

A SEMI-AUTONOMOUS DECISION SUPPORT TOOL FOR ATC IN EN-ROUTE REROUTING OPERATIONS

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Abstract

This paper presents a semi-autonomous decision-support tool to assist en route air traffic controllers in tactical rerouting operations. Unlike existing solutions focused on strategic planning or pilot-centered optimization, the proposed system provides real-time, controller-oriented guidance under dynamic conditions. The framework integrates airway geometry, flight plans, meteorological constraints, and live traffic data into a dynamic graph representation of the airspace. Rerouting is formulated as a constrained shortest-path problem that incorporates separation requirements, weather avoidance, and operational rules. An algorithm generates feasible trajectory alternatives that minimize deviation while preserving traffic flow stability. Preliminary results on a realistic SBGR–SBEG scenario, including convective weather and simulated traffic, show that the system produces operationally valid reroutes that respect separation constraints and improve decision consistency. These findings demonstrate the potential of optimization-based tools to enhance efficiency and support controller decision-making in en-route environments.

Keywords: Air Traffic Control, Tactical Rerouting, Decision Support Systems, Optimization, Air Traffic Management

1. Introduction

The continuous growth of global air traffic, combined with route densification, infrastructure limitations, and the progressive integration of civil and military operations, has made Air Traffic Management (ATM) a highly complex, information-intensive activity [1]. The modern operational environment requires the system to respond rapidly to variations in demand, meteorological changes, temporary airspace restrictions, and unforeseen events that may arise during flight execution. Coordination across multiple control centers, simultaneous flow management, and the need to continuously optimize airspace utilization have led ATM to increasingly rely on intelligent decision-support tools [2]. These tools do not replace human controllers but can enhance efficiency, predictability, and operational smoothness, particularly during phases with limited decision time.

Among all phases of air traffic control, en-route Air Traffic Control (ATC) is a challenging, cognitively demanding task in which controllers must redefine flight trajectories in real time to avoid adverse weather conditions, traffic congestion, temporary restrictions (SUA, NOTAMs, playbooks), or potential conflicts. Controllers are responsible for coordinating multiple aircraft in flight, managing converging flows, and maintaining minimum separation standards even in the face of unplanned events. In such situations, controllers frequently need to perform tactical rerouting, i.e., the real-time redefinition of flight trajectories to avoid adverse weather, congested sectors, or temporary airspace restrictions. Although routine, this process remains largely manual, relying heavily on the controller's experience and rapid evaluation of viable alternatives within airway structures and in accordance with separation

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rules. Under high-traffic conditions, this task can require significant attention and may impact both response time and operational fluidity [3, 4, 5].

In response, several research programs led by organizations such as the National Aeronautics and Space Administration (NASA), the Federal Aviation Administration (FAA), and EUROCONTROL, together with partners in the SESAR (Single European Sky ATM Research) program and standardization bodies such as EUROCAE, have explored new operational concepts and tools to assist controller decision-making and improve overall system efficiency, particularly through advancements in data communication and system interoperability [6].

One of the earliest initiatives was the Future ATM Concepts Evaluation Tool (FACET), developed at NASA Ames Research Center, which established the foundation for large-scale simulation and analysis of four-dimensional (4D) trajectories, flight paths parameterized by latitude, longitude, altitude, and time. FACET enables the study of rerouting strategies, weather impacts, and demand-capacity interactions across the entire network. It became a cornerstone platform for large-scale trajectory simulation, analysis, and visualization. It enabled detailed studies of traffic behavior under varying conditions and the evaluation of rerouting strategies, demand management policies, and the impact of meteorological or spatial constraints, and later on served as a technical enabler for later operational prototypes.

Building on FACET, NASA and the FAA developed the Traffic Aware Strategic Aircrew Requests (TASAR) [7, 8]. This concept was designed as an onboard decision-support system and demonstrated through flight trials that aircraft equipped with the Traffic Aware Planner (TAP) [9] and connected to the System Wide Information Management (SWIM) network can autonomously identify shorter, more fuel-efficient routes during flight and propose changes for pilot review and ATC coordination. Tests conducted by [7, 8] achieved average reductions of 1.5% in flight time and 2.5% in fuel burn, with no measurable increase in pilot workload. TAP operates as a cockpit decision-support system that integrates wind, weather, traffic, and aircraft-performance data to generate operationally acceptable route modifications. The program demonstrated that automation could be used safely to propose optimized in-flight reroutes while keeping the human operator in the decision loop, an operational principle that inspired later automated rerouting solutions.

On the ground, the Dynamic Weather Routes (DWR), Dynamic Arrival Routes (DAR), and Dynamic Routes for Arrivals in Weather (DRAW) families, developed jointly by NASA Ames, the FAA, and MITRE, extended rerouting automation to live operations with U.S. carriers [10, 11, 12]. The DWR system used convective weather forecasts and aircraft performance models to identify and propose near-real-time trajectory alternatives, reducing average flight time by 8–12 minutes per aircraft during field trials with American Airlines. DAR and DRAW further adapted the concept to the arrival phase, maintaining time-based metering and resolving up to 48% of weather-related conflicts. Follow-on studies examined environmental impacts, airspace constraints, and operational acceptability [13, 14, 15], concluding that rerouting opportunities often remain viable for 20–40 minutes, allowing sufficient coordination between adjacent centers.

The natural progression of this research led to the NAS Constraint Evaluation and Notification Tool (NASCENT) [16], developed by NASA in close collaboration with the FAA and major air carriers. NASCENT expanded the automated rerouting concept to multi-center operations, fully integrated with SWIM and the FAA's tactical traffic management systems. During field trials with American Airlines, the tool proposed more than 4,000 reroutes over nine months, achieving 48% acceptance and total time savings exceeding 14,000 minutes. Despite these gains, the validation and coordination processes among controllers, traffic managers, and airline dispatchers still required approximately 20 minutes, limiting the system's tactical applicability under rapidly changing conditions.

In Europe, EUROCONTROL, together with academic partners and air navigation service providers (ANSPs) participating in the SESAR program, developed complementary approaches to reduce controller workload through spatial and procedural structuring. The Point Merge System (PMS) [17, 18], developed by EUROCONTROL, restructured arrival sequencing by defining equi-distance legs converging to a merge point, thereby eliminating open vectoring. Implementations in Oslo, Dublin, and Rome demonstrated 10–15% reductions in ATC clearances and lower occupancy frequency. At the same time, trials in the Extended Terminal Maneuvering Area (Extended TMA) of Paris ACC con-

firmed improved predictability and controller efficiency [19, 20]. However, the PMS concept remains deterministic and procedural, offering limited flexibility for en route tactical adaptation under rapidly changing conditions.

Further advancements in terminal area management have introduced data-driven approaches that extend beyond procedural structures. For instance, the work on Aircraft Route Network Optimization in the Terminal Maneuvering Area (TMA) [21] proposed the Machine Learning Point Merge (ML-PM) model, which applies simulated annealing and receding-horizon control to dynamically optimize route networks and sequencing within the TMA. The study demonstrated that such hybrid optimization frameworks can reduce delay propagation and improve flow predictability under high-density traffic conditions. However, these solutions remain focused on the terminal phase of flight, operating within structured airspace and predefined merge configurations. Their design assumptions—limited maneuvering space, fixed sequencing constraints, and short-range horizons—differ fundamentally from those of the tactical en route environment, where controllers must coordinate across multiple sectors and continuously adapt to external disturbances. Consequently, despite their methodological relevance, these models do not directly address real-time, controller-centered rerouting in en-route operations.

The Aircraft Access to SWIM (AAtS) and Multi-Regional Trajectory-Based Operations (MR-TBO) projects [22, 23], led by the FAA with technical support from NASA, validated the exchange of 4D flight trajectories and operational constraints among multiple Air Navigation Service Providers (ANSPs). In the TBO framework, 4D trajectories define a flight's spatial and temporal intent coordinates (x, y, z) as functions of time (t), allowing intent-based coordination rather than point-to-point clearance control. These programs established the technical foundation for network-level interoperability. Nevertheless, they focus primarily on strategic and pre-tactical horizons rather than on real-time tactical rerouting executed by controllers during live operations. However, these initiatives operate primarily at strategic or pre-tactical horizons and do not address the controller's real-time tactical decision-making in flight operations.

Consequently, although robust tools exist for strategic and collaborative rerouting (TBO, MR-TBO, SWIM) and for automated rerouting focused on flight operators (TASAR, DWR, DRAW, NASCENT), none of these systems directly support ATC controllers in en-route tactical deviations through automatic suggestions of optimized waypoints and route alternatives that jointly minimize network impact and deviation time. In this context, modern optimization-based and heuristic-driven tools, developed under initiatives such as NextGen and SESAR, have the potential to meaningfully assist controllers' tactical decision-making, thereby enhancing responsiveness and operational efficiency in the en route environment.

The main objective of this work is to develop a semi-autonomous, optimization-based decision-support tool to assist en-route air traffic controllers during tactical rerouting operations. The system is designed to ingest real-time operational data aircraft position, airway geometry, sector capacities, temporary airspace restrictions, and meteorological constraints, and generate optimized and operationally acceptable reroute suggestions in the form of (i) candidate transition waypoints for airway crossings, (ii) alternative route segments that minimize disruption to the surrounding traffic flow, and (iii) solutions that reduce deviation time or distance while respecting mandatory separation and sector-load limits.

Moreover, the goal is not to automate controller authority but to provide a time-efficient, transparent computational assistant that proposes feasible trajectory modifications in response to rapidly evolving en route conditions. By comparing manual rerouting actions observed in real operations with the solutions produced by the proposed system, this work aims to evaluate whether optimization-driven guidance can improve the timeliness, consistency, and efficiency of tactical rerouting, laying the groundwork for future integration with NextGen/SESAR decision-support architectures.

This paper is organized as follows. Section 2. presents the methodological framework adopted in this research, including the operational assumptions, data sources, APIs, preprocessing pipeline, and the proposed system architecture for tactical en-route rerouting. Section **??** introduces the mathematical formulation of the rerouting problem, describing the graph-based representation of the airspace, operational constraints, traffic-flow modeling, and optimization strategy. Section **??** presents prelim-

inary results from the SBGR–SBEG operational scenario, including the feasible-graph construction process, candidate rerouting evaluation, and ATC-oriented rerouting outputs under weather and traffic constraints. Finally, Section 4. concludes the paper and discusses future developments in dynamic operational integration, large-scale simulations, and extensions toward NextGen- and SESAR-compatible decision-support environments.

2. Methodology

This section presents the methodological framework adopted in this research, including the operational assumptions, data sources, APIs, preprocessing pipeline, and optimization architecture used to support tactical en-route rerouting.

The proposed system integrates heterogeneous aeronautical and meteorological information obtained from multiple operational platforms into a unified dynamic navigation graph. This graph is continuously updated using real-time surveillance data, structured airway information, and weather constraints, enabling the generation of operationally feasible rerouting alternatives under dynamic airspace conditions.

The methodology is organized into four main stages:

1. Acquisition of aeronautical, surveillance, and meteorological data from operational sources;
2. Transformation and fusion of these datasets into a graph-based airspace representation;
3. Dynamic constraint modeling, including weather avoidance and longitudinal separation requirements;
4. Real-time optimization of rerouting trajectories using graph-search and combinatorial optimization techniques.

The resulting architecture operates under a rolling-horizon framework, continuously updating the operational environment as new surveillance and meteorological information becomes available.

2.1 Operational Assumptions

To enable controlled evaluation of the proposed tactical rerouting framework, several operational assumptions and scope delimitations were adopted. These assumptions simplify the initial problem formulation while preserving the essential operational characteristics required to validate the graph construction, traffic integration, and rerouting mechanisms proposed in this work.

The assumptions were selected to reduce unnecessary modeling complexity during the initial development stage, allowing the study to focus on interactions among airway topology, severe-weather avoidance, traffic-flow compatibility, and tactical rerouting feasibility.

1. **Upper-airspace operations only**: The initial operational environment is limited to upper-ATS routes. Upper airspace generally exhibits more structured traffic flows, lower geometric complexity, and fewer terminal-area constraints compared to lower airspace operations. This restriction simplifies graph generation and traffic-flow modeling while preserving the operational characteristics of en-route tactical rerouting.
2. **SBGR–SBEG corridor as operational case study**: The São Paulo–Manaus corridor (SBGR $\rightarrow$ SBEG and return) was selected as the primary case study because it crosses multiple regions frequently affected by severe convective activity and includes extensive portions of the high-altitude Brazilian ATS routes UL302, UL304, and UL795. The corridor, therefore, provides a realistic and operationally relevant environment for evaluating tactical weather rerouting under long-haul conditions.
3. **Geodesic distance as primary routing metric**: The optimization model initially minimizes geodesic route distance and estimated travel time. Atmospheric effects such as wind fields, temperature variations, aircraft performance gradients, and detailed fuel consumption dynamics are not explicitly modeled in this phase. This assumption reduces the dimensionality of

the optimization and allows the study to isolate the effects of airspace structure, weather constraints, and traffic-flow interactions on rerouting behavior.

4. **Preference for structured ATS routing**: The rerouting framework prioritizes maintaining aircraft inside the published ATS route network whenever operationally feasible. Direct-to or heading-vector maneuvers are used only to intercept downstream airways or reconnect the aircraft to the structured route system. This assumption preserves operational realism and improves the controller's interpretability of the generated rerouting solutions.

5. **Operational constraints on direct-to maneuvers**: Temporary intercept or direct-to segments are allowed only when they:

   - move the aircraft toward the destination;
   - avoid unnecessary retrograde deviations;
   - satisfy heading and geometric feasibility constraints;
   - remains within the operational rerouting horizon considered by the framework.

   These restrictions prevent the generation of unrealistic shortcuts or operationally implausible rerouting trajectories.

6. **Simplified traffic-separation model**: The current framework models longitudinal separation only, based on estimated times over fixes and temporal spacing between aircraft projected onto airway segments. Vertical separation, wake turbulence effects, aircraft-category differences, and detailed considerations of controller workload are not explicitly represented at this stage. This assumption enables tractable validation of the queue-insertion and traffic-gap identification mechanisms proposed in the study.

7. **Rolling-horizon operational updates**: The operational environment is assumed to evolve dynamically through periodic surveillance and meteorological updates. At each optimization cycle, the navigation graph is reconstructed using the latest available information, enabling the framework to continuously adapt to changing traffic and weather conditions.

2.2 Data and APIs

The proposed system relies on multiple operational data sources, APIs, and software tools to construct and continuously update the airspace representation used during tactical rerouting. These heterogeneous datasets are integrated into a unified dynamic graph that models airway topology, traffic flow, meteorological hazards, and operational constraints in real time.

2.2.1 Flight planning data

Baseline operational trajectories are generated using SimBrief[1], a professional flight-planning platform widely used in operational flight simulation environments. The exported Operational Flight Plan (OFP) contains the planned sequence of waypoints, ATS routes, cruising flight levels, estimated times, aircraft performance assumptions, fuel estimates, and alternate routing information.
The OFP serves as the initial reference trajectory for the rerouting framework. From this trajectory, the system extracts the airway sequence and constructs a localized operational subgraph surrounding the aircraft's current route. This subgraph defines the initial search space for tactical rerouting and significantly reduces computational complexity compared with dynamically constructing the entire continental airway network.

2.2.2 Airway and waypoint data

Aeronautical route structure data are obtained from AISWEB[2], the official Aeronautical Information Services platform maintained by DECEA (Departamento de Controle do Espaço Aéreo, Brazil).

[1] https://www.simbrief.com
[2] https://aisweb.decea.mil.br

Specifically, airway and waypoint information is extracted from the Brazilian Electronic Aeronautical Information Publication (eAIP), which provides standardized, regulator-approved navigation data.
The extracted information includes:

- geographical coordinates of fixes and navigation points;
- ATS route topology and ordered airway segments;
- lower and upper flight-level restrictions;
- route classifications and RNP requirements;
- published distances and magnetic courses;
- directional flow rules and parity constraints, when available.

The airway structure is transformed into a directed graph representation, where nodes correspond to navigation fixes and edges represent feasible airway transitions. Each edge stores operational metadata required by the optimization process, including distance, heading, flight-level restrictions, airway class, and directional constraints.
When explicit directional metadata are unavailable in structured form, operational directionality is inferred from airway sequencing, parity rules, and official chart symbology. In uncertain cases, segments are conservatively treated as bidirectional to avoid artificially restricting feasible rerouting alternatives.

2.2.3 Meteorological data

Meteorological constraints are obtained from REDEMET[3], the Brazilian Aeronautical Meteorological Network maintained by DECEA. The system integrates multiple weather products relevant to tactical air traffic management, including:

- radar reflectivity mosaics;
- Severe Convective Weather (SCW) polygons;
- SIGMET advisories;
- convective storm-cell information.

These meteorological products are periodically updated and converted into georeferenced polygonal obstacles, each with an associated temporal validity interval. The polygons are geometrically intersected with airway segments and candidate rerouting edges during graph construction.
Edges that fully intersect hazardous meteorological regions are removed from the feasible graph, while partially affected segments incur penalty costs proportional to the severity and extent of the intersection. This enables the optimization module to naturally prioritize safer rerouting alternatives while preserving operational flexibility, even as deviations around weather systems remain feasible.

2.2.4 Traffic surveillance data

Real-time surveillance information is obtained from the OpenSky Network[4], which provides aircraft state vectors derived from ADS-B, MLAT, and Mode-S surveillance systems.
The retrieved data include:

- aircraft geographical position;
- barometric altitude;
- ground speed;

[3] https://www.redemet.aer.mil.br
[4] https://opensky-network.org

- track angle;
- aircraft identifiers and timestamps.

Aircraft positions are projected onto airway geometries to model traffic flow along each ATS segment as a one-dimensional ordered queue. Based on current aircraft state vectors and estimated propagation along the airway, the system computes Estimated Times Over (ETO) future fixes and predicts temporal occupancy of airway segments.
These predictions enable the identification of feasible insertion windows for rerouted aircraft while respecting longitudinal separation minima defined by Brazilian ICA regulations. Consequently, the framework incorporates not only geometric feasibility, but also dynamic traffic-flow compatibility into the rerouting decision process.

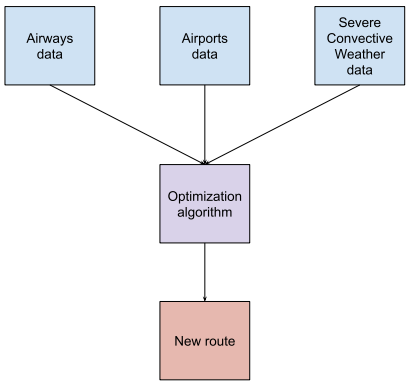
2.2.5 Path optimization software

The computation of feasible rerouting trajectories in the dynamic graph $\mathscr{G}(t)$ is performed using Google OR-Tools[5], an open-source suite for combinatorial optimization developed by Google.
OR-Tools provides efficient graph search and optimization algorithms that incorporate operational constraints such as airway topology, weather restrictions, temporal feasibility, and traffic-flow compatibility into a unified optimization framework.
At each update cycle, the optimizer receives the dynamically reconstructed graph—already filtered by meteorological hazards, airway restrictions, and longitudinal-separation feasibility—and computes candidate rerouting trajectories between the aircraft's current position and a downstream target fix.
This rolling-horizon optimization strategy enables near-real-time responsiveness while preserving operational feasibility and the controller's interpretability of the generated rerouting recommendations.

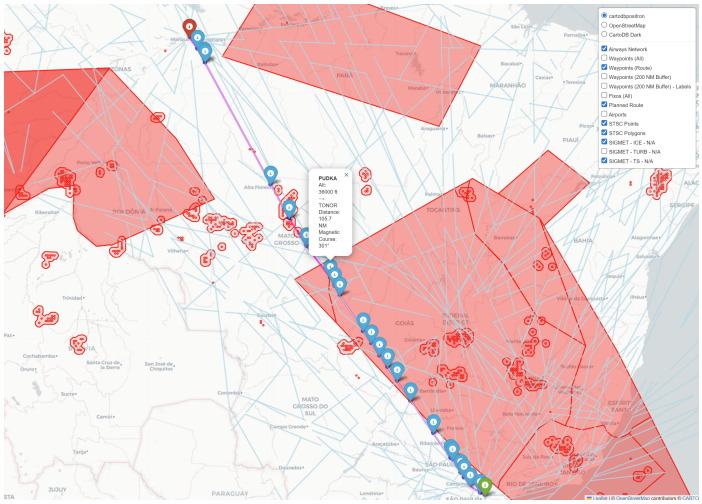
2.3 System Overview and Architecture

The proposed architecture serves as a semi-autonomous tactical decision-support system for en route rerouting under dynamic operational constraints. The framework continuously integrates heterogeneous operational datasets—including structured airway information, surveillance data, meteorological hazards, and flight-planning information—into a unified graph-based representation of the airspace.
Unlike static route-planning systems, the proposed framework dynamically reconstructs the feasible navigation graph as operational conditions evolve. Weather constraints, airway occupancy, aircraft sequencing, and interception feasibility are continuously re-evaluated in each optimization cycle, enabling rolling-horizon tactical rerouting recommendations that are compatible with real operational environments.
Figure 1 illustrates both the logical control flow of the optimization architecture and the operational data integration process for generating the dynamic rerouting graph. Figure (a) illustrates the high-level control flow of the system, where heterogeneous operational data sources—including airway geometry, airport information, and severe convective weather products—are continuously integrated into the optimization engine to generate dynamically feasible rerouting trajectories. Figure (b) presents an example of the operational environment generated by the system for the SBGR–SBEG corridor. The visualization combines ATS airway structures extracted from AISWEB/eAIP, real-time aircraft surveillance data from the OpenSky Network, and hazardous meteorological regions obtained from REDEMET, including severe convective weather polygons and SIGMET areas. The resulting integrated airspace representation is transformed into a dynamic navigation graph that the optimization module uses to compute operationally feasible rerouting alternatives while respecting airway topology, weather-avoidance constraints, and longitudinal separation requirements.
At each optimization cycle, the system constructs a dynamic graph that represents the operational airspace surrounding the aircraft and the affected rerouting region. In this graph, nodes correspond to operationally feasible navigation locations where aircraft may continue, merge, or transition between ATS routes.

[5] `https://developers.google.com/optimization`



(a) Control flow of the proposed system.



(b) Operational data integration pipeline for the SBGR–SBEG corridor.

Figure 1 – Overview of the proposed tactical rerouting architecture and operational data-integration pipeline.

The node set includes published airway fixes imported from AISWEB/eAIP, airway intersections where multiple ATS routes share common navigation points, and virtual intercept nodes representing controller-authorized heading maneuvers toward downstream airways. These virtual nodes are necessary because tactical rerouting frequently involves radar vectors or direct-to clearances that are not explicitly represented in the published airway structure.
Each node stores operational attributes such as geographical coordinates, associated airways, admissible flight levels, meteorological status, and local routing constraints.
Edges represent feasible transitions between nodes. Two categories of edges are considered:

- official airway edges corresponding to published ATS route segments;
- temporary intercept or heading-vector edges representing tactical maneuvers toward downstream airways.

Airway edges contain operational metadata including geodesic distance, magnetic course, airway classification, RNP requirements, minimum and maximum flight levels, directional restrictions, and parity constraints.
Intercept edges represent temporary tactical maneuvers and are only permitted when they:

- reduce progression toward the destination;
- remain inside the operational rerouting horizon;
- satisfy meteorological feasibility constraints;
- preserve traffic-flow compatibility.

Therefore, intercept edges do not represent arbitrary shortcuts between waypoints, but operationally plausible ATC vectoring procedures.
Traffic surveillance data from the OpenSky Network is incorporated by projecting nearby aircraft onto airway geometries. This transforms each airway segment into a one-dimensional ordered traffic queue, enabling estimation of future aircraft positions and temporal occupancy of airway fixes.
Using estimated times over fixes and aircraft progression along airway segments, the system computes feasible insertion windows for rerouted aircraft while maintaining the required longitudinal separation minima. This mechanism approximates the metering and sequencing procedures commonly used during en route tactical flow management.

Meteorological constraints are integrated directly into graph construction. Severe convective weather polygons, SIGMET regions, and storm-cell structures are geometrically intersected with both airway and intercept edges.
When an edge is significantly affected by hazardous weather, it is removed from the feasible graph. When the intersection is partial or operationally undesirable but not strictly prohibitive, the edge incurs a higher traversal penalty, making it less attractive during optimization while still preserving operational flexibility.
Once the dynamic graph is constructed, the optimization module searches for feasible rerouting trajectories that minimize operational cost while respecting airway topology, weather constraints, and traffic-separation requirements.
The resulting output consists of candidate rerouting trajectories, airway transitions, and insertion points that support controller tactical decision-making under adverse operational conditions. Consequently, the proposed framework integrates structured airspace information, real-time surveillance data, meteorological hazard modeling, and optimization-based routing into a unified decision-support architecture for tactical en-route rerouting. “‘

3. Results and Discussion

3.1 Experimental Design

The preliminary static experiment presented in the previous version of this work demonstrated the end-to-end construction of a locally feasible graph from a fixed REDEMET snapshot and simulated traffic. The extended evaluation reported in this section assesses the rolling-horizon implementation under evolving meteorological and traffic conditions. The evaluation comprises the no-threat baseline ATC-00 and twelve test scenarios, ATC-01 to ATC-12. All experiments use the SBGR–SBEG corridor, continuous monitoring of the field route, an ownship propagation step of 10 NM, and periodic reassessment of the active recommendation after diversion initiation.
Each experiment generated an auditable evidence package containing the scenario configuration, run manifest, cycle-level operational states, planning decisions, candidate rejections, traffic and weather snapshots, graph summaries, and final metrics. The results were classified according to both the expected functional behavior and the hard post-planning safety validation. Because most scenarios currently have a single execution, the findings should be interpreted as functional case-study evidence rather than statistical validation or operational certification.
Table 1 summarizes the objective and observed outcome of each experiment. A result in which no complete route was found is not automatically interpreted as an algorithmic failure. If every candidate violates an active constraint, the operationally correct behavior is to avoid publishing an unsafe recommendation and report that contingency action is required.

3.2 Nominal Monitoring and Weather-Driven Rerouting

ATC-00 establishes the reference behavior in the absence of a threat requiring rerouting. The aircraft completed the 1461.78 NM simulated route in 148 cycles and remained in `PLANNED_ROUTE`. No planning decisions were generated, the feasible graph was not invoked, and the maximum deviation from the filed route was 0.54 NM. This result indicates that continuous SCW and traffic monitoring did not generate a false-positive diversion in the evaluated case.
ATC-01 evaluates the nominal tactical-rerouting sequence. Once a future SCW intersection was detected, the system generated an initial complete alternative and reassessed it as the aircraft progressed. The resulting decision history contained one `INITIAL_ROUTE`, ten `KEEP_ROUTE`, and four `OPTIMIZE_ROUTE` decisions. The aircraft subsequently reached `REJOINING` and returned to `PLANNED_ROUTE`. The executed trajectory measured 1502.22 NM, compared with 1461.78 NM for the filed route, corresponding to an additional 40.44 NM, or approximately 2.77%. No post-plan safety-validation failure occurred.
Figure 2 presents the decision profile across the experiments. Incumbent-route retention was more frequent than replacement in the nominal and incremental-optimization cases. This behavior is operationally relevant because a controller-oriented tool should avoid presenting a new route at every rolling-horizon update when the active recommendation remains feasible, and a candidate improvement is not material.

Table 1 – Objectives and observed outcomes for the baseline and twelve test scenarios.

Case	Objective	Observed result	Assessment
ATC-00	Verify that continuous monitoring does not generate unnecessary reroutes	The aircraft remained on the filed route for 148 cycles. No rerouting decision or shortest-path search was invoked.	Baseline behavior demonstrated.
ATC-01	Demonstrate nominal rerouting after timely SCW detection	One initial route, ten retained recommendations, four material optimizations, and safe rejoin were observed.	Nominal workflow demonstrated.
ATC-02	Verify that geometric crossing alone does not imply temporal conflict	The minimum estimated temporal separation was 19.91 min, above the adopted 10 min requirement.	Temporal-separation criterion respected.
ATC-03	Resolve a conflict by adjusting ownship speed	Planning artifacts contain recommended speeds from 450 to 260 kt, but the consolidated execution was incomplete.	Partial evidence of speed adaptation.
ATC-04	Demonstrate incremental optimization without unnecessary route replacement	Ten `KEEP_ROUTE` and four `OPTIMIZE_ROUTE` decisions were issued.	Recommendation stability demonstrated.
ATC-05	Retain the incumbent route when candidate improvements are not material	Twenty-four `KEEP_ROUTE` and four `OPTIMIZE_ROUTE` decisions were issued.	Stability under repeated reassessment demonstrated.
ATC-06	Replace a recommendation invalidated by an SCW change	The SCW initially did not intersect the route, but moved over the active reroute after diversion initiation. One structural `UPDATE_ROUTE` replaced the invalidated recommendation.	Dynamic weather-driven replanning demonstrated.
ATC-07	Escalate when traffic invalidates the active recommendation	Eleven traffic-driven updates and one emergency replan occurred; one post-plan safety-validation failure was recorded.	Critical safety limitation identified.
ATC-08	Handle late SCW detection when no complete route is available	The search returned `NO_ROUTE`, followed by 70 cycles in `CONTINGENCY_REQUIRED`.	Contingency entry demonstrated.
ATC-09	Cancel diversion when the SCW dissipates before route departure	No rerouting was issued, but the expected `SCW_MONITORED` state was not recorded.	Functional result with an incomplete scenario contract.
ATC-10	Safely rejoin the field route and close diversion planning	`REJOINING` was observed, followed by return to `PLANNED_ROUTE`; no new planning graphs were generated afterward.	Safe rejoin demonstrated.
ATC-11	Operate with combined OpenSky and synthetic traffic	Both traffic sources were integrated, but no complete route was found, and the system entered contingency.	Integration demonstrated and feasibility limit observed.
ATC-12	Evaluate search expansion and robustness under rerouting-zone saturation	With 48 configured synthetic aircraft and multiple SCW restrictions, no The complete route was found, and the system entered contingency.	Saturation limit and safe absence-of-solution response demonstrated.

3.3 Traffic Separation and Speed Adaptation

ATC-02 isolates the distinction between geometric intersection and temporal conflict. A crossing trajectory was present, but the minimum estimated time separation was 19.91 min, exceeding the adopted 10 min requirement. The planner therefore retained a feasible rerouting solution without treating the geometric crossing alone as a loss of separation.

ATC-03 investigates speed adaptation. Its decision artifacts show progressively reduced recommended speeds, from 450 to 260 kt, while preserving the candidate-route geometry. However, the consolidated execution was interrupted and did not record the expected `speed_adjustment` event. Consequently, this case demonstrates that the planning mechanism explored speed as a control variable, but it does not yet validate complete conflict resolution by speed adjustment.

ATC-07 evaluates a more restrictive traffic condition. The active recommendation was invalidated by `traffic_separation` during eleven consecutive reassessments, after which the system issued an `EMERGENCY_REPLAN`. The run ended in `CONTINGENCY_REQUIRED`, and one post-plan safety-validation failure was recorded. This result must be treated as a critical limitation rather than a successful reroute: the escalation logic was activated, but the system did not maintain the required hard-safety guarantee throughout the case.

3.4 Recommendation Stability and Dynamic Invalidation

ATC-04 and ATC-05 assess whether rolling-horizon optimization creates excessive route changes. ATC-04 produced ten `KEEP_ROUTE` and four `OPTIMIZE_ROUTE` decisions. ATC-05 increased the number of reassessments and produced twenty-four `KEEP_ROUTE` decisions against four optimizations. The predominance of incumbent retention indicates that the material-improvement rule prevented unnecessary replacement of a still-valid recommendation.

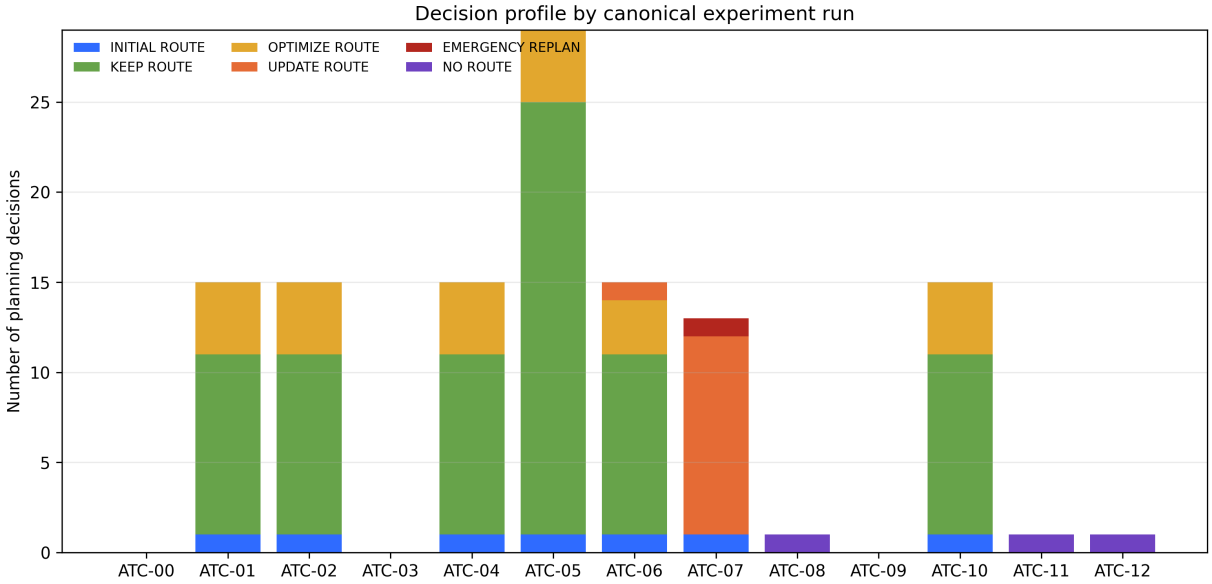


Figure 2 – Planning-decision profile for the canonical experiment runs. Incumbent-route retention predominates in the nominal stability cases, whereas ATC-07 requires repeated traffic-driven route updates.

The experiments use a variable replacement threshold with a 60 NM floor, consistent with the current $\max(60\ \mathrm{NM}, 8\%)$ policy. Therefore, a feasible candidate is not adopted solely because its distance is marginally lower. This policy favors operational stability and reduces the number of route revisions presented to the controller.

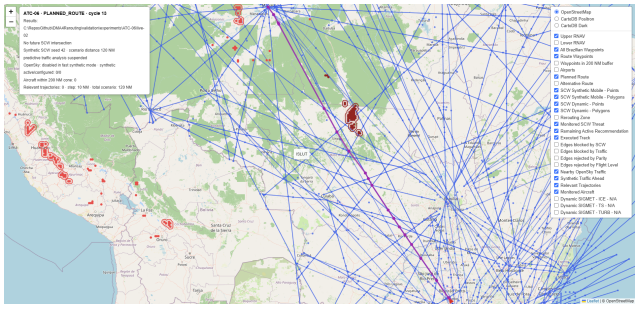
ATC-06 tests a different condition: the active recommendation becomes structurally invalid after a new SCW intersection. This case is particularly relevant because the hazardous region did not initially intersect the flight route or the first portion of the flight. As illustrated in Figure 3, the SCW moved as the aircraft progressed and subsequently affected a route that had already been recommended and was being executed.

The first future intersection requiring action was identified at cycle 75, after 740 NM of simulated flight, at approximately 94.02 NM ahead of the aircraft. The initial complete reroute was `CURRENT-XINGU-LOLIR-MOPR`. While the aircraft was already executing this recommendation, the evolving SCW moved over the active reroute. At cycle 79, a new future intersection was detected approximately 61.98 NM ahead. In the following planning cycle, the incumbent route was explicitly classified as invalid due to `scw_intersection`. At cycle 80, after 790 NM of simulated flight, the system issued one `UPDATE_ROUTE` and replaced the affected initial segment with `CURRENT-VUGAR-LOLIR-MOPRA-ESMAR-MAMGI-UTPAM`. The downstream rejoin point at `UTPAM` was preserved. The updated route was then maintained or incrementally optimized during subsequent reassessments, and The aircraft eventually returned safely to the flight route. The full experiment contained one `INITIAL_ROUTE`, one `UPDATE_ROUTE`, ten `KEEP_ROUTE`, and three `OPTIMIZE_ROUTE` decisions, without any post-plan safety-validation failure.

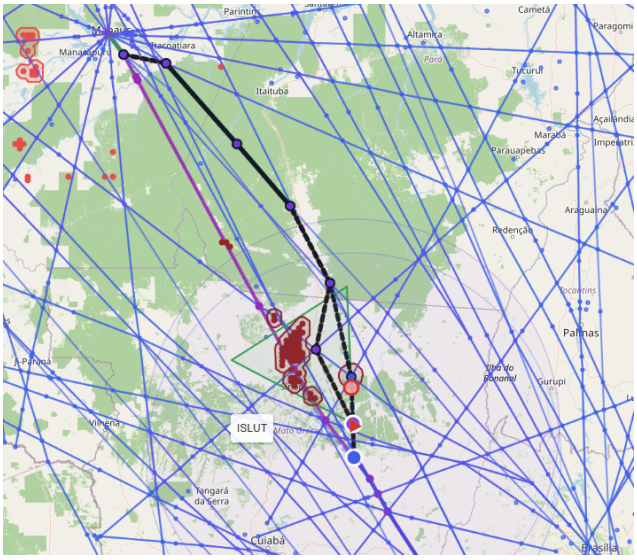
This result demonstrates an essential property of the rolling-horizon architecture. A reroute that is feasible at its publication time cannot be assumed to remain feasible until rejoin, because meteorological restrictions may move, expand, or emerge over the recommended trajectory. The system must therefore continue monitoring both the filed route and the active recommendation, invalidate the incumbent route when necessary, and compute a new complete reroute from the aircraft's updated position.

3.5 Contingency and Safe Rejoin

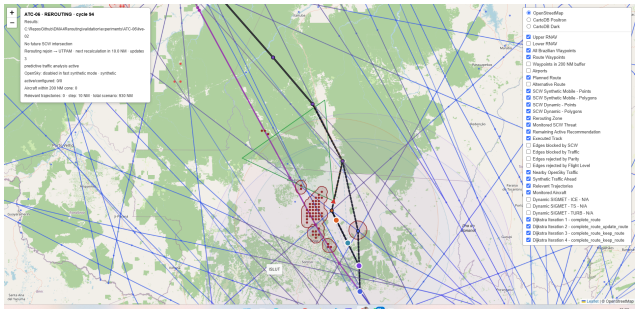
ATC-08 evaluates late SCW detection under a configuration in which no complete alternative route could be found. The planner expanded the search to a graph containing 829 nodes and 54,809 edges, requiring approximately 17.05 s for the planning attempt. It then recorded `NO_ROUTE` and



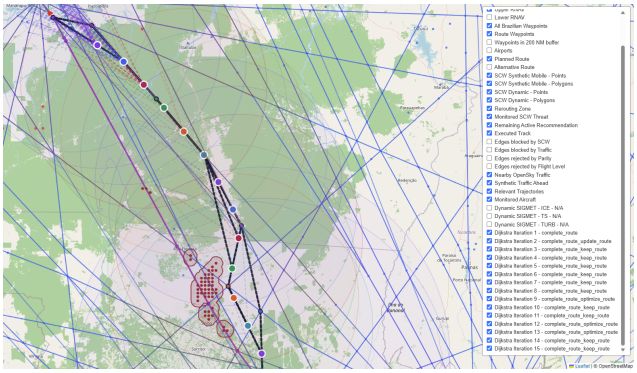
(a) Initial monitoring condition with no future SCW intersection.



(b) Initial complete reroute generated after the first actionable intersection.



(c) Updated recommendation after the moving SCW invalidates the active reroute.



(d) Complete set of rolling-horizon recommendations and reassessments.

Figure 3 – ATC-06 dynamic-weather sequence. The SCW initially does not intersect the route, but its evolution subsequently invalidates a reroute already under execution. The system detects the new intersection, replaces the affected recommendation, and continues reassessment until safe rejoin.

remained in `CONTINGENCY_REQUIRED` for 70 cycles. No unsafe route was published. However, the scenario did not demonstrate the expected temporary vector mechanism, so the result validates contingency entry but not an operational recovery maneuver.

ATC-09 evaluates threat cancellation before diversion execution. The aircraft remained on the filed route, and no initial reroute was generated. Although this behavior is consistent with the disappearance of the threat, the expected `SCW_MONITORED` state was not recorded. The operational behavior was therefore plausible, but the complete scenario contract was not satisfied.

ATC-10 demonstrates the opposite transition. After executing the diversion, the aircraft entered `REJOINING` and subsequently returned to `PLANNED_ROUTE`. The final cycles contain no new planning time or graph generation, which is consistent with suspension of diversion planning after the field route was recovered.

3.6 Combined Traffic and Saturation Cases

ATC-11 evaluates the integration of live OpenSky traffic and persistent synthetic traffic. Both sources were observed simultaneously over 59 cycles. The maximum traffic snapshot contained 84 nearby aircraft, 23 active synthetic aircraft, and three trajectories classified as relevant to the rerouting problem.

When the monitored SCW required action, the ATC-11 planner expanded the search to 600 NM.

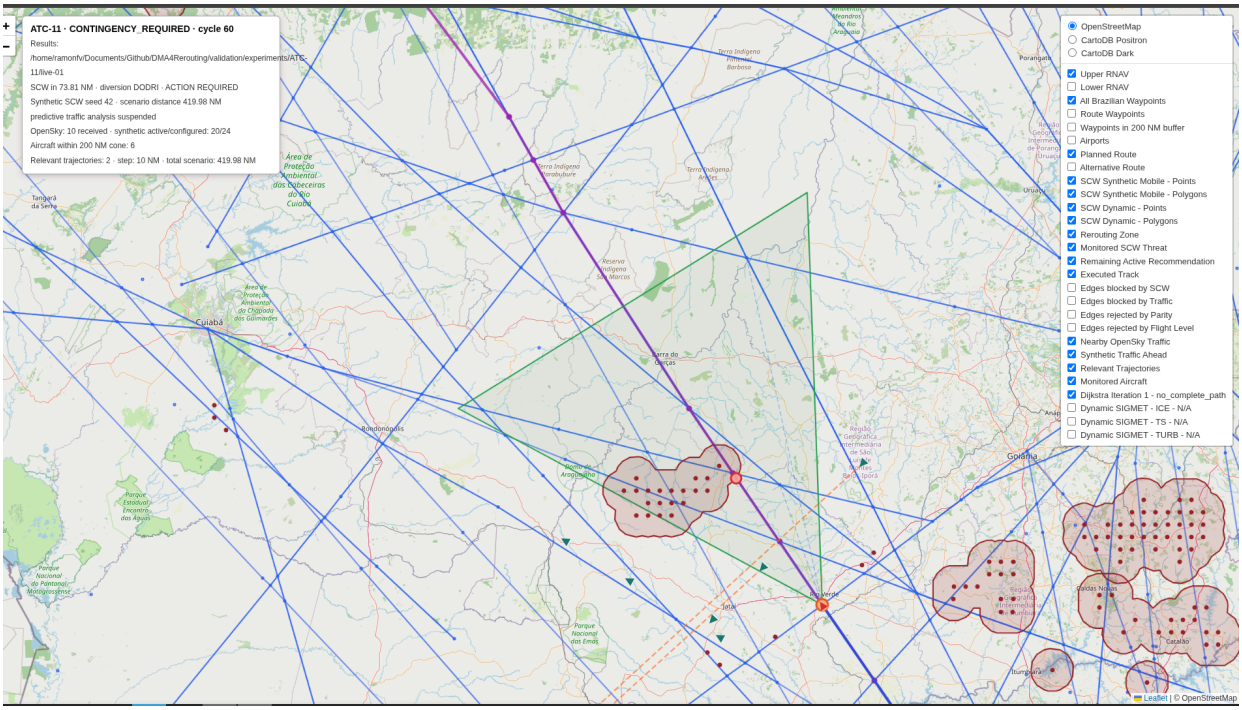


Figure 4 – ATC-11 final operational condition. The experiment combines OpenSky and synthetic traffic, detects an SCW requiring action, and reports that no complete path satisfies all active constraints.

The resulting graph contained 1,431 nodes and 174,401 edges, including 172 edges blocked by SCW and 92 edges blocked by traffic. No complete route satisfying all constraints was found. The system recorded `NO_ROUTE` and entered `CONTINGENCY_REQUIRED`, without publishing an unsafe recommendation. Figure 4 illustrates the final operational condition.

ATC-12 increases the complexity by configuring 48 synthetic aircraft and multiple SCW restrictions. The run reached `CONTINGENCY_REQUIRED` after the planner returned `NO_ROUTE`. The largest graph contained 1,454 nodes and 181,673 edges, with 138 blocked by SCW and 92 by traffic. The planning attempt required approximately 40.13 s. The maximum snapshot contained 48 active synthetic aircraft, 17 aircraft within the 200 NM cone, and nine relevant trajectories. No post-plan safety-validation failure was recorded because no unsafe route was published.

The absence of a complete route in ATC-11 and ATC-12 is not, by itself, an algorithmic failure. Under a constrained graph, the correct result may be to report that no feasible solution exists. Nevertheless, these cases expose an operational limitation: the current implementation identifies infeasibility and enters contingency, but it does not yet provide a complete recovery action when the feasible graph is exhausted.

3.7 Computational Behavior

Figure 3.7 compares maximum planning time and feasible-graph size across the canonical runs. Conventional rerouting cases generated graphs with up to 311 nodes and 18,410 edges, with maximum planning times below 1 s. Cases without a complete solution were substantially more expensive. ATC-08 required approximately 17.05 s for a graph with 54,809 edges, ATC-11 required approximately 27.99 s for a graph with 174,401 edges, and ATC-12 required approximately 40.13 s for a graph with 181,673 edges.

This contrast indicates that proving infeasibility under a broad search region is substantially more expensive than finding a route in the nominal cases. The result motivates explicit computational budgets, early infeasibility detection, and contingency policies for high-complexity operational states. Figure 7 summarizes the maximum traffic load observed in each scenario and highlights the difference between controlled single-conflict experiments, the combined OpenSky/synthetic case, and the synthetic saturation case.

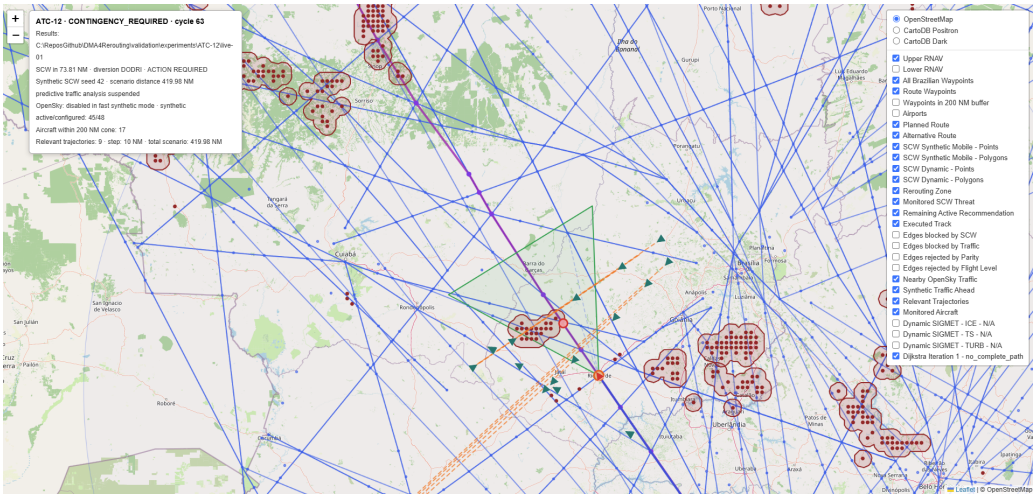


Figure 5 – ATC-12 saturation experiment. The increased synthetic traffic load and multiple SCW restrictions result in no complete path satisfying all active constraints.

Table 2 – Quantitative summary of selected canonical runs. Graph size is shown as nodes/edges.

Case	Final state	Decisions	Maximum graph	Max. planning time	Safety result
ATC-00	PLANNED_ROUTE	0	Not invoked	0 ms	Passed
ATC-01	PLANNED_ROUTE	15	311 / 18,410	821.46 ms	Passed
ATC-02	PLANNED_ROUTE	15	311 / 18,410	511.49 ms	Passed
ATC-04	PLANNED_ROUTE	15	311 / 18,410	445.79 ms	Passed
ATC-05	PLANNED_ROUTE	29	311 / 18,410	422.76 ms	Passed
ATC-06	PLANNED_ROUTE	15	311 / 18,410	437.84 ms	Passed
ATC-07	CONTINGENCY_REQUIRED	13	311 / 18,410	645.81 ms	Failed once
ATC-08	CONTINGENCY_REQUIRED	1	829 / 54,809	17,049.30 ms	No unsafe route
ATC-09	PLANNED_ROUTE	0	Not invoked	0 ms	Passed
ATC-10	PLANNED_ROUTE	15	311 / 18,410	479.40 ms	Passed
ATC-11	CONTINGENCY_REQUIRED	1	1,431 / 174,401	27,986.06 ms	No unsafe route
ATC-12	CONTINGENCY_REQUIRED	1	1,454 / 181,673	40,131.50 ms	No unsafe route

Table 2 presents the principal quantitative results. The hard-safety gate was satisfied in the nominal, contingency, and saturation cases because no invalid complete route was published. ATC-07 is the exception and recorded one post-plan safety-validation failure.

3.8 Discussion and Limitations

The baseline and twelve test scenarios demonstrate the principal behaviors required from the proposed semi-autonomous tool: avoiding false-positive reroutes, detecting future weather intersections, generating and incrementally reassessing a complete recommendation, respecting a temporal separation constraint, invalidating an unsafe incumbent route, safely rejoining the field route, combining live and synthetic traffic, and reporting when no feasible route exists.

Among these behaviors, ATC-06 provides the clearest demonstration of why a static shortest-path solution is insufficient for tactical operations. The first recommendation was valid when issued, but became invalid while it was being executed because the SCW evolved over the rerouted trajectory. The successful transition from INITIAL_ROUTE to UPDATE_ROUTE, followed by safe rejoin, shows that the proposed approach does not treat the initial Dijkstra result as a definitive flight-to-destination solution. Instead, it treats each complete route as an operationally valid incumbent recommendation that remains subject to continuous monitoring and replacement whenever the dynamic feasible graph changes.

The experiments also demonstrate the auditability of the decision process. Candidate alternatives and graph edges preserve rejection reasons associated with SCW intersection, traffic separation, flight-level incompatibility, parity restrictions, maneuver geometry, and total operational cost. This allows the controller or analyst to determine not only which route was recommended, but also why alternative transitions were rejected.

The results identify limitations that are directly relevant to future development. ATC-03 did not com-

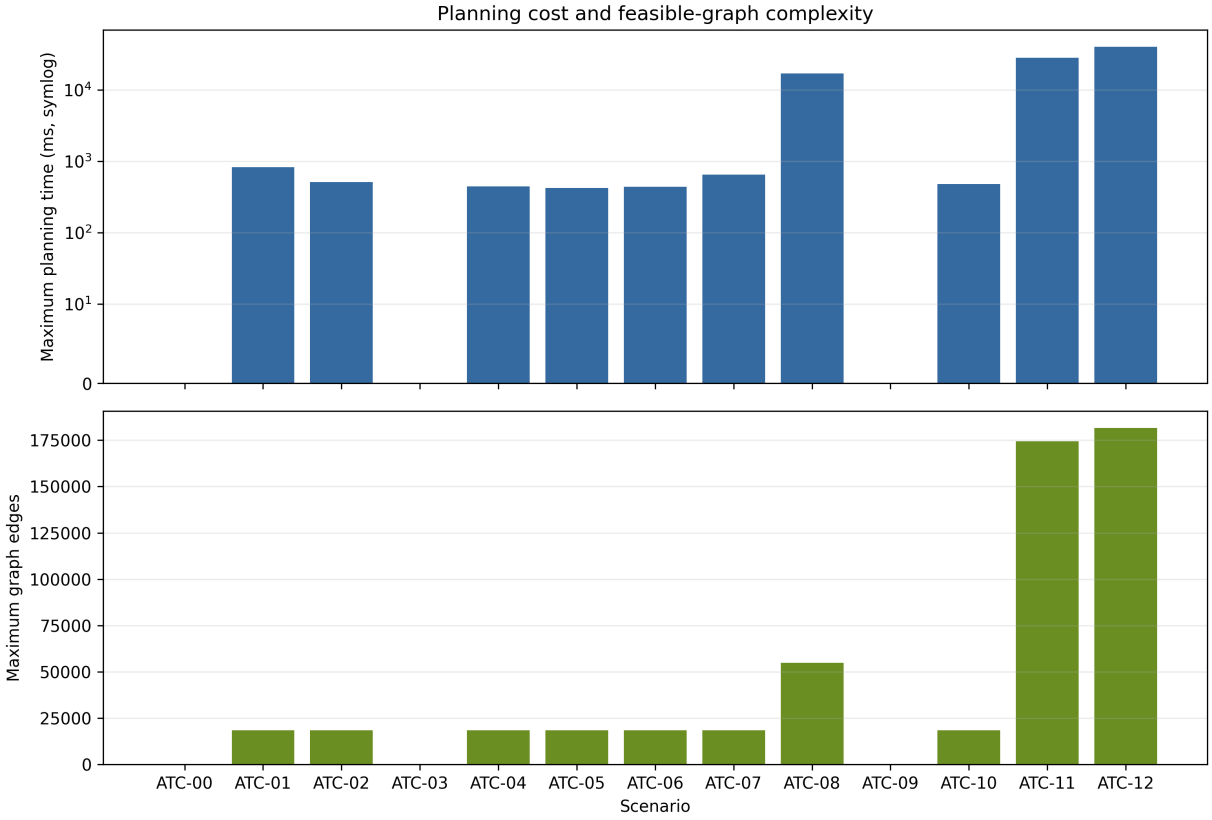


Figure 6 – Maximum planning time and feasible graph size.
Cases without a complete route require substantially larger graphs and longer searches than the nominal rerouting cases.

plete the intended validation of speed-based conflict resolution. ATC-07 exposed a post-plan safety-validation failure. ATC-09 did not record its expected monitoring state. ATC-08, ATC-11, and ATC-12 entered contingency without producing a temporary vector recovery action. Furthermore, most scenarios currently have only one run; live OpenSky traffic does not yet have a frozen replay, vertical separation, and climb/descent dynamics are outside the present model, and peak-memory Consumption was not measured.

Accordingly, the findings support the functional feasibility and auditability of the proposed approach, but they should not be interpreted as statistical validation or operational certification. The next evaluation stage should Repeat the scenarios under controlled seeds and frozen traffic snapshots, evaluate contingency-recovery strategies under explicit computational limits, and extend the safety model to vertical trajectory evolution.

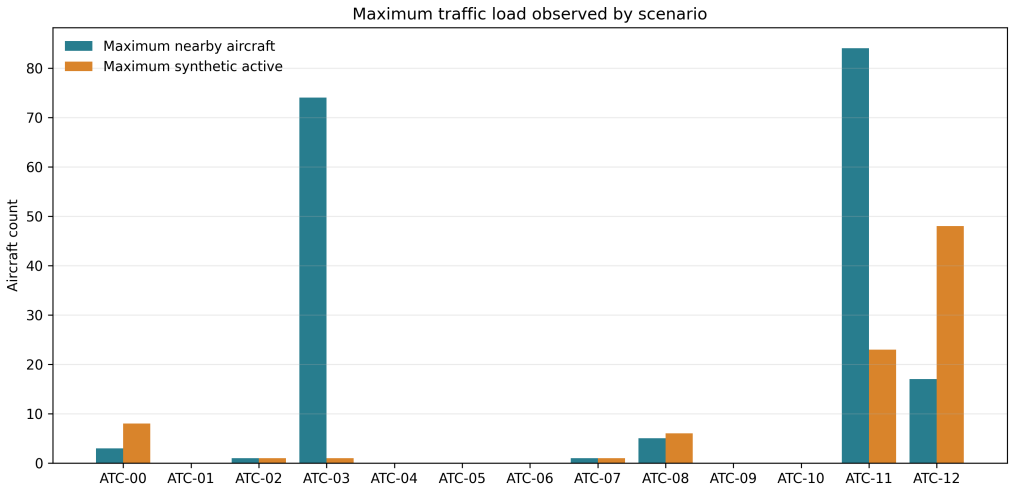


Figure 7 – Maximum traffic load observed by scenario. ATC-11 combines live OpenSky and synthetic traffic, whereas ATC-12 evaluates a controlled synthetic saturation condition.

4. Conclusion

This paper presented a semi-autonomous decision-support tool for tactical en-route rerouting under dynamic weather and traffic constraints. The proposed framework integrates the filed flight plan, the published ATS route network, SCW information and surveillance-derived traffic trajectories into a directed feasible graph. Complete rerouting recommendations are generated from this graph and continuously reassessed under a rolling-horizon strategy, while the air traffic controller remains responsible for the operational decision.

The experiments conducted in the SBGR–SBEG corridor demonstrated the main functional behaviors required by the proposed concept. The system avoided unnecessary rerouting in the no-threat baseline, generated a complete alternatives when future SCW intersections were detected, retained valid recommendations when candidate improvements were not operationally material, and safely rejoined the field route. The ATC-06 experiment was particularly relevant because it demonstrated that a recommendation initially considered feasible may become invalid during execution. After the SCW moved over the active reroute, the system detected the new intersection, invalidated the incumbent recommendation, and generated an updated route from the aircraft's current position.

The experiments also demonstrated that the absence of a feasible path is an important operational result. In the contingency and saturation cases, the system reported `NO_ROUTE` instead of publishing a recommendation that violated the active constraints. At the same time, the evaluation exposed limitations that must be addressed before operational use. These include the post-plan safety-validation failure observed in ATC-07, incomplete validation of speed-based conflict resolution, the computational cost of proving infeasibility in highly constrained graphs, and the absence of a complete recovery maneuver after contingency entry. Therefore, the present results support the functional feasibility and auditability of the approach, but do not constitute operational certification.

Future work will extend the evaluation beyond the Brazilian SBGR–SBEG corridor to more complex and highly interconnected airspace structures, particularly those found in Europe and the United States, allowing the assessment of scalability, computational performance, and recommendation stability under denser traffic and airway networks. Historical real-world Rerouting events will also be reconstructed using the operational context available at the time of the controller's decision, enabling comparison between the route recommended by the proposed system, and the clearance actually issued by ATC in terms of traveled distance, response time, and separation margins, route changes, airway usage, and operational interpretability. Additional developments will include reproducible OpenSky traffic replay, vertical-separation and climb/descent modeling, multiple simultaneous rerouting aircraft, explicit computational budgets, contingency-recovery strategies such as temporary vectors, and controller-in-the-loop experiments to assess acceptance, workload, trust, and practical integration into tactical ATC operations.

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