaining a FL that does not correspond to the aircraft's intended evolution (climb or descent). Besides, this value is customised for this project and can be adapted.
- Conflict resolution manoeuvres based on “direct-to” navigation only consider the next two waypoints the aircraft is currently flying towards. The objective is to limit the number and scope of possible manoeuvres. In the future, this should be restricted to the first waypoint outside the airspace sector, as this requires coordination.

Regarding the mode of operation:

- Different time horizons for CDR are selected. In this project the CD calculation horizon is not limited and calculates the CPA for conflicts without time boundaries based only on the available trajectory prediction. CD presentation horizon, which represents the time when CD metrics are shown to the ATCO, is limited to 10 minutes and CR is only activated if TimetoConflict is lower than 10 minutes (5 minutes for execution mode). It should be evaluated in further work the way these horizons should be integrated into the AAA.

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4. Transfer Tool

4.1 Purpose & Functionality

The purpose of the Transfer Tool is to support, and where applicable automatically execute, the transfer of flights between control units. The tool analyses the current traffic situation and identifies flights that can be safely transferred. It operates in accordance with predefined temporal constraints, safety requirements, and established operational rules and practices.

The Transfer Tool assists ATCOs by proposing or automatically executing flight transfers that meet all required conditions. If a flight cannot be safely transferred, or if coordination with an adjacent unit is required prior to transfer, the tool informs the ATCO and provides additional support for completing the necessary actions.

To achieve this functionality, the Transfer Tool relies on surveillance data extracted from the Knowledge Graph (KG) and on a set of conditions that define whether a flight is a valid transfer candidate. A prerequisite for transfer is that the flight is within the Transfer Tool's time horizon. The following conditions must be satisfied:

- The flight must be clean, meaning it is following the previously coordinated route.
- The flight must be assumed.
- The flight must comply with the common Letters of Agreement (LoA).
- The coordinated (agreed) route must not be changed.
- The flight must not be in a Situation of Interest (as defined by the output of the CD&R module).

Common LoA are created exclusively for this project and do not constitute operational agreements. They are adapted exclusively for validation purposes, with extended content designed to cover a wide range of scenarios that may otherwise be addressed by LoAs, internal rules, or operational practices.

When and if all conditions are met, the transfer tool will suggest transfer of the flight.

Condition	Description
Flight is clean	The flight is not subject to locked heading, speed, or vertical rate.
Flight is assumed	Flight is within the AoI.
Flight is in line with LoA	The flight complies with the common LoA, specifically: ● The flight maintains XFL at least 2.5 NM before the sector boundary, or for climbing/descending flights, remains within the approved XFL range. ● The flight maintains at least 10 NM separation from succeeding traffic. ● Semi-circular flight level allocation rules are respected.

Coordinated (agreed) route is not changed	The coordinated route, as defined by revision or coordination messages, is respected.
Flight is not in situation of interest	The flight is neither in a potential conflict nor in an actual conflict.

Table 3. Transfer tool - conditions for transfer suggestion

4.2 Technical Description

Transfer tool uses flight data, LoA and general rules and practices to check conditions that assure safe and operationally appropriate transfer. The tool works by running Datalog rules over a knowledge-graph based representation of the situation. This approach ensures a high level of system explainability, which is treated as a key design priority. Common operational requirements for both transfer tool are:

- Keep the ATCO informed at all times by providing feedback on executed tasks.
- The tool's output must be explainable in all situations; the ATCO should be clearly informed when the transfer tool initiates an action, as well as when and why an expected action is not performed.
- If the transfer tool's output is rejected, the tool's functionality is limited, and the ATCO remains responsible for executing the transfer of communication manually.
- All flights are eligible to receive clearances generated by the transfer tool.

The process consists of two phases:

1 Transfer conditions assessment: Once a flight enters the time horizon of the Transfer Tool, the condition assessment process is triggered. The tool uses multiple data sources to evaluate whether transfer conditions are met:
   - Surveillance (track) data is used to verify conditions such as whether the flight is clean, assumed, and within the transfer time horizon.
   - Flight plan data is used to extract the requested route, XFL, and COP.
   - CD&R module output stored in KG is used to determine whether the flight is in a Situation of Interest.

   Based on the outcome of this assessment, the Transfer Tool either suggests the transfer of the flight to the ATCO or triggers the Coordination Tool if additional actions are required.

2 Coordination tool coaction: If the transfer conditions are not met, the Transfer Tool does not issue a transfer suggestion and instead forwards its output to the Coordination Tool to assist the ATCO. In other words, the absence of a transfer suggestion triggers the Coordination Tool. The Transfer Tool is activated shortly before the sector boundary—approximately 2.5 minutes prior to horizontal sector crossings and 30 flight levels before vertical sector crossings. Therefore, the coordination messages considered at this stage are Tactical Instruction Proposals (TIP) or Referred Revision Proposals (RRV). Further details on the Coordination Tool are provided in Section 5.

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Datalog rules

The following Datalog rules have been implemented, these rules identify if the flight is in line with LoA and to extract CD module results stored in KG.

1 Check if exit conditions are met:
1.1 Is aircraft flying towards exit point when cleared heading is assigned
1.2 Is aircraft flying towards exit point when cleared heading is not assigned
1.3 Will aircraft reach exit point on required flight level
2 Other helper rules used in the above-mentioned rules:
2.1 Is aircraft within sector
2.2 Is aircraft flying to cleared point
2.3 Distance to exit point
3 Check if flight is approaching border (approx. 2'):
3.1 Is aircraft approaching to sector boundary
4 Other helper rules used in the above-mentioned rule:
4.1 Is aircraft already assumed
4.2 Is aircraft already transferred
4.3 Distance to closest horizontal boundary
5 Aircraft is not in the situation of interest
5.1 Realized as the output of the conflict detection module

```
# 5.4.2 Check that aircraft will reach the exit point on the required FL
[?flight, :aircraftWillReachExitPointOnRequiredFL, ?indicator] :-
    [?airspace, ax:geometryComponent, ?sector],
    [?flight, :withinSector, ?sector],

    [?flight, :currentElement, ?currElement],
    [?currElement, fx:point4D, ?currPoint4D],
    [?currPoint4D, fx:level, ?currLevel],
    [?currLevel, fb:flightLevel, ?currFL],
    [?currPoint4D, :speed, ?currSpeed],

    [?flight, :agreedElement, ?clearedElement],
    [?clearedElement, fx:point4D, ?clearedPoint4D],
    [?clearedPoint4D, fx:level, ?clearedLevel],
    [?clearedLevel, fb:flightLevel, ?clearedFL],

    [?flight, fx:enRoute, ?enRoute],
    [?enRoute, fx:boundaryCrossingCoordination, ?boundaryCrossingCoordination],
    [?boundaryCrossingCoordination, fx:level, ?exitLevel],
    [?exitLevel, fb:flightLevel, ?exitFL],

    [?flight, :distanceToExitPoint, ?distToExitPoint],

    BIND(
        IF(
            ?exitFL = 0,
            ?clearedFL,
            ?exitFL
        )
        AS ?sectorExitFL
    ),
    BIND(
        ?sectorExitFL - ?currFL AS ?diffLevel
    ),
    BIND(
        ?currSpeed * 0.514444444 AS ?currSpeedInMS
    ),
    BIND(
        ?distToExitPoint/?currSpeedInMS AS ?timeToExitPoint
    ),
    BIND(
        (?diffLevel/?timeToExitPoint) * 60 AS ?calculatedVRate
    ),
    BIND(
        IF(
            (?calculatedVRate > 0 && ?calculatedVRate < 800) ||
            (?calculatedVRate < 0 && ?calculatedVRate > -1400) ||
            ?calculatedVRate = 0,
            1,
            0
        )
        AS ?indicator
    ).
```

Figure 10. Source code for one of the exit conditions rules

Each rule implemented within the system can be visualised to support transparency and explainability. Figure 10 illustrates the visualisation of an example rule that evaluates whether an aircraft will reach the exit point at the required flight level. In the visual representation, the node corresponding to the evaluated flight is linked to a binary indicator (1/0), which denotes whether the rule conditions are satisfied. The graph also includes all relevant input data as well as intermediate rules that contribute to the evaluation of the final rule outcome. Predicates associated with derived facts are highlighted in light blue colour and they represent results of Datalog rules. Predicates coloured in grey are part of explicit facts stored in a knowledge graph.

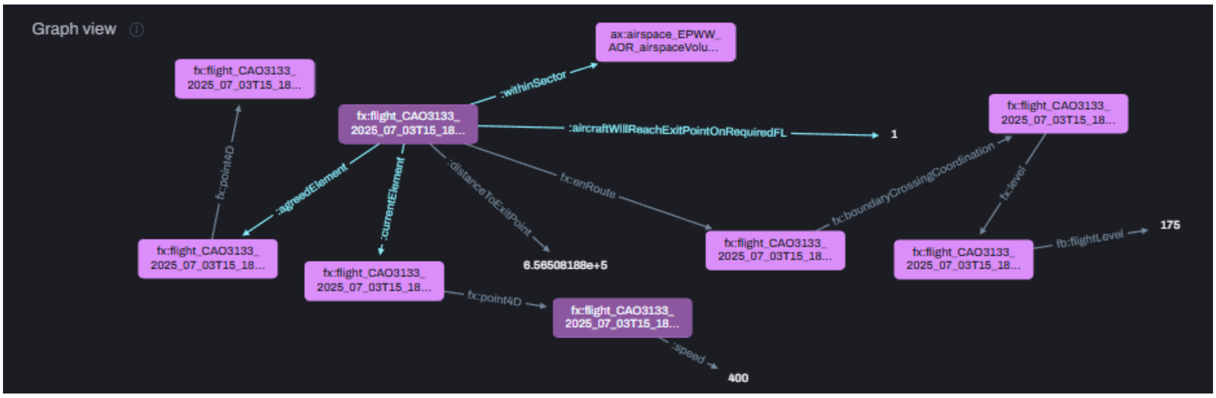

Figure 11 Visualization of the rule.

Figure 12 further presents the complete proof tree for the rule evaluation. The proof tree demonstrates how the final binary decision (whether the aircraft will reach the exit point at the required flight level) is derived through the combination of existing data, logical conditions, and intermediate rules. Each branch of the tree represents a logical dependency that must be satisfied for the rule to hold. The final row of the graph, highlighted in blue, represents the concluding step. This step integrates all prerequisite conditions and intermediate results and produces the final decision. By explicitly exposing the reasoning chain in this manner, the system enables ATCOs and system engineers to understand, verify, and trust the automated decision-making process.

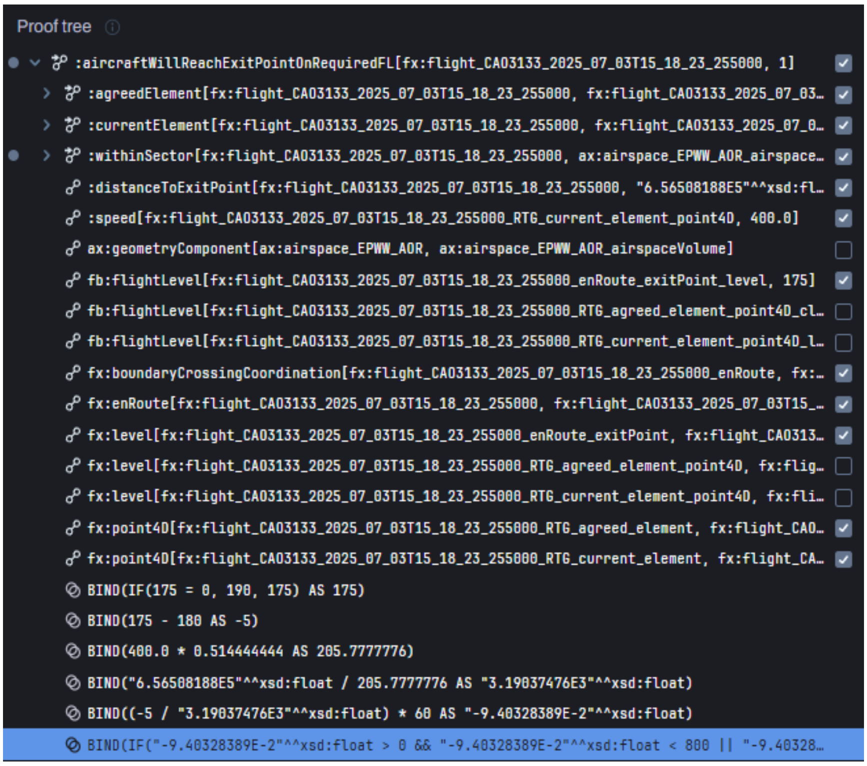

Figure 12 Proof tree of the rule

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4.3 Operational Description

Dataflow of the Transfer tool is presented in Figure 13.

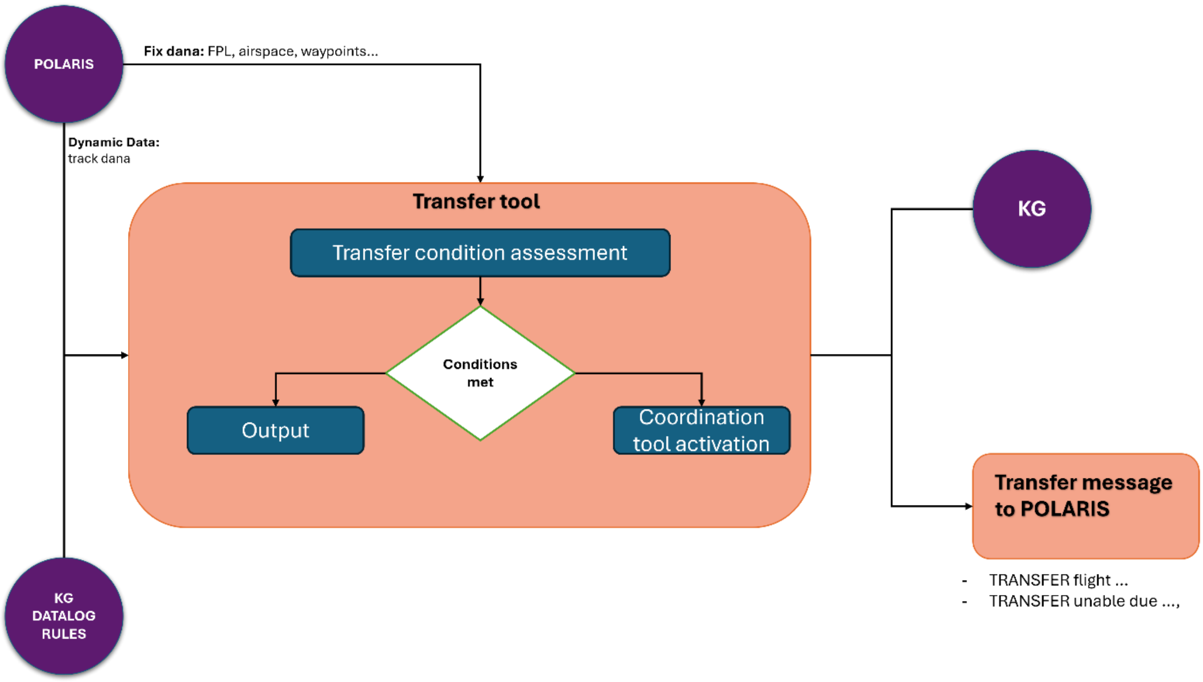

Figure 13 Data flow - Transfer tool

The process of data flow:

- The Transfer tool relies on data received from POLARIS and stored in the KG. This data must have a consistent JSON/XML structure and include flight plan, track (current position), and trajectory information. In addition, the Transfer tool uses Datalog rules to evaluate whether a flight qualifies as a transfer candidate. CD module results stored in the KG are also provided as input to determine whether the flight is in SI or in conflict.
- The transfer data flow is initiated when track records are received from POLARIS. Based on the flight's distance from the sector boundary, the tool evaluates whether the conditions for transfer are met.
- To verify that a flight is "clean", the coordinated route has not changed and the flight is assumed, the Transfer tool uses dynamic data from POLARIS.
- Compliance with the LoA is checked using KG Datalog rules.
- To determine whether the flight is in a situation of interest or a conflict, CD module results stored in KG are used.
- If all conditions are met, a Transfer message is sent.
- If the flight does not meet the required conditions, the Coordination tool is activated, or the ATCO is notified that the flight cannot be transferred and further action is required.
- The cancellation feature is an integral part of the Transfer tool. The system continuously monitors traffic scenario changes to detect when previously satisfied conditions are no longer met. In such cases, a cancellation message is sent to the system.

4.4 Requirements of data flow

The Transfer tool integrates data from several sources:

- Flight Data: real-time information about flights, including callsigns, positions (latitude, longitude), ground speeds, headings, FLs, aircraft types, and route trajectories (cleared, requested, and predicted). This data is essential to trigger Transfer tool, assess conditions for transfer and support the CD module
- Airspace Data: static airspace information. This includes AIXM-compliant data for sectors and waypoints.
- KG Datalog rules: outputs from Datalog rules stored in the KG, used by the Transfer tool to determine whether a flight complies with the applicable LoA and if the flight is in SI or conflict.
- System Configuration Data: level of system support (advisory vs. execution), validity periods for outputs, frequencies of adjacent units.

All data must be in standardized formats (e.g., JSON for events, XML for FIXM, Turtle for RDF) to enable seamless integration into the knowledge graph.

The Transfer tool has several dependencies that must be satisfied before processing can begin:

- Pre-loaded Static Data: AIXM data (airports, sectors, waypoints) must be loaded at system startup.
- Knowledge Graph Initialization: RDF triples for static airspace must be imported into the RDFox database before dynamic data processing starts.
- Conflict Detection Module: requires sector polygons and buffer zones to be pre-computed. If sectors are not defined, conflict checks default to basic separation rules.
- Level of system support: must be set (advisory or execution) to determine suggestion validity periods. Changes during runtime require graph updates.

Processing only triggers flights within the transfer tool's time horizon and flights with complete current point data. Incomplete records are skipped to prevent errors.

Output data from the Transfer tool is clearance suggestion in the form of Transfer messages, each containing:

- ASA tool identifier: "transfer".
- Callsign: the affected flight's identifier.
- Frequency flight should be transferred to.
- Indicator whether the flight is eligible for transfer or not
- Reason for non-eligibility, a textual explanation provided only if the flight is not eligible; otherwise, this field is empty.

4.5 Operational Use

This section describes how the transfer tool is presented to ATCOs and in which way they will interact with it. The ASA system supports the transfer tool in both advisory and execution mode. As previously

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mentioned, the tool checks through Datalog rules if the flight is a good candidate for transfer of frequency.

The prerequisite of transfer tool activation is time horizon. Transfer tool checks for the transfer conditions only when flight is 2 minutes from the sector boundary (for flights leaving sector horizontally) or is in descent to XFL and is less than 30FL from XFL.

With this condition being checked, the rest of transfer conditions are being assessed.

Transfer tool holds the information about the sector flight should be transferred to and sends flights to the following unit either for external units or internal units.

Depending on the mode of operation. The tool will either suggest transfer or automatically execute transfer. In both cases, clearance to the pilot is communicated via CPDLC. For advisory mode ATCO is informed that the flight is ready for transfer by visual cues. ATCO can remove the indication by clicking on 'X'. In execution mode, ATCO is informed that the flight is about to be transferred automatically by visual cues after the time out. The countdown timer visually represents the time left for ATCO intervention.

Transfer tool functionality in advisory and execution mode

Detailed comparison of tool functionality in both operational modes is presented in Table 4. The considered sector is Sector 23 in Malmo ACC operated by LFV (ESMM23). Values in the table are grounded in SME opinions.

	Advisory mode	Execution mode
Action execution responsibility	Transfer tool in the advisory mode will send an output to the ATCO once flight meets all the conditions. ATCO will be responsible for executing that transfer. Transfer message is sent to the pilot via CPDLC.	Transfer tool in the execution mode will send an output to the ATCO once flight meets all the conditions. The tool will inform the ATCO about the action it wants to execute and give ATCO enough time to validate that action and interfere if needed. ATCO can accept the tool's output or reject it. If there is no interference from ATCO, the tool will execute the transfer. Transfer message is sent to the pilot via CPDLC.
Activation of the tool	For flights leaving sector ESMM 23 horizontally, the tool will activate when flight is 2 minutes or less to the sector boundary. For flights leaving sector ESMM 23 vertically, the tool will activate when flight is 30FL or less to the sector boundary.	For flights leaving sector ESMM 23 horizontally, the tool will activate when flight is 2 minutes or less to the sector boundary. For flights leaving sector ESMM 23 vertically, the tool will activate when flight is 30FL or less to the sector boundary.

Time out of the tool's output	The transfer tool doesn't have a time-out. Output will be removed if flight is no longer following all the mentioned conditions.	**Time-out is 30 seconds.**
Protocol after the time-out	After the time-out, the system will send another message if the time to CPA is less than 3 minutes.	After the timeout of the tool output and if ATCO didn't interfere with it, **the system will execute the transfer.**
Protocol after the rejection of the tool's output	After the rejection of tool output, the tool won't send another output until flight is less than 1 minute or less than 10FL to sector boundary.	After the rejection of tool output, the tool won't send another output until flight is less than 1 minute or less than 10FL to sector boundary.

Table 4. Transfer tool - comparison of advisory and execution mode

4.6 Expected Benefits

The primary benefit of the Transfer Tool is the **reduction of ATCO workload** and the improvement of situational awareness. Flight transfer is a routine task that requires controller attention and can divert focus from more time-critical and safety-critical activities. By automating or supporting this task, the Transfer Tool allows ATCOs to concentrate on higher-priority operational responsibilities.

The tool should improve **safety** by serving as an additional safety net, preventing the flights from exiting the sector without being transferred to the appropriate unit. Safety is expected to be enhanced also through the application of rule-based logic that explicitly evaluates whether a flight is involved in a conflict or a potential conflict prior to transfer. This reduces the risk of unsafe transfers that could lead to entry or exit conflicts at sector boundaries.

In addition to safety benefits, the Transfer Tool contributes to improved operational **efficiency**. Transferring flights that are identified as suitable candidates and at the appropriate time enables approach units to provide continuous descent, which positively impacts efficiency and environmental performance.

Furthermore, the Transfer Tool increases system **resilience**. During periods of high workload, such as when ATCOs are managing conflicts, emergencies, or other attention-demanding tasks, the ability to assist with or automatically execute flight transfers helps ensure that the processes continue reliably without degradation of overall operational performance.

4.7 Limitations / Challenges

Identified limitations/challenges regarding the tool and its developed functionalities:

- Transfer of control is considered only to the adjacent sector which is gathered from the FPL. If the route is changed or if a flight needs to be transferred to a sector other than the adjacent one, the tool's capability is limited.

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- The tool applies a rigid rule set uniformly to all flights. The predefined time horizon for transfer may be inadequate for certain flights. Future development should consider variable time horizons based on specific flight characteristics.
- The transfer tool determines whether a flight is eligible for transfer by checking if it is on a coordinated route and compliant with the LoA. However, it does not proactively inform the ATCO of the actions required to make a flight a suitable candidate for transfer. Instead, the tool only notifies the ATCO at the trigger time if the flight is not eligible. It should be considered whether the tool could be extended to also monitor and support the actions necessary to enable safe and efficient transfer where possible.

Regarding the mode of operation:

- In execution mode, the tool's functionality is limited by dependency on ATCO interventions. If a flight cannot be transferred automatically, additional actions are required, such as tactical route changes or coordination. Without activation of either ATCO input or the coordination tool, the transfer tool cannot complete the transfer, thereby limiting its effectiveness.
- Advisory mode follows similar principles; however, since it always requires ATCO approval before task execution, the tool's functionality remains fully dependent on ATCO actions.

5. Coordination tool

5.1 Purpose & Functionality

The Coordination Tool is designed to improve coordination processes between units by proactively identifying traffic situations that require coordination for both inbound and outbound flights. The tool detects specific scenarios that necessitate coordination and is triggered either by other ASA tools or by defined time horizons. By identifying flights that require coordination before transfer, as well as flights that need coordination due to entry conflicts, the tool supports ATCOs in managing a wide range of complex coordination scenarios. Given the high variability and complexity of situations requiring coordination, this proactive support significantly reduces manual workload and helps ensure smooth and timely transfers of communication.

Since coordination is a planner ATCO task, this tool explores several support options: assisting the planner directly, enhancing situational awareness for both planner and executive ATCO, improving communication between planner and executive, and assessing whether, when sufficient tool support is available, the coordination task could be handled by the executive ATCO.

The Coordination Tool consists of two main components: inbound coordination support and outbound coordination support.

1. Inbound coordination: cases when the subject of coordination is not within the considered sector. When coordinating traffic out of the considered sector and the flight is inbound, messages are RTI (Request Tactical Instruction) and RRQ (Request release). RTI is sent for flights that are not assumed. RRQ message is sent for flights that are assumed, but the flight is outside of the sector considered sector.
2. Outbound coordination: cases when the subject of coordination is within the considered sector. When coordinating traffic in a considered sector and the flight is outbound going into external sectors, messages are RRV (Referred Revision Proposal), REV (Revision) and TIP (Tactical Instruction Proposal). The specific message type depends on the time remaining until the sector boundary [5].

Both inbound and outbound coordination components operate in advisory and execution modes. Inbound coordination is triggered exclusively by the CD&R tool, whereas outbound coordination can be triggered by the CD&R tool, QoS, the transfer tool, or direct ATCO intervention.

5.2 Technical Description

The Coordination tool uses traffic data from surveillance, airspace data, common LoA and operational procedures for its decision-making process. The coordination tool works by running Datalog rules over the knowledge-graph representation of the situation. Common operational requirements for both inbound and outbound coordination are:

- Keep ATCO in the loop (provide feedback on executed tasks)
- The tool's output should be explainable in all situations, meaning ATCO should be informed why the coordination tool is triggered.

- Rejected autonomous coordination in second attempt downgrades to manual voice coordination.
- Adjacent units can receive and answer coordination messages from the Coordination tool.

5.2.1 Inbound Coordination

The process of inbound coordination is as follows:

1. CD&R tool coaction
   Inbound coordination is initiated by the CD&R tool. When a proposed conflict-resolution manoeuvre requires coordination, the Coordination Tool is automatically triggered. As described in the CD&R section, the tool generates resolution proposals 10 to 5 minutes before the CPA, but only when the CPA is within the concerned sector.
   In specific entry-conflict scenarios, the resolution manoeuvre typically applies to traffic that is not yet under the control of the ATCO responsible for conflict resolution. Therefore, operational co-action between the CD&R and Coordination tools provides a logical and efficient workflow.
2. Coordination conditions assessment
   Once the CD&R tool identifies a manoeuvre that resolves the conflict, the Coordination Tool uses this output to generate the appropriate coordination message. The tool determines whether the manoeuvre should trigger an RRQ or an RTI message. For both message types, a prerequisite is that the transfer of control has not yet occurred. The distinction is based on the transfer of communication:
   - **RTI** is generated when the transfer of communication has not yet taken place.
   - **RRQ** is generated when the transfer of communication has already occurred.

5.2.2 Outbound Coordination

The process of outbound coordination is as follows:

1. Coordinated route calculation
   Outbound coordination relies on specific time-based triggers. The initial flight estimate is received through the **ACT (**Activate) message, sent 10 minutes before the sector boundary. The route contained in the ACT message is considered the initial coordinated route. Any deviation from this coordinated route requires further coordination. Accordingly, the first function of the Coordination Tool is to calculate and register this initial coordinated route based on the ACT message.
2. Coordinated route re-assessment
   Unlike inbound coordination, outbound coordination is triggered at predefined time points. The coordinated route established in the previous step is re-evaluated 5.5 minutes before the sector boundary. If the current route differs from the previously coordinated route, the Coordination Tool is triggered, and a **REV** message is sent. The route agreed through the REV message then becomes the new coordinated route. A second re-assessment occurs 2.5 minutes before the sector boundary. If the current route is breaking LoA or if XFL is changed, an **RRV** message is sent. In addition to time-based triggers, the coordinated route is re-assessed whenever the ATCO intervenes in a flight that falls within the Coordination Tool's time horizon. The tool evaluates whether the ATCO's action deviates from the coordinated

route; if a deviation is detected, a **TIP** message is generated. A detailed explanation of the Coordination Tool's time horizons is provided in figure 14.

3. Co-action with other ASA support tools.
   Beyond time-based and ATCO-driven triggers, the Coordination Tool operates in co-action with other ASA support tools, including QoS, Transfer, and CD&R. If any of these tools generate an output that results in a change to the coordinated route, the Coordination Tool is activated to manage the resulting coordination.

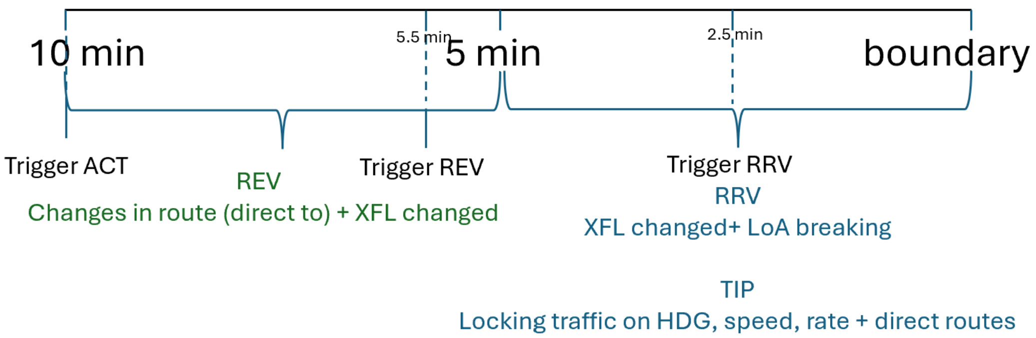

Figure 14. Coordination tool time horizon triggers

5.3 Operational description

Figure 15 presents the dataflow of the Coordination Tool.

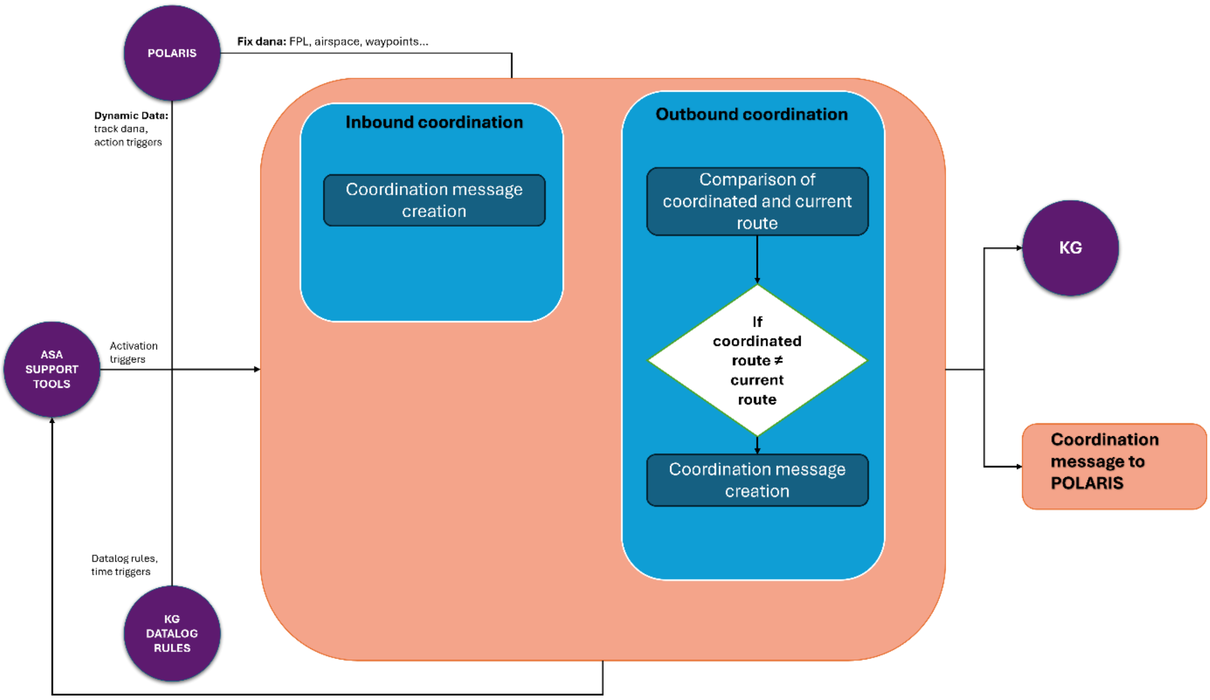

Figure 15. Coordination tool - Data flow

The process of data flow:

- The Coordination tool uses data from POLARIS to gather dynamic and fixed data. This includes flight plan data, track data, and airspace data, provided in JSON/XML formats. The tool is activated by specific triggers such as an ATCO action, a time-to-boundary condition, or another ASA tool. These data inputs are essential for the activation and execution of the Coordination Tool. In addition, the tool applies Datalog rules to determine whether a flight is a candidate for coordination and to identify the appropriate coordination message to be generated.
- The data flow of the Coordination Tool is initiated either by another ASA tool, by a time-to-boundary trigger, or by ATCO action. The tool is activated only for flights that require coordination with external sectors.
- To determine the content of the coordination message, the tool evaluates coordination requirements using Datalog rules. Based on these rules and the flight's position, the tool distinguishes between inbound and outbound coordination and selects the appropriate message type.
- Unlike other ASA tools, the Coordination Tool does not introduce any new rules beyond those already considered by other tools. For inbound coordination, it operates as a co-actioned tool with CD&R. For outbound coordination, it acts as a fallback mechanism, activating when the Transfer Tool is unable to transfer the flight. As a result, the Coordination Tool is always linked to another ASA tool.
- For outbound coordination, the tool compares the current route with the coordinated route. Based on the result of this comparison, an outbound coordination message is sent to POLARIS and forwarded to KG.
- The cancellation is also part of the Coordination Tool. The system continuously monitors changes in the traffic scenario to detect situations where previously coordinated conditions are no longer valid. In such cases, a cancellation message is issued, and a new coordination message is generated as required.

5.4 Requirements of data flow

The Coordination tool integrates data from multiple sources to determine whether coordination is required and to generate the appropriate coordination message:

- Flight Data: real-time flight information, including callsign, position (latitude and longitude), ground speed, heading, flight level, aircraft type, route trajectories (cleared, requested, and predicted), and transfer status. This data is essential for assessing the need for coordination and selecting the appropriate coordination message.
- Airspace Data: airspace information, including AIXM-compliant data for sectors and waypoints.
- KG Datalog rules: outputs from Datalog rules stored in the KG. These rules are primarily used by the Transfer Tool to verify compliance with the applicable LoA. If these conditions are not met, the Coordination tool is triggered. Additional rules are applied based on time-based triggers.
- ASA tool output: when another ASA support tool requires co-action with the Coordination tool, its output is used to re-evaluate the required coordination message.
- System Configuration Data: level of system support (advisory vs. execution), validity periods for outputs, information about the external sector.

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All data must be in standardized formats (e.g., JSON for events, XML for FIXM, Turtle for RDF) to enable seamless integration into the knowledge graph.

Before the Coordination Tool can begin processing, the following dependencies must be satisfied:

- Pre-loaded Static Data: AIXM data (airports, sectors, waypoints) must be loaded at system startup.
- Knowledge Graph Initialization: RDF triples for static airspace must be imported into the RDFox database before dynamic data processing starts.
- Level of system support: must be set (advisory or execution) to determine suggestion validity periods. Changes during runtime require graph updates.

The Coordination tool produces output in the form of coordination messages, either as standalone outputs or as a coordination field within the output of another ASA support tool. Each coordination message includes:

- ASA Tool Identifier: coordination.
- Callsign: Identifier of the affected flight.
- Coordination Reason: The trigger or condition that initiated the coordination.
- Coordination Message Type: The specific type of coordination message to be sent.

5.5 Operational Use

The coordination tool helps ATCOs to identify flights that need to be coordinated with the adjacent units usually by voice. The functionality of the coordination tool is limited to external coordination, for internal coordination ATCOs need to coordinate via the voice. The coordination tool supports ATCO in both advisory and execution ASA system mode.

5.5.1 Inbound coordination

The inbound Coordination tool is triggered upon activation of the CD module of the CD&R tool. Since the CD module identifies flight pairs which are in SI or conflict and alerts the ATCO 10 to 5 minutes in advance, this represents the earliest point at which inbound coordination can be initiated.

Once a conflict resolution is identified, the ATCO is presented with the proposed manoeuvre and offered the option to send the appropriate RTI or RRQ coordination message to the relevant adjacent sector. The system feeder ATCO responsible for the adjacent sector responds to the coordination request, and the initiating ATCO is informed accordingly. All coordination messages are exchanged through the Polaris system and communicated to the flight via CPDLC.

Depending on the selected mode of operation, the Coordination Tool either suggests coordination actions or executes them in cooperation with the CD&R tool. In advisory mode, the ATCO is notified of the co-action between the CD&R and Coordination tools through visual cues, which can be dismissed by selecting the “X” icon. In execution mode, the ATCO is informed that the flight is about to be coordinated based on the manoeuvre proposed by the CR module once a predefined timeout expires. A countdown timer provides a visual indication of the remaining time available for ATCO intervention.

5.5.2 Outbound coordination

The outbound Coordination Tool is triggered multiple times, based on predefined time thresholds and ATCO interventions.

When a flight approaches the 10-minute boundary separation, an ACT message is sent by the ATC system without ASA involvement to the subsequent unit, containing the estimated data for the flight under consideration. If the ATCO or another ASA tool proposes a tactical route change or a change in XFL, a REV message is sent at a specific point, 5.5 minutes before the boundary. REV messages are sent only to external units; for internal units, REV coordination is handled internally by the system.

As the flight approaches the 5-minute boundary separation, the Coordination Tool is triggered more frequently. One trigger is any ATCO tactical intervention where the flight is cleared onto a route that deviates from the previously coordinated route. Specifically, when a flight is locked on heading, speed, or vertical speed, or when a direct-to-point is issued, a TIP message is generated. TIP messages may also be triggered by the CD&R or QoS tools. In such cases, the ATCO is presented with a single combined message that includes both the initiating tool's clearance and the required coordination message.

An RRV message is triggered at a specific time, 2.5 minutes before the boundary. The RRV message is sent if the flight violates the LoA or if the XFL has changed. As previously noted, the Transfer tool is triggered 2 minutes before the sector boundary. If coordination has not been completed earlier (for example, if the ATCO disregarded the tool's suggestion or intervened after the RRV message was sent) the Transfer Tool will trigger the RRV coordination message again.

Table 5 summarises Coordination tool messages in time horizon from 5-minute boundary separation.

Once the Coordination Tool generates an output, the ATCO is presented with the proposed coordination message, which may be combined with another clearance if the tool is co-actioned with another ASA tool. When the message is sent, the feeder ATCO responds to the coordination proposal, and the initiating ATCO is informed of the response. All coordination messages are exchanged via the Polaris system and communicated to the flight through CPDLC.

Depending on the selected mode of operation, the Coordination Tool either suggests coordination actions or executes them in cooperation with the CD&R, QoS, and Transfer tools. In advisory mode, the ATCO is notified of suggested coordination actions through visual cues. In execution mode, the ATCO is informed that the flight will be coordinated automatically once a predefined timeout expires.

Condition	Coordination message
Traffic is not "clean" – locked on HDG, speed, vertical rate.	TIP message
Traffic changes coordinated route – flight is given direct point	TIP message

Traffic is not in line with LoA: • The flight doesn't maintain XFL at least 2.5 NM before the sector boundary, or for climbing/descending flight, it does not remain within the approved XFL range. • The flight doesn't maintain at least 10 NM separation from succeeding traffic. • Semi-circular flight level allocation rule is not respected	RRV message

Table 5. Outbound coordination messages

Coordination tool functionality in advisory and execution mode

Table 6 presents a detailed comparison of tool functionality in both operational modes, based on SME input for Sector 23 at Malmö ACC (LFV, ESMM23).

	Advisory mode	Execution mode
Action execution responsibility	The coordination tool in the advisory mode will send an output to the ATCO once the conditions are met. **ATCO will be responsible to execute coordination**. Coordination message is sent to the adjacent unit via the AAA system	The Coordination tool in the execution mode will send an output to the ATCO once the conditions are met. The tool will inform the ATCO about the coordination message it wants to send and give ATCO enough time to validate that message and interfere if needed. ATCO can accept the tool's output or reject it. If there is no interference from ATCO, **the system will send a coordination message**.
Activation of the tool	For outbound coordination, the tool is activated from 10 minutes to the sector boundary. Specifically, the tool will activate at 5.5 minutes before leaving the sector ESMM 23 to send a REV message and 2.5 minutes before leaving the sector to send a RRV message. TIP message is sent for the outbound flights, the tool will activate upon CD&R, QoS message or after ATCO interference. Additionally, RRV message is triggered upon Transfer tool message.	For outbound coordination, the tool is activated from 10 minutes to the sector boundary. Specifically, the tool will activate at 5.5 minutes before leaving the sector ESMM 23 to send a REV message and 2.5 minutes before leaving the sector to send a RRV message. TIP message is sent for the outbound flights, the tool will activate upon CD&R, QoS message or after ATCO interference. Additionally, RRV message is triggered upon Transfer tool message.

	For inbound coordination, the tool is activated upon CD&R co-action.	For inbound coordination, the tool is activated upon CD&R co-action.
Time out of the tool's output	Time-out of the tool output is 30 seconds. Valid only when coordination message is sent alone (not as a part of CDR or QoS). Otherwise, it is limited by the time-out of the CDR or QoS tool.	Time-out of the tool output is 30. Valid only when coordination message is sent alone (not as a part of CDR or QoS). Otherwise, it is limited by the time-out of the CDR or QoS tool.
Protocol after the time-out	After the time-out, coordination should be initiated by ATCO via voice.	After the timeout of the tool output and if ATCO didn't interfere with it, **the system will send a coordination message.**
Protocol after the rejection of the tool's output	After the rejection of tool output, the system will not send another message.	After the rejection of tool output, the system will not send another message.

Table 6. Coordination tool -comparison of advisory and execution mode

5.6 Expected Benefits

The primary expected benefit of the Coordination tool is improved operational **efficiency**. By integrating coordination with the CR module and Quality of Service tool, flights are guided along routes that are predicted to be both conflict-free and operationally optimal, without introducing operational constraints or misunderstandings. This approach also reduces the **workload** for both executive and planner ATCOs.

In addition, the Coordination tool determines whether coordination is required by taking into account LoAs and other operational rules and practices, thereby enhancing **safety**. When co-acting with other ASA tools, the Coordination Tool minimises the potential for misunderstandings between units. Coordination messages are clear, concise, and explainable, while ensuring that the ATCO remains in the loop.

Finally, the tool improves the **resilience** of the ATM network. In safety-critical or emergency situations, ATCOs can rely on the Coordination tool to efficiently communicate requests and proposals to adjacent units, supporting timely and consistent coordination.

5.7 Limitations / Challenges

Several limitations and challenges have been identified in relation to the Coordination Tool and its current functionality:

- The Coordination Tool is activated only for coordination with external adjacent units. This is based on the assumption that coordination between internal units differs across service providers.

However, extending the tool to support internal unit coordination should be further discussed and assessed.

- The tool uses time-based triggers to initiate outbound coordination messages, which contributes to system resilience. However, in situations where coordination is triggered first by a time trigger and subsequently by ATCO intervention, the tool may appear overly intrusive, as ATCOs typically coordinate a given action only once. Further analysis is needed to identify ATCO intent more accurately and to ensure that coordination is initiated only when necessary.
- The Coordination Tool currently does not support negotiation with adjacent units; coordination messages can only be accepted or rejected. Support for negotiated coordination is identified as future work.
- The scope of the Coordination Tool is currently limited to the coordination message types described in this section. Additional coordination message types should be considered for future implementation.

Limitations related to the tool's modes of operation have also been identified:

- In execution mode, the tool's functionality is constrained by its dependency on ATCO intervention. If the ATCO rejects automatic coordination, additional actions are required, such as tactical route modifications or voice coordination.
- In advisory mode, similar principles apply; however, because ATCO approval is always required before task execution, the tool's effectiveness remains fully dependent on ATCO actions.

6. Quality of Service Tool

6.1 Purpose & Functionality

The Quality of Service (QoS) improvements Tool is designed to enhance flight operations by suggesting and implementing optimal routing and altitude changes. It aims to streamline ATM, improve fuel efficiency, and ensure smoother operations. The tool recommends or executes the more direct routes, reducing fuel consumption and travel time. It suggests continuous climbs or descents to the requested FL, minimising level-offs and improving efficiency.

Quality of service relies on surveillance data extracted from the KG and on a set of conditions that define whether a flight is a valid QoS candidate. QoS functionality considers pilot requests, requested FL from FPL and direct routes while considering following conditions:

- Check if the suggested action is in line with the LoA,
- Check if the suggested action creates a conflict with other traffic,
- Check if the suggested action creates a conflict with TRA.

Detailed conditions are presented in table 7.

QoS subject	Condition	Description
Pilot request	Check if the request complies with the LoA	If LoA is violated, request will trigger Coordination tool, or request won't be approved by the tool
	Check if the request create conflict	If a request creates a conflict, the request won't be approved by the tool.
	Check if the request is clear of any military area.	If a request crosses a military area, the request won't be approved by the tool.
Requested FL from FPL	Check if the request FL complies with the LoA	If LoA is violated, request will trigger Coordination tool, or request won't be approved by the tool
	Check if the request create conflict	If requested FL creates a conflict, the request won't be suggested by the tool.
	Check if the request is clear of any military area.	If a request crosses a military area, the request won't be suggested by the tool.

Direct routing	Checks if direct route creates conflict	If direct routing creates conflict, route change won't be suggested by the tool.
	Checks if direct route crosses military area	If direct routing crosses the military area, route change won't be suggested by the tool.

Table 7. QoS tool functionality

6.2 Technical Description

The QoS tool uses flight data, information about TRA activation, and CD module to evaluate and suggest clearances that enhance operational efficiency, reduce flight times, and maintain safety. The tool operates by processing flight trajectories in real-time, identifying opportunities for shortcuts and validating these against potential conflicts. The primary focus is on proactive suggestions that allow ATCOs to issue clearances improving service without compromising safety. Operational Requirements are:

- Keep the ATCO informed at all times by providing feedback on executed tasks.
- The tool's output must be explainable in all situations; the ATCO should be clearly informed when the QoS tool initiates an action, as well as when and why an expected action is not performed.
- The tool should suggest only safe clearances
- If the tool's output is rejected, the tool's functionality is limited, and the ATCO remains responsible for executing the quality of service manually.
- All flights are eligible to receive clearances generated by the QoS tool.

The process is divided into two main phases, with distinct handling for different clearance types:

1. Clearance opportunity evaluation
   Once a flight enters the processing window (flight is within the considered sector, flight is assumed) the evaluation begins. The tool integrates multiple data sources to determine eligibility for QoS improvements: Flight trajectory data is analysed to extract route points, headings, speeds, and altitudes; Airspace data (TRA) is used to identify airspace volumes that may constrain QoS routing, including activation status, vertical limits, and boundaries; Current flight state (position, speed, heading, flight level) is evaluated to assess proximity to restricted areas and generate predicted trajectories if possible. Based on this, the tool identifies "safe segments" which are possible direct routes from the current point to one of the further points of the route that avoid TRA. If no safe options exist, the flight is not considered a candidate, and no suggestion is generated.
2. Trajectory prediction and validation

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For possible candidates, the tool simulates optimised trajectories and checks for conflicts. Using current flight parameters and proposed route segment, the tool predicts future positions over a simulated time horizon (the time needed to cover the found segment distance at current speed). This includes interpolating points and adjusting for altitude changes. The predicted trajectory is cross-referenced with the predicted trajectories of other flights in the airspace using a CD module.

If the trajectory is conflict-free, a clearance suggestion is formulated, including details like the proposed route segment, validity period, and timestamp. Duplicate suggestions are avoided to prevent redundancy. The tool outputs QoS messages to the ATCO, which can be accepted or rejected. If conflicts are found, the tool suppresses suggestions, maintaining safety. In edge cases (e.g., incomplete data), the tool skips processing to avoid inaccurate outputs.

As the subject of QoS is either direct routing or change of FL to RFL, the tool approaches these scenarios differently.

When processing **RFL change**, the tool calculates where the aircraft will reach the RFL using a fixed climb/descent rate of 10 FL per minute. This point is validated against sector vertical limits. If the point is not in TRA, the tool then determines if the segment intersects with the TRAs. Afterwards, if no collisions with TRAs are found, the tool constructs a complete trajectory by combining the predicted climb/descent segment with the remaining portion of the initial trajectory and checks for conflicts.

Main Steps for FL calculation:

1. Extract the RFL (from pilot requests or FPL).
2. Calculate the predicted point based on the FL difference (e.g., using a time-based index from existing trajectories).
3. Check if the predicted point intersects any active TRAs within vertical limits.
4. If not, start a trajectory prediction module and generate a trajectory for the altitude change and check if it intersects any active TRAs.
5. If valid, run the CD module on the updated trajectory.
6. If no conflicts are detected, create a QoS suggestion for the flight level change.

For **direct routing**, the tool identifies safe segments by checking intersections with TRA (including buffers), generates predicted trajectories for the direct route, and validates against CD module to ensure the direct route doesn't create new conflicts.

Main steps for direct routing calculation:

1. Extract the waypoints from FPL.
2. Generate a trajectory prediction for the proposed route segment.
3. Check if it intersects any active TRAs.
4. If valid, run the CD module on the updated trajectory.
5. If no conflicts are detected, create a QoS suggestion for the direct routing.
6. If conflict is detected, use exit waypoint-1 and go back to step 2.

Datalog rules

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The QoS tool works by running Datalog rules over the knowledge-graph representation of the situation. As described briefly in previous chapter, QoS directs two Datalog rules:

- Rule 1: qosSatisfied
- Rule 2: aircraftPassesThroughMilitaryZone -

Rule 1 is set only if QoS suggestion is possible, which means that either FL or DCT found viable results. That implies the Rule 2 attribute will be set to 0. Otherwise, once QoS detects crossing with TRA, Rule 2 is set to 1 and Rule 1 attribute won't be created. These are set exclusively by the pipeline and operate independently; they do not trigger any knowledge generation.

Visualization

An example of Rule 1 is presented in figure 16. Rule 1 is set to 1 because the QoS tool determined there is no conflict and military sector intersection when changing FL to RFL. As this attribute is directly asserted by the pipeline rather than inferred through rules, its derivation can be traced through the QoS tool's processing steps.

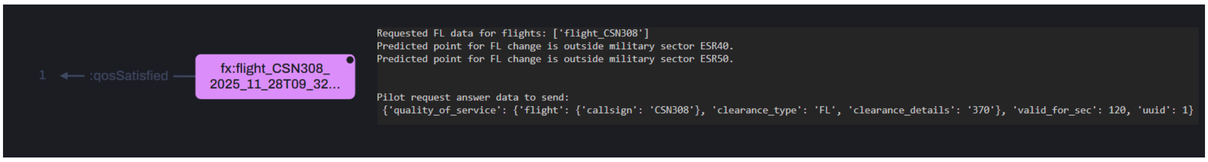

Figure 16. Datalog Rule for QoS tool

6.3 Operational description

Dataflow of the QoS tool is presented in Figure 17.

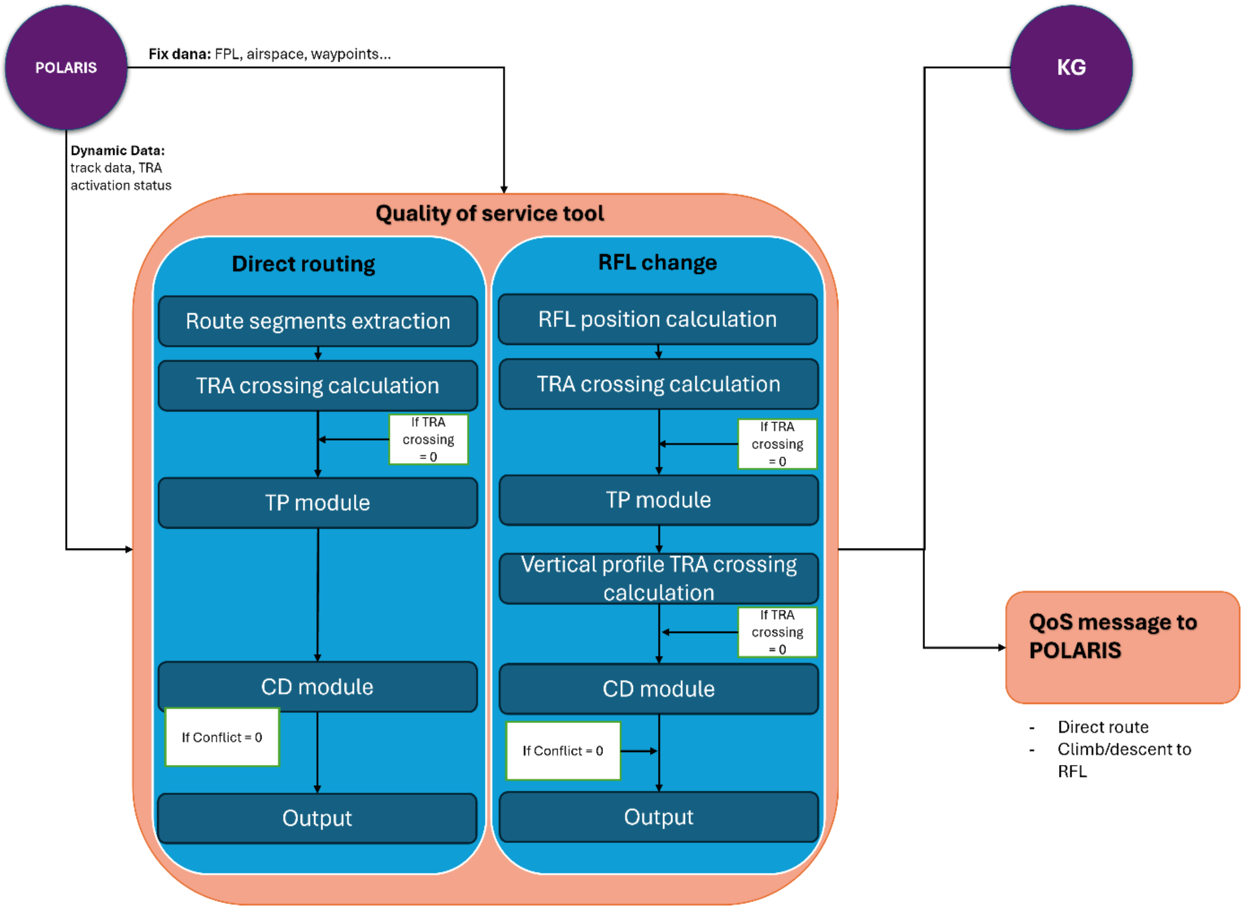

Figure 17. QoS dataflow

The process of data flow:

- The QoS tool fully relies on data received from POLARIS which are stored in KG. That data should have consistent JSON/XML structure and contain flight plan, track (current position) and trajectory information.
- QoS data flow starts once track records come from POLARIS. Based on current position, the tool calculates possible route optimisations or comparing current FL with the RFL.
- For the direct scenario case, each QoS segment (one segment is from current position to waypoint from the FPL excluding the point flight is currently flying towards) is validated against TRAs.
- If a route doesn't cross TRA or TRAs are not active, the trajectory prediction (TP) module implemented in the system is used to generate predicted trajectory of that segment.
- Lastly, the CD module checks if the generated trajectory creates a conflict.
- For the RFL scenario, the tool checks whether a point corresponding to the flight will end up at climbing/descending to RFL is in any TRA.

- If not, the TP module is used to generate a trajectory of mentioned climb/descent, which if not intersecting with any TRA, is then combined with initial trajectory excluding the part which would be flown if flight stayed on the same FL.
- Once those procedures are done, the CD module is triggered.
- For flights that are not in conflict, a QoS message is sent.
- The cancellation feature is part of the QoS. The system continuously monitors potential changes in traffic scenarios. If a conflict or TRA activation is detected, and a previously generated message has not yet been processed by the ATCO but is no longer valid due to the detected change, a cancellation message is sent to the POLARIS.

6.4 Requirements of data flow

The QoS tool integrates data from several sources to build a comprehensive view of the airspace situation:

- Flight Data: real-time information about active flights, including callsigns, positions (latitude, longitude), ground speeds, headings, FLs, aircraft types, and route trajectories (cleared, requested, and predicted). This data is essential for TP and CD module
- Airspace Data: Static and dynamic airspace information, such as military sector boundaries, activation statuses, vertical limits (lower/upper altitudes), and buffer zones. This includes AIXM-compliant data for sectors, waypoints, and navaids.
- Predicted Trajectories: These are used to simulate future positions and validate clearances. Sources: Internal trajectory prediction modules or external trajectory data feeds.
- Conflict Detection Data: Outputs from conflict detection algorithms, including aircraft pairs in conflict
- System Configuration Data: Execution mode (advisory vs. execution), validity periods for outputs, and tool-specific parameters (e.g., buffer sizes for TRA).

All data must be in standardized formats (e.g., JSON for events, XML for FIXM, Turtle for RDF) to enable seamless integration into the knowledge graph.

The QoS tool has several dependencies that must be satisfied before processing can begin:

- Pre-loaded Static Data: AIXM data (airports, sectors, waypoints) must be loaded at system startup. Without this, sector polygons and TRA crossing checks cannot function.
- Knowledge Graph Initialization: RDF triples for static airspace must be imported into the RDFox database before dynamic data processing starts.
- Trajectory Prediction Readiness: BADA aircraft performance models and geodesic services must be initialized. Missing aircraft types or incomplete position data can halt predictions.
- Conflict Detection Module: Requires sector polygons and buffer zones to be pre-computed. If sectors are not defined, conflict checks default to basic separation rules.
- Execution Mode: Must be set (advisory or execution) to determine suggestion validity periods. Changes during runtime require graph updates.

Processing only triggers flights within the considered sector and assumed flights with complete current point data. Incomplete records are skipped to prevent errors.

Output data from the QoS tool is clearance suggestion in the form of QoS messages, each containing:

- ASA tool identifier: “quality_of_service”.
- Callsign: the affected flight’s identifier.
- Clearance type: DCT or FL.
- Clearance details: Remaining points of the route if DCT, requested flight level if FL.
- Graph attributes are set as follows: when a QoS suggestion is possible, Rule 1 (qosSatisfied) is set to 1 and Rule 2 (aircraftPassesThroughMilitaryZone) to 0; otherwise, only Rule 2 is set to 1.

6.5 Operational Use

This Section describes how the QoS tool is presented to ATCOs and in which way they will interact with it. ASA system supports QoS tool in both advisory and execution mode. As previously mentioned, the tool checks for several conditions to assess if the flight is a QoS candidate.

The prerequisite of QoS tool activation is that flight is assumed and/or within sector ESMM 23. With this condition being checked, the rest of QoS conditions are being assessed. The tool handles route changes and RFL changes. RFL change can be proposed based on RFL from FPL or requested on frequency by pilot. Pilot requests are checked for conflicts with other traffic and with TRA.

The QoS tool holds the information about the QoS improvement and sends output to Polaris which presents information adequately. Depending on the mode of operation. The tool will either suggest QoS improvement or automatically execute clearance. In both cases, clearance to the pilot is communicated via CPDLC. In case when output from QoS needs to be Coordinated (considering RRV, REV and TIP messages), QoS activates Coordination tool and sends output to POLARIS where suggested clearance is accompanied by appropriate coordination message. For advisory mode ATCO is informed that the flight is a QoS candidate by visual cues. ATCO can remove the indication by clicking on ‘X’. In execution mode, ATCO is informed that the flight is about to be issued a clearance automatically by visual cues after the time out. The countdown timer visually represents the left time for ATCO intervention.

QoS tool functionality in advisory and execution mode

Detailed comparison of tool functionality in both operational modes is presented in Table 8. The considered sector is Sector 23 in Malmo ACC operated by LFV (ESMM23). Values in the table are grounded in SME opinions.

	Advisory mode	Execution mode
Action execution responsibility	The QoS tool in the advisory mode will send an output to the ATCO once flight meets all the conditions. ATCO will be responsible to execute that quality of service.	The QoS tool in the execution mode will send an output to the ATCO once flight meets all the conditions. The tool will inform the ATCO about the action it wants to execute and give ATCO enough time to validate that action and interfere if needed.

		ATCO can accept the tool's output or reject it. If there is no interference from ATCO, the tool will execute the QoS action.
Activation of the tool	The tool will activate once the flight enters the ESMM 23 area of responsibility and is assumed.	The tool will activate once the flight enters the ESMM 23 area of responsibility and is assumed.
Time out of the tool's output	The QoS tool doesn't have time-out unless for pilot requests. Pilot requests will time out after 2 minutes. Otherwise, output will be removed if flight is no longer following all the mentioned condition	Time-out is 1 minute or if flight is no longer following all the mentioned conditions.
Protocol after the time-out	For Pilot requests, the system won't send another message after the time out. For other QoS functionalities, there is no time-out.	After the timeout of the tool output and if ATCO didn't interfere with it, **the system will execute QoS action**.
Protocol after the rejection of the tool's output	After the rejection of tool output, the system won't send another output until the message from the tool is different from the previous message. For example, the pilot made another request, or direct routing is now considering different points of the route.	After the rejection of tool output, the system won't send another output until the message from the tool is different from the previous message or the pilot made another request.

Table 8. QoS tool - comparison of advisory and execution mode

6.6 Expected Benefits

The QoS tool provides several operational benefits. Its main contribution is the improvement of **efficiency** and **environmental** impact. By supporting more direct routings and enabling aircraft to operate at FLs that are optimal for operators, the tool improves quality of service while reducing fuel consumption.

During the activation of TRAs, ATCO **workload** increases due to the need to vector aircraft and subsequently return them to their requested FPL routes once the restricted area is deactivated. The QoS tool detects these situations and proposes suitable route modifications that ensure military airspace avoidance and conflict-free trajectories.

The tool also contributes to **safety** by assessing pilot requests and proposed route segments to identify potential safety risks before a clearance is issued. This is particularly relevant during high-traffic or high-workload periods, when such checks may be more difficult to perform consistently.

In addition, the QoS tool improves the **resilience** of the ATM system by supporting ATCOs with timely suggestions or by handling routine tasks in the background, allowing ATCOs to maintain situational awareness while managing challenging traffic demands.

6.7 Limitations / Challenges

Identified limitations/challenges regarding the tool and its developed functionalities:

- The QoS tool is currently limited to the functionalities described in this Section (direct routing and RFL changes). Its scope could be extended to include additional capabilities, such as Top of Descent calculation and notification to ATCOs when a vectored flight can be safely re-cleared onto its planned route.
- QoS identifies candidate route segments and validates them using the CD module and TRA crossing checks. However, if an aircraft is already flying on a route segment that crosses an active TRA, the tool does not currently alert ATCO that a route modification is required.
- The tool operates in cooperation with the coordination tool. When a proposed solution requires prior coordination, QoS automatically triggers the coordination process. As a result, the coordination tool may be activated more frequently than in current ATCO operational practice, potentially increasing workload. This design choice reflects the complexity of the coordination process
- QoS relies on the TP module, which uses standard aircraft performance models. If these models do not accurately reflect the actual performance of aircraft, the outputs of the TP and CD modules may fail to detect certain conflicts. Future developments should incorporate the aircraft's current vertical profile as input to these modules.
- QoS is activated only once an aircraft is assumed to be within the considered sector. This approach reduces the number of coordination events; however, as this rule is rigid, further assessment is required to determine whether different activation criteria should apply to specific flight characteristics.
- Pilot requests cannot be negotiated by the tool; it can only recommend acceptance or rejection of a request.

7. Integration of ATCO tools into ATM System

The development process began with a series of online workshops, conducted with AWARE partners, including air traffic controllers, domain experts, and system designers. The workshops focused on aligning the functionalities of the supporting tools with operational needs, while also identifying opportunities to improve controller workload and support decision-making. A key outcome of this process was the definition of the functional requirements for the AWARE supporting tools, providing a solid foundation for subsequent design activities.

7.1 HMI Design

The AWARE Human-Machine Interface (HMI) is built on top of the Polaris Air Situation Display (ASD). Customised to support AWARE specific requirements, the Polaris ASD, incorporates dedicated UI elements designed for enhanced situational awareness and interaction.

An initial prototype of the interface was developed in Figma, providing a visual and interactive foundation for partner evaluation. Following this, a hybrid HMI Design Workshop was organized with all project partners, where the proposed concepts were jointly reviewed, assessed, and refined. The workshop outcomes informed the evolution of the HMI design, ensuring alignment with user needs and operational expectations.

The design aims to provide a clear and intuitive user experience by making AI suggestions visually distinct. All suggestions follow the same design language: location (track label), glow effect and interaction pattern.

The primary interaction interface between the ATCO and flight information on the ASD is the track label. It offers immediate access to the primary flight information and allows the controller to note clearances and to influence the state of the flight record. AI suggestions are presented as interactive action buttons. Action buttons are placed directly to the left of their relative track label. This placement ensures that suggestions are always connected to core information, and easily noticeable.

A key visual element is the "AI Glow", a soft outline indicating AI involvement. Upon receiving a suggestion from the AI, the glow is applied to the track label and interactive buttons. By attaching suggestions to the track label and using subtle highlights, the interface avoids overwhelming the user.

The design of the interactive action button, representing AI suggested actions, differs slightly depending on the operational mode. In both advisory and execution mode the action button includes the suggestion and a "X" button to dismiss the suggested action. In execution mode, the action button additionally includes a countdown bar visualising time left before the action will automatically be performed, the controller can choose to accept or dismiss the suggested action before the time runs out. In advisory mode, the suggested action expires after a short timeout, default 30 seconds. If the action has not been accepted before it expires, it is dismissed.

Multiple states of the track label are defined and presented in Figma: normal (default), hover and selected states, and the corresponding states with the AI Glow in advisory and execution mode. These states are supported by a clearly defined colour system that ensures visual consistency across all tools.

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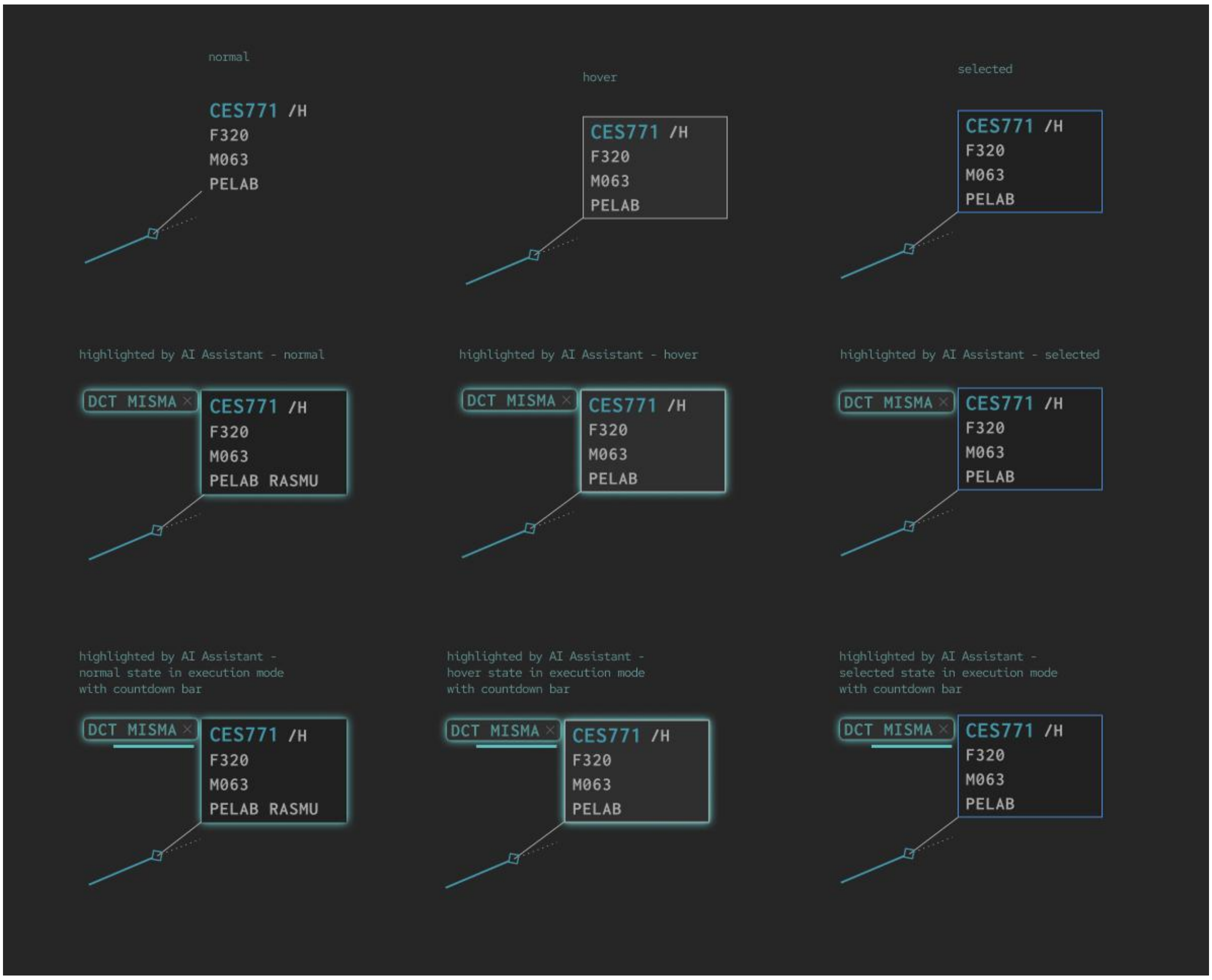
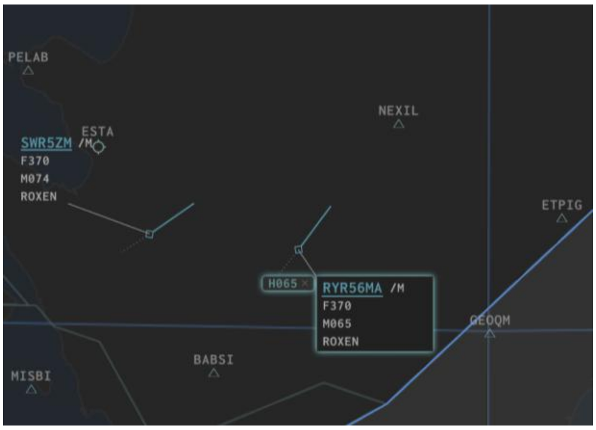


Figure 18. Different states of the track label, and the position of the AI Suggestion button in Figma

7.1.1 CD&R Tool Design

When the CD&R Tool detects a conflict, the suggested resolutions appear next to the associated track label as action buttons. The system presents the detected conflict by displaying separation between the flights involved. For actions that include a route change, the suggested route change is visible next to the current route on hovering the action button or when the track label is selected. The ATCO can interact with the suggestions directly by either accepting or rejecting them. Accepting a suggestion will prompt the AI Assistant to execute the resolution by sending a CPDLC message.



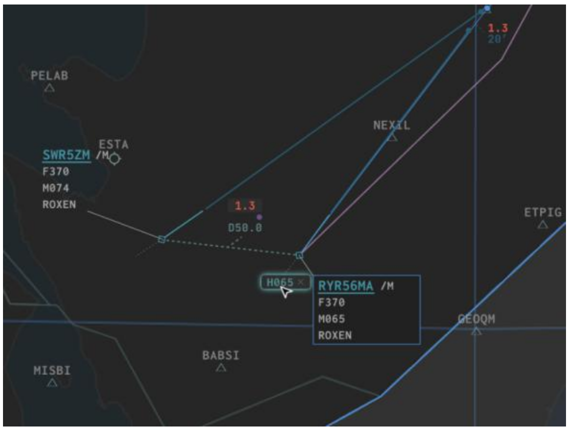
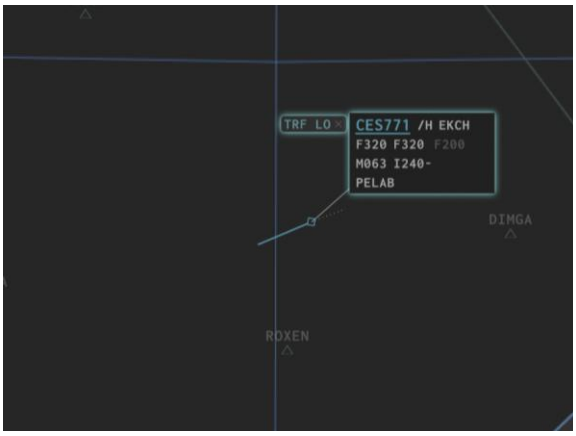


Figure 19a. The AI Assistant highlights the track label to draw attention to it

Figure 19b. Polaris ATM presents the conflict and the resolution options

7.1.2 Transfer Tool Design

In the case presented in the Figma prototype, when a flight is ready for transfer, the Transfer Tool sends a transfer suggestion to Polaris ATM. As with suggestions from the other tools, the transfer suggestion is presented as the previously detailed action button, outlined with the AI Glow left of the track label. Upon review, the ATCO can accept or dismiss the suggestion, triggering Polaris ATM to initiate the sector transfer process if accepted.



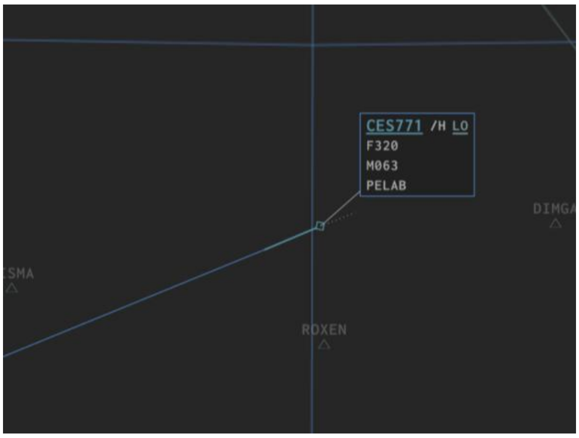


Figure 20a. The AI Assistant highlights the track label and AI Suggestion button to draw attention to it

Figure 20b. Track label selection opens the flight visualization

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7.1.3 Coordination Tool Design

In the Figma prototype, the tool detects inconsistencies between predicted and required exit levels based on the LoA. If an aircraft cannot meet its exit condition due to performance limitations, the AI Assistant sends an RRV message with a revised flight level. Selecting the flight reveals a visual route display. As in previous cases, the AI suggestion is presented in the form of an action button next to the track label.

The ATCO is notified via a free-text explanation in the track label to communicate reasoning behind the action, maintaining transparency and aiding controller trust.

Figure 21a. Highlighted track label with AI suggestion and execution mode countdown

Figure 21b. Reasoning in the track label

7.1.4 QoS Tool Design

In the examined QoS Tool flow, when the AI Assistant identifies an opportunity for route optimization, such as being able to fly through a previously restricted area, the associated track label is highlighted using the AI Glow and the suggested optimization given in the form of the action button. Selecting the track label or hovering the action button, reveals visualized flight paths for both the original and suggested route.

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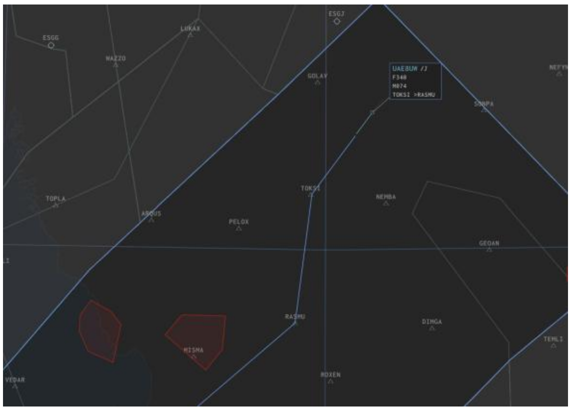

Figure 22a. Selected track label and route with restricted airspace

Figure 22b. Selected track label with AI suggestion and optimized route

7.2 System/ASA interface

The ATCO support tools represent the primary means through which the ASA system interacts with the Air Situation Display (ASD). While the ASA system functions as the “brain” of the architecture, responsible for analyzing the airspace situation assessing the controller’s intent, the support tools serve as the interface layer that makes this intelligence available to the user.

The ASA system makes decisions based on the controller’s intent and the current airspace situation. These decisions are transmitted via the interface to the Polaris platform, where they are either displayed to the user on the ASD as decision-support suggestions or displayed and then executed directly by the system after a short timeout. This setup ensures that controllers are continuously supported with context-aware, timely information and suggestions/actions relevant to the task that the controller is currently performing.

7.2.1 Proxy

The Air Traffic Management (ATM) system employed in this project was not originally designed to receive external inputs or to provide outputs describing its internal processes to external systems. However, it was built on a service-oriented architecture, and as such works by passing messages over a network between various services. This design allows us to incorporate the ASA into the ATM system with minimal changes to the ATM system.

Communication between the ATM and ASA systems goes through an ad-hoc proxy written for this project. The proxy runs alongside the ASD of the ATM system and listens to the same data streams as it does for information about tracks, flight plans, environmental data and so on. It also receives data about user actions in the ASD. It then writes messages that describe this data to a NATS server, which is a message streaming system. There are several consumers of this message stream, including the ASA system and an event recording program that saves the messages for later analysis.

The ASA system writes its suggestions to the same NATS server. A different program forwards those messages to the ASD, where they are displayed to the ATCO and, if accepted, forwarded to the relevant backend services for processing. When a suggestion is accepted or rejected, notice of this is written to the data stream, ensuring that the ASA is kept in the loop of the global system state.

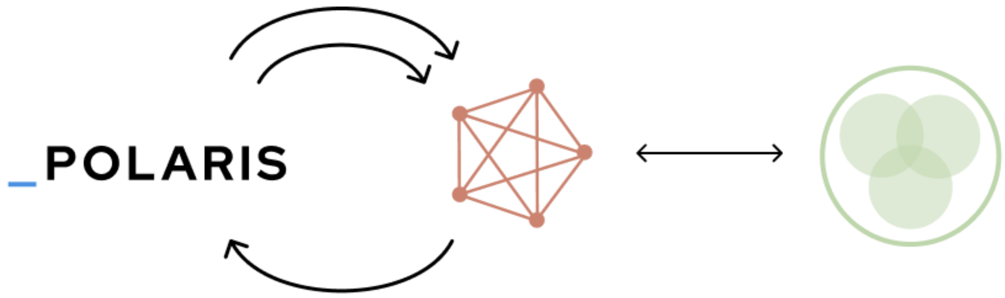

Figure 23. Polaris ATM System - Proxy - AAA

8. Conclusions

The ATCO support tools described in this report are a core component of the AWARE ASA system and demonstrate a technical robust approach to enhancing en-route ATM through an adaptive, knowledge-driven system. Their design reflects a consistent application of the AWARE ConOps principles, ensuring that all functionalities remain explainable and aligned with human-centred operational requirements.

The CD&R tool provides the safety-critical functionality by combining CPA-based conflict detection with a structured, rule-driven resolution engine. Its modular architecture: conflict detection, resolution manoeuvre generation, trajectory modification, and prioritisation; ensures that proposed resolutions are operationally feasible and transparent to the ATCO. The use of activation horizons, manoeuvre validity buffers, and multi-trajectory evaluation enhances robustness under varying traffic conditions.

The Transfer Tool supports frequency handover by continuously monitoring flights, sector boundaries, and transfer conditions. Its logic ensures that transfer tools output is generated at appropriate time, thereby reducing ATCO workload and promoting consistent application of standard operating procedures.

The Coordination Tool automates the identification of situations requiring voice coordination and proposes suitable coordination actions. Its framework assesses trajectory and common rules and practices, enabling timely and standardised coordination. This reduces communication load while ensuring that coordination activities are performed reliably and without introducing opportunities for error.

The QoS Tool monitors compliance with operational constraints and identifies opportunities for route optimisation. It evaluates whether proposed route changes would introduce conflicts and whether they fit into operational rules and practices.

Together, these tools form an integrated assistance layer that enhances situational awareness, supports consistent decision-making, and reduces controller workload in complex or high-demand scenarios. By accounting for traffic complexity and ATCO intent, the tools adapt its behaviour to avoid both premature and delayed action. Their technical design ensures compatibility with the ASA architecture, while their rule-based, explainable reasoning mechanisms promote transparency and trust. Ongoing validation activities will further assess their performance, human-machine interaction characteristics, and contribution to key performance outcomes.

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9. References

[1] AWARE consortium, Concept of Operations for AWARE, 2024.

[2] AWARE consortium, Functional Requirements Document, 2025.

[3] AWARE consortium, AWARE Exploratory Research Plan – Intermediate,2025.

[4] AWARE consortium, AWARE Validation Scenarios, 2025.

[5] EUROCONTROL, Specification of On-Line Data Interchange (OLDI), 2023.

10. List of acronyms

Acronym	Description
AAA	AI Assistant Application
ACT	Activate message
ADEP	Aerodrome of Departure
ADS-B	Automatic Dependent Surveillance–Broadcast
AI	Artificial Intelligence
AIXM	Aeronautical Information Exchange Model
ANSP	Air Navigation Service Provider
AoI	Area of Interest
AoR	Area of Responsibility
ASA	Artificial Situational Awareness
ASD	Air Situation Display
ATCO	Air Traffic Controller
BADA	Base of Aircraft Data
CD&R	Conflict Detection and Resolution
CFL	Cruise Flight Level
COP	Coordination Point
CPA	Closest Point of Approach
CPDLC	Controller–Pilot Data Link Communications
CR	Conflict Resolution
DCT	Direct-to
FIXM	Flight Information Exchange Model
FL	Flight Level
FPL	Flight Plan
GS	Ground Speed
HDG	Heading
HMI	Human–Machine Interface
KG	Knowledge Graph
LAT	Look-Ahead Time
LoA	Letter of Agreement

QoS	Quality of Service
RAT	Resolution Activation Time
RDF	Resource Description Framework
REV	Revision
RFL	Requested Flight Level
RRQ	Request Release
RRV	Referred Revision Proposal
RTI	Request Tactical Instruction
SI	Situation of Interest
SME	Subject Matter Expert
TIP	Tactical Instruction Proposal
TP	Trajectory Prediction
TRA	Temporary Reserved Area
XFL	Exit Flight Level

Table 9: List of acronyms

Appendix A Conflict Detection and Resolution tool

This annex provides a technical description of the CDR tool.

Conflict detection functions

This section provides details about the performance of the CD tool, functions developed, data flow and some examples. Several functions have been developed to enhance CD performance. Generic names have been included for the outputs of the different functions to establish sequential order.

Format_modification(cd_polaris_data)

This function modifies the format of the info from POLARIS to be usable for the CD functions.

- Inputs: database from POLARIS with selected info for CD.
- Outputs: same database but formats for prediction variables modified (df_format)

The function follows the following process:

1. It adapts the variables pred_lons, pred_lats and pred_fl to be a list of iterable elements in vectors and ensuring their type is float.
2. It adapts the variable pred_times to a datetime format.

pred_lats	pred_lons	pred_fl	pred_times
[46.73361897468567, 46.7353439718909, 46.73706...	[16.81261718273163, 16.814300442266273, 16.815...	[360.00000054720005, 360.11240442421, 360.2252...	[2023-09-19 12:08:05, 2023-09-19 12:08:06, 202...
[47.71437406539917, 47.714345243157126, 47.714...	[17.29796290397644, 17.30104045581371, 17.3041...	[390.00000059280006, 389.5687408790858, 389.13...	[2023-09-19 12:08:05, 2023-09-19 12:08:06, 202...
[47.66019880771637, 47.65932746445635, 47.6584...	[20.58117985725403, 20.58395449039175, 20.5867...	[390.00000059280006, 389.6532720725674, 389.30...	[2023-09-19 12:08:05, 2023-09-19 12:08:06, 202...

Figure A1. Results of function Format_modification()

Figure A1 shows the results of the format modifications using this function.

Separation_with_time_matching(df_format)

This function calculates separation variables for the first aircraft on the list (the aircraft that is supposed to have updated its 4D trajectory prediction) and the rest of aircraft within the sector at that time. It calculates separations based on the geographical coordinates of the 4D trajectory predictions and altitude. The longitudinal separation has been calculated using the haversine formula, and altitude separation as the difference. The main feature of this function is that it calculates separation only when trajectory times match.

- Inputs: database from the function Format_modification() denoted as df_format
- Outputs: database (df_1) which includes new variables:
    - Separation: this variable is a list of vectors constituted by the longitudinal, vertical and timestamp calculations for each 4DT prediction.

The function follows this process:

1. It finds indices where time match between 4DT predictions.
2. For each index, it calculates horizontal and vertical separation and stores them in a list of vectors with matching time.

vertical_separation	horizontal_separation	separation
[(0.0, 2023-09-19 12:08:05), (0.0, 2023-09-19 ...	[(0.0, 2023-09-19 12:08:05), (0.0, 2023-09-19 ...	[(0.0, 0.0, 2023-09-19 12:08:05), (0.0, 0.0, 2...
[(-30.000000045600018, 2023-09-19 12:08:05), (...	[(62.12133679450773, 2023-09-19 12:08:05), (62...	[(62.12133679450773, -30.000000045600018, 2023...
[(-30.000000045600018, 2023-09-19 12:08:05), (...	[(163.47845869193634, 2023-09-19 12:08:05), (1...	[(163.47845869193634, -30.000000045600018, 202...

Figure A2. Results of function Separation_with_time_matching()

Figure A2 shows the results of this function where is calculated the vertical and horizontal separation as a lists depending on time.

Process_conflicts_and_SI(df_1)

This function identifies SIs and conflicts for each aircraft pair. It determines if any of the separation values calculated in the previous function meet the conditions for SI or conflict at the same timestamp. SI and conflict columns are added as binary variables in the dataframe (1 – conflict/SI or 0 – No conflict/No SI).

- Inputs: database from the function Process_conflicts_and_separations() denoted as df_1

- Outputs: database (df_2) which includes new variables:
  - SI: Binary variable (1/0) in the case an SI is predicted or not
  - Conflict: Binary variable (1/0) in the case a conflict is predicted or not.

The function follows this process:

1. It iterates for each row (timestamp) of the variable separation to check if SI or conflict conditions are fulfilled.
2. It adds a new SI and conflict variable depending on 4DT predictions.

$$SI = 1 \; if \; Sep_{lon} < 10 \; NM \; and \; Sep_{ver} < 1000 \; ft$$

$$Conflict = 1 \; if \; Sep_{lon} < \; 5 \; NM \; and \; Sep_{ver} < 1000 \; ft$$

$$otherwise \; SI, Conflict = 0$$

	Aircraft Pair	Conflict	SI
0	(WZZ274D, WZZ274D)	1	1
1	(WZZ274D, SWR2290)	0	0
2	(WZZ274D, BAW143)	0	0

Figure A3. Results of function Process_conflicts_and_SI()

Figure A3 shows the results obtained with this function. It shows that there is a conflict and SI for the first aircraft pair because it is compared one aircraft with its own.

process_separations_MinSep_and_tcpa(df_2)

This function calculates different variables related to separation to mathematically ensure the calculation of minimum separation. Separation conditioned and combined separation are adaptations of the separation between an aircraft pair that are required to correctly identify the CPA. This function only works with the variable separation, and the goal is to find the minimum separation between the aircraft pair. As the separation variable is a list of vectors constituted by $(Sep_{lon}, Sep_{vert}, t)$, only the MinDis is identified as a combination of both separations and the time at which this occurs, which represents the tcpa (in datetime format).

- Inputs: database from the function Process_conflicts_and_SI() denoted as df_2
- Outputs: database (df_3) which includes new variables:
  - Conditioned_separation: vector which contains values from separation variables that matches SI condition and vector which contains the separation variables when SI condition is not matched.
  - Combined_separation: combination of separation values (longitudinal and vertical) where vertical separation is adapted to the longitudinal range.
  - Tcpa: time at which is predicted to occur the CPA in datetime format.

- Min_sep: vector which contains the info about the longitudinal, vertical, and euclidan separation at tcpa.

The function follows this process:

1. Aircraft pairs are identified as SI or not:
2. Aircraft pairs identified as SI: first) it is identified the timestamps where both aircraft are in SI. This information is stored in a new variable denoted as conditioned_separation.
   a. A new variable, denoted as combined_separation, is calculated. It combines vertical and horizontal separation, with vertical separation adapted to the range of horizontal separation. The goal is to use a common scale to calculate the minimum separation between trajectories, as horizontal and vertical separations use different ranges.

   For instance, an aircraft pair crossing with a separation at the Closest Point of Approach (CPA) of 0 ft vertically and 2.5 NM horizontally has a Euclidean distance of 2.5 NM at the minimum value. However, an aircraft pair crossing at 0 NM horizontally and 500 ft vertically has a Euclidean distance of 0.08 NM. Without combining the separation ranges, the minimum values are dominated by vertical rather than horizontal separations[2]. The value of the combined separation equals the value at 2.5 NM.

$$Sep_{comb} = Sep_{lon} + Sep_{vert}\left(\frac{S_{min}}{H_{min}}\right)$$

   b. Then, it is identified the CPA based on the minimum value of this variable:

$$CPA(t) \rightarrow (Sep_{comb}(t))$$

3. Aircraft pairs not identified as SI: conditioned_separation is feed with the separation variable. MinSep and tcpa is calculated based on the minimum value obtained based on the Euclidean distance between both aircraft.

Figure A4 shows the results obtained with this function. Variable min_sep is a vector constituted by longitudinal, vertical, time and Euclidean value of the predicted minimum separation.

[2] The application of the Euclidean distance constitutes a sphere of radius Sephor2+Sepvert2 while the current shape of the combination of both separation minima is a cylinder.

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conditioned_separation	combined_separation	min_combined_sep	tcpa	min_sep
[(0.0, 0.0, 2023-09-19 12:08:05), (0.0, 0.0, 2...	[0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, ...	0.000000	2023-09-19 12:08:05	(0.0, 0.0, 2023-09-19 12:08:05, 0.0)
[(62.12133679450773, -30.000000045600018, 2023...	[62.271336794735724, 62.18687500828568, 62.102...	44.898023	2023-09-19 12:14:09	(44.898023351338146, 0.0, 2023-09-19 12:14:09,...
[(163.47845869193634, -30.000000045600018, 202...	[163.62845869216434, 163.6139228517815, 163.59...	163.028219	2023-09-19 12:09:26	(163.01852642713396, -1.9385877685635933, 2023...

Figure A4. Results of function process_separations_MinSep_and_tcpa()

process_cpa_and_times(df_3)

This function calculates the position of the CPA of both aircraft, an intermediate value of the CPA based on geographical distance, and the time to the CPA from the current timestamp.

- Inputs: database from the function process_separations_MinSep_and_tcpa() denoted as df_3
- Outputs: database (df_4) which includes new variables:
  - Position_cpa_1st_aircraft, Position_cpa_2nd_aircraft, position_cpa_intermediate: vector which contains the latitude, longitude and vertical position of the CPA for the first and second aircraft and an intermediate value from them.
  - Tcpa_hms: value of the tcpa in format h:m:s
  - Time_to_cpa_hms: value of the time (format h:m:s) to the CPA from the current timestamp.
  - Index_cpa_1st_aircraft and Index_cpa_2nd_aircraft: position index of the separation variable when it occurs the CPA.

The function follows this process:

1. It obtains the position index of the separation variable when it occurs the CPA for each aircraft pair.
2. It obtains the predicted location of both aircraft at the CPA based on the previous index and store them in variables position_cpa_1st/2nd_aircraft.
3. position_cpa_intermediate is calculated based on geographical intermediate position of both CPAs, and the altitude is the difference between both altitudes.

4. It calculates the time to CPA of both aircraft as the time difference between the timestamp when the CPA will occur (indicated by the position index) and the original time.

Figure A5 shows the results of the variables obtained.

position_cpa_1st_aircraft	position_cpa_2nd_aircraft	position_cpa_intermediate	tcpa_hms	time_to_cpa_hms	index_cpa_1st_aircraft	index_cpa_2nd_aircraft
(46.73361897468567, 16.81261718273163, 360.000...	(46.73361897468567, 16.81261718273163, 360.000...	(46.73361897468567, 16.81261718273163, 360.000...	12:08:05	00:00:00	0	0
(47.35827816568358, 17.430942670933845, 370.0,...	(47.6984616020981, 18.417201196775487, 370.0, ...	(47.5294268118721, 17.92247269773481, 370.0, 2...	12:14:09	00:06:04	364	364
(46.872935342758126, 16.948988878015786, 368.0...	(47.58917644550262, 20.80634205276226, 370.0, ...	(47.2472393193084, 18.864628028796854, 369.030...	12:09:26	00:01:21	81	81

Figure A5. Results of function process_cpa_and_times()

calculate_distance_to_cpa(df_4)

The final function calculates the distance from the original position to the CPA for both aircraft. This calculation is based on geographical separation principles.

- Inputs: database from the function process_cpa_and_times () denoted as df_4
- Outputs: database (df_3) which includes new variables:
    - Distance_to_cpa_1st_aircraft and Distance_to_cpa_2nd_aircraft: separation between the original position and the CPA.

The function follows this process:

1. It is identified the predicted position of the CPA based on the index_cpa_1st/2nd_aircraft.
2. The separation between the original position and the CPA position is calculated for each aircraft based on the flight plan and not the difference between the waypoint and the current position. This calculation considers the cumulative distance based on the 4D trajectory prediction using the calculate_cumulative_distances() function. This subfunction calculates the separation between consecutive points from the 4D trajectory prediction.

distance_to_cpa_1st_aircraft	distance_to_cpa_2nd_aircraft
0.000000	0.000000
45.273384	45.364053
10.076014	10.084140

Figure A6. Results of function calculate_distance_to_cpa()

Figure A7 shows the graphical representation of the 4DT predictions of an aircraft pair and the main information of the CPA for both aircraft.

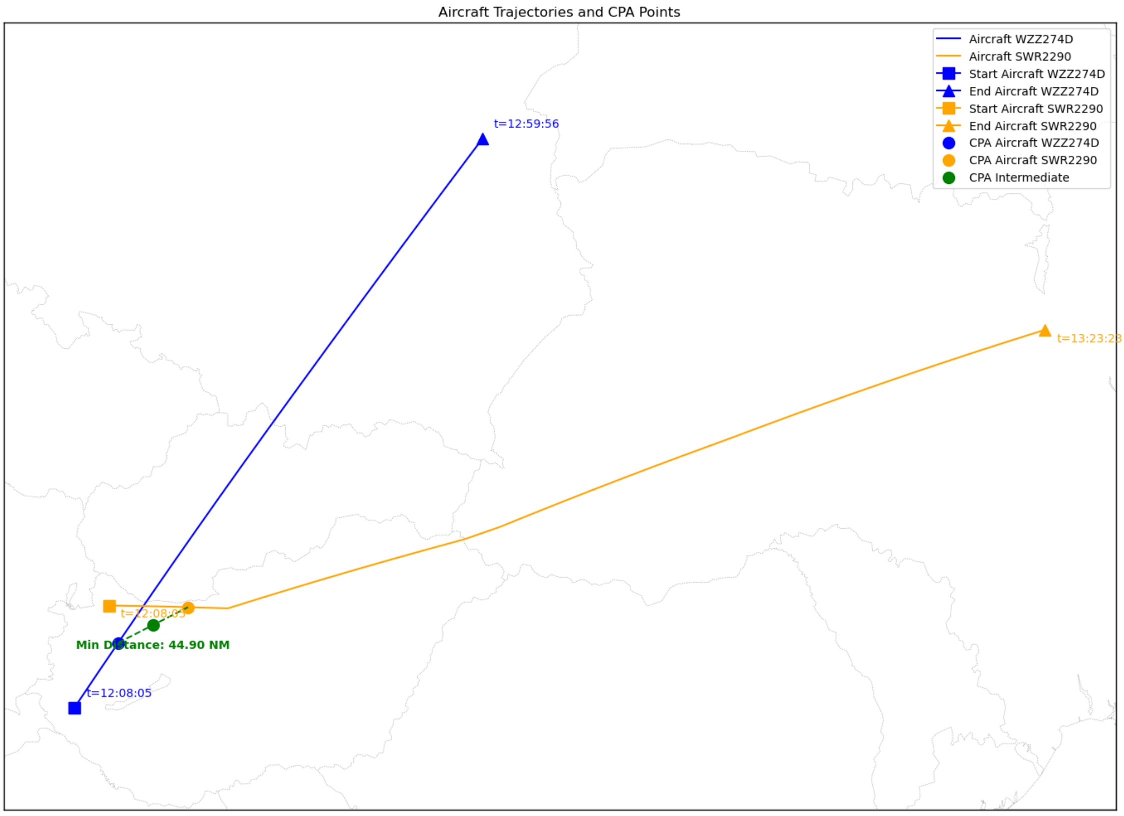


Figure A7. Graphical representation of CD outputs.

CR functions

Several functions have been developed to enhance CR performance. Generic names have been included for the outputs of the different functions to establish sequential order.

Family A: FL adaptation based on operational requirements

The purpose of this family of solutions is to provide manoeuvres that aim to adapt the altitude to the aircraft's operational conditions, based on the sector's exit conditions, the cruise level approved in the flight plan, or to block the aircraft's evolution until the CPA while maintaining the flight level.

Function A1. Match FL with XFL or Cruise FL.

This function identifies if Ac_i is flying at the same FL than XFL or CFL. In the case FL is lower than XFL or CFL then the function calculates new trajectories considering the climbing phase up to XFL or CFL.

- Inputs:
    - CD database.
    - XFL or CFL
- Outputs:
    - CR_A1 database with new predicted trajectories and CR metrics of the solution

The function follows the following process:

1. It checks if current FL is lower than XFL or CFL. If yes it continues, otherwise stops.
2. It calculates new predicted trajectories considering a climb from current FL up to XFL or CFL. Two new trajectories are generated with buffer of 15 seconds (1500 ft/min) and 30 seconds (1000 ft/min) as worst case.
3. CD evaluates new predicted trajectories with the rest of non-modified trajectories to check if the new trajectory is conflict-free. CD Results of both new trajectories are stored in CR_A1 database.

Figure A8 shows a graphical description of the original and new predictions.

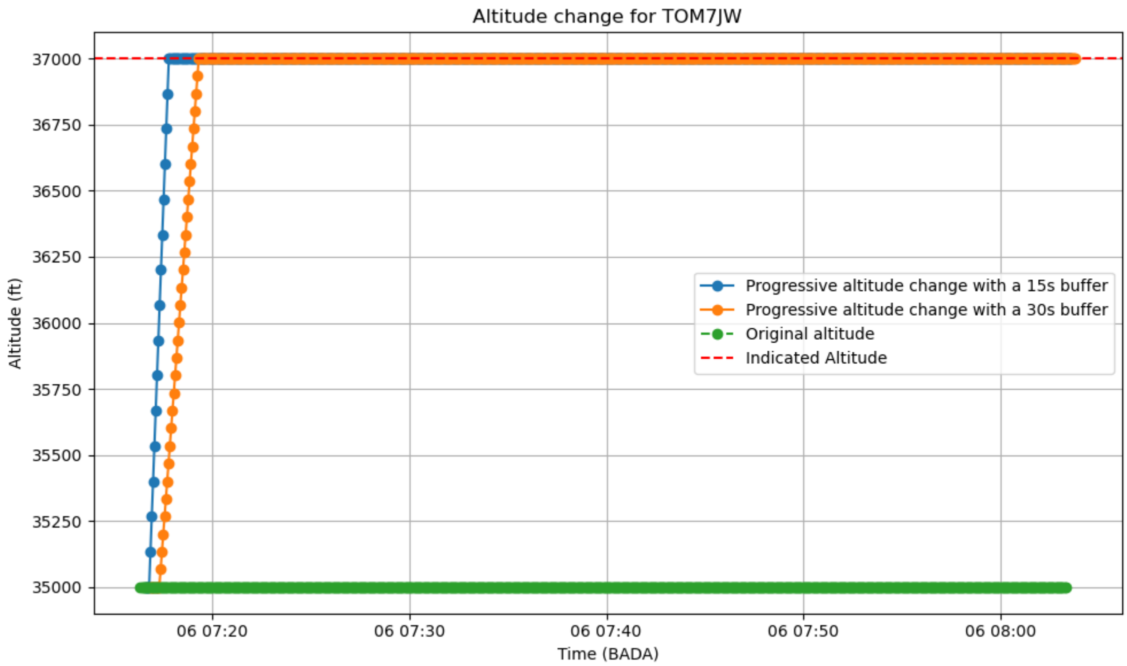


Figure A8. Results of match FL to CFL including buffers

Function A2. Block ascend or descend until CPA.

This function identifies if Ac_i is closer than 3 minutes to the CPA and is climbing/descending. If both conditions are matched, then the solution is to block the climb/descend until the CPA maintaining current FL

- Inputs:
  - CD database.
- Outputs:
  - CR_A2 database with new predicted trajectories and CR metrics of the solution

The function follows the following process:

1. It checks the following conditions:
   a. $TimetoCPA < 3\,min$
   b. $status_{CPA} \neq cruise$ either both aircraft (it can be one or both)
2. It calculates new predicted trajectories considering a descend or climb 30 seconds after the CPA. We have considered this buffer as the same limiting time the aircraft will begin the descend/climb (similar concept as validity solution). The new trajectory maintains current FL and then is integrated to original climbing/descending trajectory.
3. CD evaluates new predicted trajectories with the rest of non-modified trajectories to check if the new trajectory is conflict-free. CD Results of both new trajectories are stored in CR_A2 database.

Figure A9 shows a graphical description of the original and new predictions.

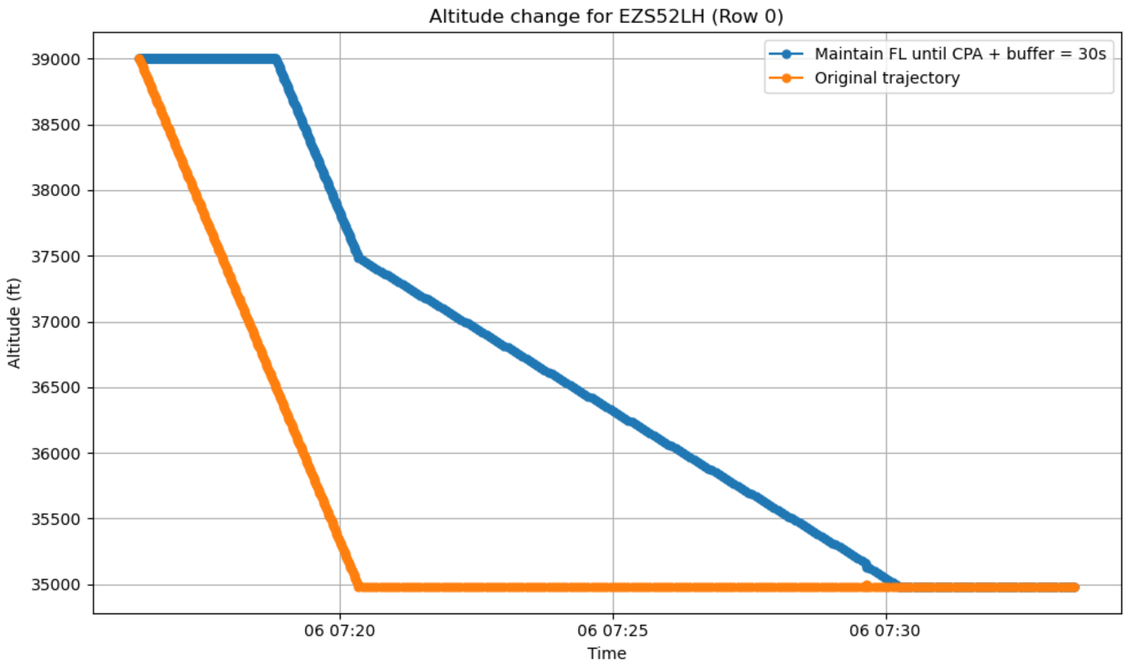


Figure A9. Results of block descend until CPA manoeuvre

Family B: Direct to WPXXX

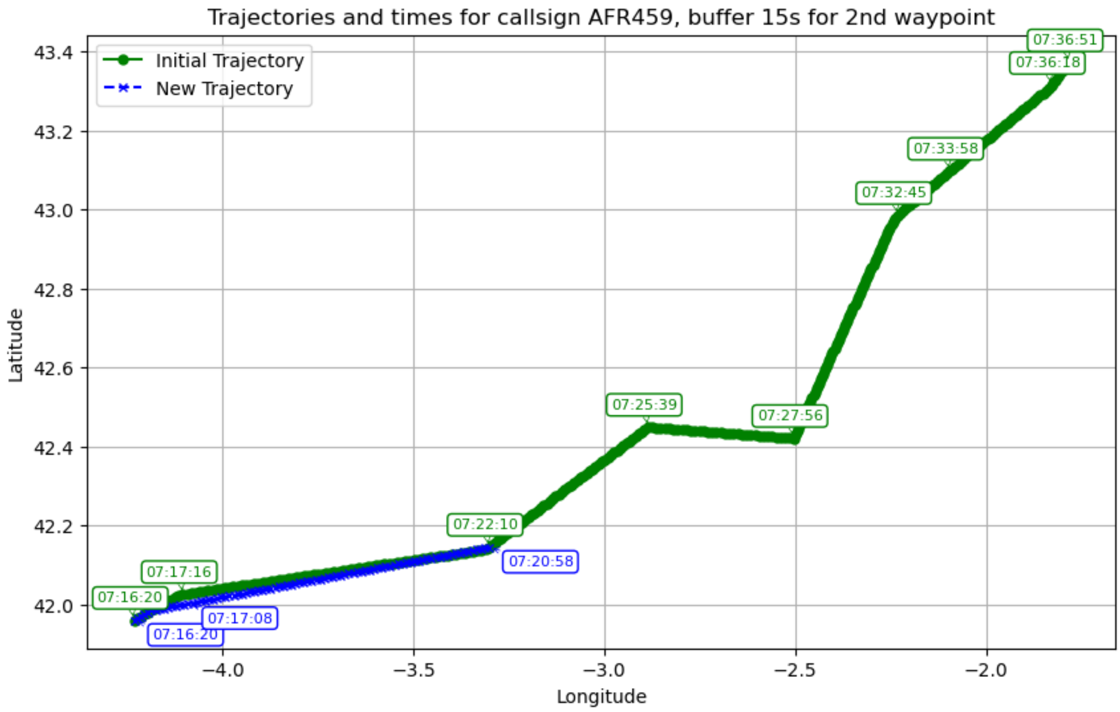
This function generates new trajectories maintaining current speed (no wind is considered) to WPXXX. This function is developed only for second and third waypoint considering that far away waypoints can be out of collateral sectors.

- Inputs:
  - CD database.
  - WPs from Flight Plan
- Outputs:
  - CR_B database with new predicted trajectories and CR metrics of the solution

The function follows the following process:

1. It calculates new predicted trajectories direct to WPXXX. The trajectory is generated maintaining constant the groundspeed.
2. CD evaluates new predicted trajectories with the rest of non-modified trajectories to check if the new trajectory is conflict-free. CD Results of both new trajectories are stored in CR_A2 database.

Figure A10 shows a graphical example of the application of this function.



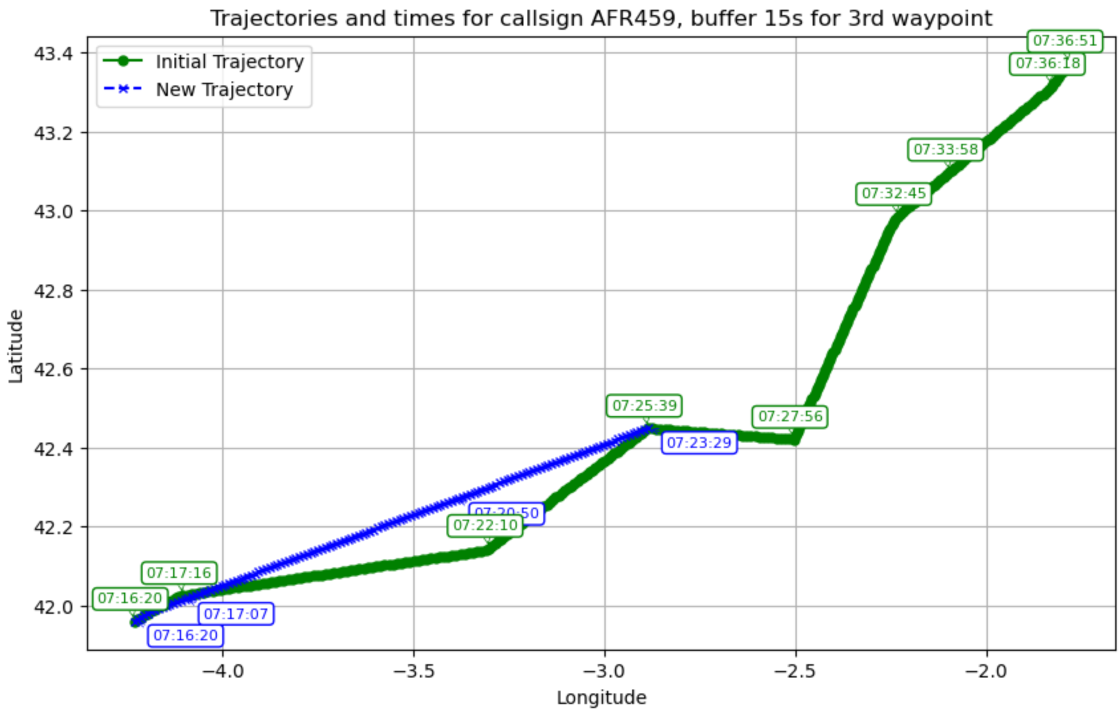


Figure A10. Top) original and modified trajectories for the 2nd waypoint and bottom) original and modified trajectories for the 3rd waypoint

Family C: FL change +-1000/2000 ft

This function generates new trajectories seeking for an adjacent FL that can resolved the conflict. To avoid larger penalties to aircraft involved in the conflict due to modification of current FL, it has been included a condition regarding distance to destination airport based on 75% requirement. The goal is to block descends to aircraft that should be climbing or flying on cruise and, vice versa, to block ascends to aircraft that are closer to the destination airport.

- Inputs:
    - CD database.
    - Departing and destination airport coordinates
- Outputs:
    - CR_C database with new predicted trajectories and CR metrics of the solution

The function follows the following process:

1. It checks the distance to destination airport to avoid solutions:
    a. If distance to departing airport is $< 75\%$ distance from departing to destination airport, it is blocked descending manoeuvres.
    b. If distance to departing airport is $> 75\%$ distance from departing to destination airport, it is blocked climbing manoeuvres.
2. It calculates new predicted trajectories based on previous criteria (climbing and descending) for adjacent flight levels, 1000 or 2000 ft. Similar validation criteria are considered as in function A1.
3. CD evaluates new predicted trajectories with the rest of non-modified trajectories to check if the new trajectory is conflict-free. CD Results of both new trajectories are stored in CR_C1 database.

Figure A11 shows a graphical description of the original and new predictions.

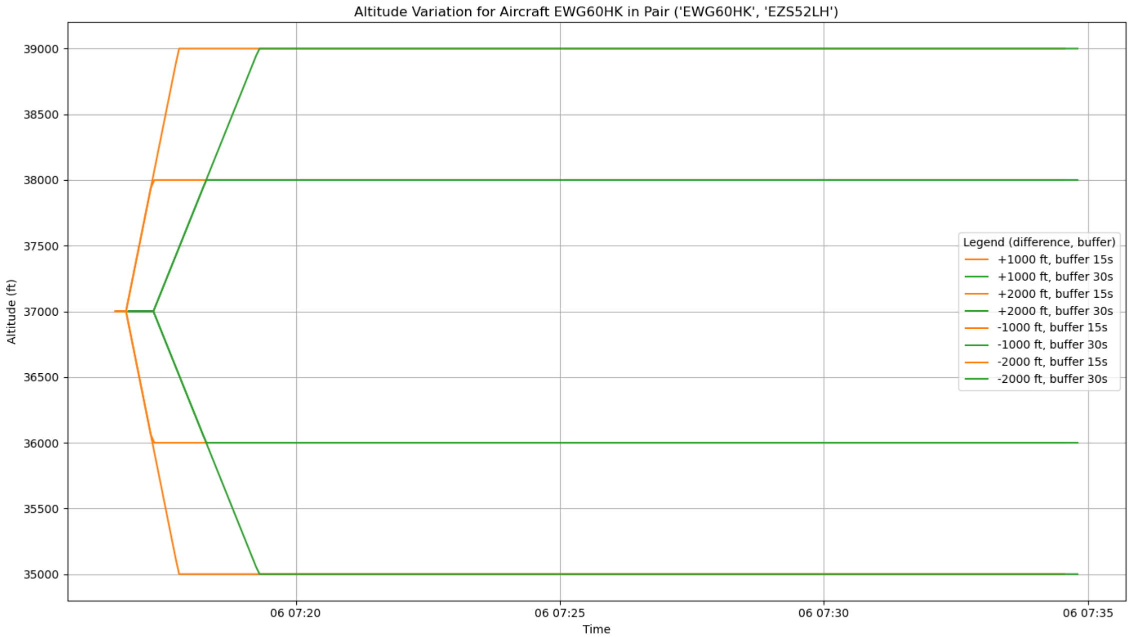


Figure A11. Original and modified trajectories based on FL change resolutions

Lastly, Figure A12 shows an example of the set of manoeuvres considered for an aircraft pair including all CR metrics.

	Aircraft Pair	Aircraft to solve	Solution	tcpa	time_to_cpa_hms_1	time_to_cpa_hms_2	Comments	Valid until time	Validity	Post ATC CLR
0	(AFR459, EZS52LH)	AFR459	Direct to 2nd WP	2023-07-06 07:18:17	00:01:57	00:01:57	Conflict with EZS52LH	2023-07-06 07:16:50	NO	NO
1	(AFR459, EZS52LH)	AFR459	Direct to 3rd WP	2023-07-06 07:18:17	00:01:57	00:01:57	Conflict with EZS52LH	2023-07-06 07:16:50	NO	NO
2	(AFR459, EZS52LH)	AFR459	FL+10	2023-07-06 07:18:17	00:01:57	00:01:57	Conflict with aircraft EZS52LH; Conflict with ...	2023-07-06 07:16:50	NO	YES
3	(AFR459, EZS52LH)	AFR459	FL+20	2023-07-06 07:18:17	00:01:57	00:01:57	Valid action although Conflict with aircraft R...	2023-07-06 07:16:50	YES	YES
4	(AFR459, EZS52LH)	AFR459	FL-10	2023-07-06 07:18:17	00:01:57	00:01:57	Conflict with aircraft EWG60HK; SI with	2023-07-06 07:16:50	NO	YES

Figure A12. Set of resolution manoeuvres calculated by CR tool

Results that can be extracted from this example are:

- A conflict exists between aircraft AFR459 and EZS52LH. The displayed manoeuvres apply only to AFR459, though manoeuvres for both AFR459 and EZS52LH have been calculated.
- The "Validity" column indicates that the only valid manoeuvre shown for AFR459 is a Flight Level (FL) change of +2000 ft.
- The "Comments" column explains why the other manoeuvres are not valid. It also shows that the valid manoeuvre is due to the constraint that any conflict with another aircraft must be resolved within 10 minutes.
- The "Post ATC CLR" column indicates whether, after the resolution manoeuvre, the Air Traffic Controller (ATCo) needs to issue a clearance to return the aircraft to its original FL.

Glossary CDR

Variable	Description
Fundamentals variables	
S_{min}	Longitudinal separation minima (5 NM)
H_{min}	Vertical separation minima (1000 ft)
lon	Longitude
lat	Latitude
h	Altitude (ft)
t	Time (sec)
$Pred$	4DT prediction for an aircraft
$Pos(t)$	Position of an aircraft at time t
CD variables	
SI	Binary variable (1 or 0) if an aircraft pair matches SI requirements
$Conflict$	Binary variable (1 or 0) if an aircraft pair matches Conflict requirements
POS_{CPA_i}	Position of the CPA for the aircraft Ac_i based on longitude, latitude, altitude and time
$Sep(t)$	Euclidean separation (horizontal and vertical) of an aircraft pair at time t
$Sep_{hor}(t)$	Horizontal separation of an aircraft pair at time t
$Sep_{vert}(t)$	Vertical separation of an aircraft pair at time t
$Sep_{comb}(t)$	Combined separation of an aircraft pair at time t, it is a combination of horizontal separation and converted vertical separation into horizontally ranged
$MinSep$	Expected minimum separation at CPA (combined longitudinal and vertical)
$TimetoCPA$	Time from position at time t to the CPA location
$DistoCPA$	Distance from position at time t to the CPA location
(Ac_i, Ac_j)	Aircraft pair Ac_i and Ac_j
LAT	Look-Ahead Time that represents the conflict horizon considered
CR variables	
XFL	Exit Flight Level of Ac_i at the AoR
CFL	Cruise flight level indicated at the Flight Plan

RAT	Resolution-Activation Time represents the maximum time CR is triggered
$Actosolve$	Aircraft that executes resolution manoeuvre
$Solution$	Resolution manoeuvre evaluated
$tcpa$	Datetime of the CPA time
$Comments$	description of the analysis of the resolution manoeuvre
$tvalidity$	date time format of validity time of the resolution manoeuvre
$Validity$	it specifies whether the resolution manoeuvre is valid or not
$PostCLR$	this variable specifies if the resolution manoeuvre demands a post clearance by ATC
$Coordination$	It specifies if the resolution manoeuvre of an aircraft demands coordination with other sector because the aircraft is out of AoR boundaries