ActSoon: Intelligent Aircraft Taxiing Scheduling through Integrated Spatio-Temporal Visual Analytics

Luge Yang*
Sichuan University

Guoqiang Wang
Sichuan University
The Second Research Institute of the Civil Aviation Administration of China

Fengjie Wang
Hong Kong University of Science and Technology
Nanyang Technological University

Yimeng Wang
Sichuan University

Qipeng Wang
Sichuan University

Yong Wang
Nanyang Technological University

Xiaolin Wen†
Nanyang Technological University

Min Zhu‡
Sichuan University

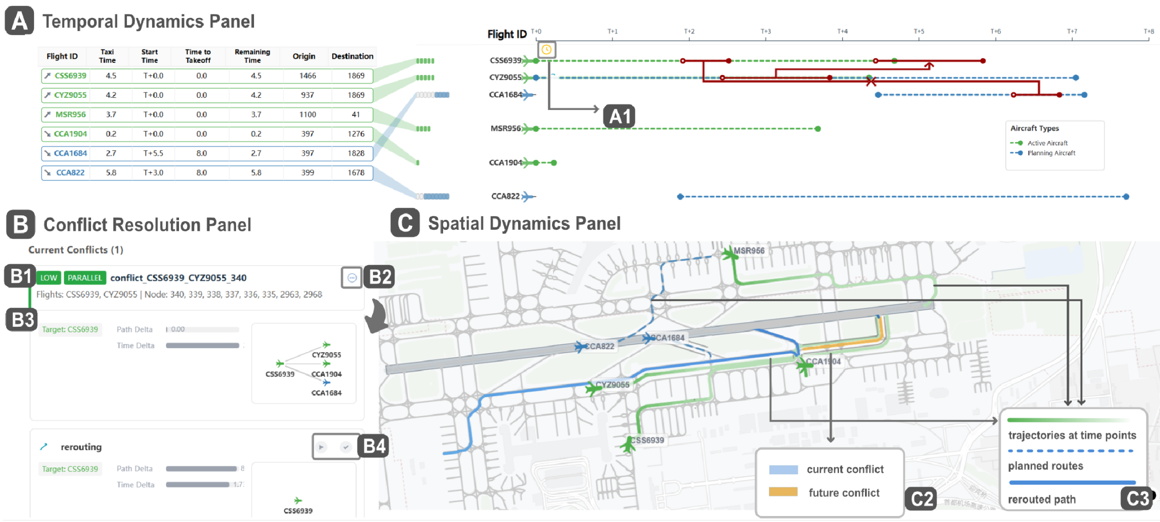

Figure 1: The interface of ActSoon consists of (A) a *Temporal Dynamics Panel* to visualize taxiing schedules and temporal progressions with embedded spatial context, (B) a *Conflict Resolution Panel* to present recommended conflict resolution strategies and impact evaluations, and (C) a *Spatial Dynamics Panel* to depict surface traffic and potential conflict points to provide holistic situational awareness.

Abstract

Aircraft taxiing scheduling involves the planning and control of aircraft movements between gates and runways, which is a critical component of airport operations. However, it remains challenging for controllers to continuously assess the dynamic traffic environment and rapidly anticipate the cascading effects of different response strategies during unexpected events to make timely and appropriate decisions. For example, when a potential conflict is detected, they need to have one of the aircraft wait or change its route. We present ActSoon, an intelligent interactive system that assists ground controllers in aircraft taxiing scheduling through integrated spatio-temporal visual analytics. Specifically, ActSoon provides two complementary views to support spatio-temporal reasoning, i.e., a *Temporal Dynamics Panel* that visualizes temporal taxiing and pushback movements while embedding spatial relationships via the arrangement and overlap of taxiways, and a *Spatial Dynamics Panel* that depicts spatial routes while also encoding their temporal evolution. Additionally, a *Conflict Resolution Panel* enables controllers to assess conflict-resolution strategies and their cascading effects through numeric indicators and a treemap. For evaluation, we conducted a case study and in-depth interviews with five ground controllers, and the results demonstrate the effectiveness and usefulness of ActSoon in supporting aircraft taxiing scheduling.

Index Terms: Aircraft Taxiing Scheduling, Visual Analysis, Conflict Detection, Decision Support

1 Introduction

Driven by rapidly growing demand for air transport, many major hub airports have approached or reached their operational capacity, resulting in increased pressure on ground movement management and subsequent flight delays [21, 19, 2]. Central to addressing this challenge is the optimization of **aircraft taxiing scheduling** [42], which determines when and how aircraft move on the ground between gates and runways during departures and arrivals [15]. In current practice, ground controllers execute this process in real time by issuing directives to pilots [32], determining taxi routes and pushback times based on pre-planned flight schedules, algorithm-suggested route options, and dynamic operational conditions. As conditions evolve, controllers continuously adjust their directives to maintain safe separation and resolve emerging conflicts through actions such as holding, rerouting, or adjusting taxi speeds. Fundamentally, this process can be abstracted as a network-constrained,

*e-mail: 2023223045184@stu.scu.edu.cn
†Corresponding author. e-mail: xiaolin004@e.ntu.edu.sg
‡Corresponding author. e-mail: zhumin@scu.edu.cn

dynamic multi-agent spatio-temporal routing and scheduling problem for multiple moving objects , where geographic network constraints and time-varying aircraft states are deeply coupled. Despite the critical role of ground controllers, their current workflow is cognitively demanding: they must piece together fragmented information sources, mentally simulate future spatio-temporal interactions, and rely on experience to assess the ripple effects of their interventions. This gives rise to two key challenges:

C1. Limited holistic awareness of evolving spatio-temporal dynamics. Aircraft taxiing scheduling is inherently a coupled spatio-temporal problem, where route selection (spatial decisions) and taxiing durations (temporal outcomes) mutually influence each other. Current commercial products (e.g., A-SMGCS) and traditional decision-support tools [30, 17] support basic situational awareness but present airport maps and flight schedules in fragmented, independent views, thereby increasing controllers' cognitive load. Although automated scheduling algorithms [3, 43, 6] and visualization techniques [18, 36] offer partial assistance, they fail to provide the integrated spatio-temporal awareness required for tightly coupled, human-in-the-loop operations. Effective decision support therefore requires tools that tailor automation to augment human reasoning rather than replace it. [38]

C2. Insufficient conflict detection, impact anticipation, and resolution support. Airport surface operations are complex and filled with uncertainties. Minor speed deviations can violate spatio-temporal constraints, manifesting as conflicts (i.e., following, head-on, and crossing) across locations and time scales. While detection methods exist [47, 41], dynamic operational uncertainties (e.g., speed fluctuations) make it challenging for controllers to readily perceive and track these conflicts within evolving traffic. Moreover, resolving conflicts requires evaluating cascading impacts across the broader spatio-temporal network rather than making local adjustments. Addressing these operational needs through a visual analytics lens introduces design challenges. Existing STVA approaches struggle to reconcile the tight coupling of spatial-temporal relations, represent continuous temporal evolution, and depict complex traffic conflicts across space and time. Therefore, practical support for such impact anticipation and decision-making remains limited, forcing controllers to rely primarily on mental simulation.

In this paper, we introduce ActSoon, an intelligent visual analytics system designed to augment ground controllers' decision-making in aircraft taxiing scheduling. We first conduct a formative study with air traffic management experts to identify operational pain points and derive six design goals. Guided by these goals, we propose two novel visual designs that integrate and present spatio-temporal dynamics (C1): a *Temporal Dynamics Panel* and a *Spatial Dynamics Panel*. The *Temporal Dynamics Panel* "spatializes" temporal schedules by layout-arranging timelines based on their relative spatial relationships. The *Spatial Dynamics Panel* "temporalizes" the spatial airport map by projecting continuous temporal trajectory projections onto the network topology. To support conflict detection and resolution (C2), ActSoon automatically identifies and highlights potential conflicts in these views and provides a *Conflict Resolution Panel* that enables users to inspect impact propagation and review recommended resolution strategies. We evaluate ActSoon through a case study and expert interviews with controllers, demonstrating its effectiveness and usability for assisting in aircraft taxiing scheduling. Our major contributions are as follows:

- Through a formative study with experts in air traffic management, we formulate the design requirements for aircraft taxiing scheduling, based on which we propose a novel, integrated visual analytics workflow.
- We propose ActSoon, an intelligent visual analytics system driven by a spatio-temporal integration method. It spatializes schedules in the *Temporal Dynamics Panel* by arranging them according to spatial relationships, and temporalizes the map in the *Spatial Dynamics Panel* by encoding trajectory evolution, thereby enabling ground controllers to intuitively monitor traffic and make informed decisions.
- We evaluate the effectiveness and usability of ActSoon through a case study and interviews with frontline ground controllers.

2 Related Work

This work is related to prior research on *automated aircraft ground taxiing scheduling* and *spatio-temporal visual analytics for traffic decision-making*.

2.1 Automated Aircraft Ground Taxiing Scheduling

Existing automated approaches in aircraft ground taxiing scheduling have evolved from *global path planning* and *dynamic control methods* toward intelligent, learning-based techniques [4, 11].

The first category focuses on pre-planned static paths using mathematical models [10] or heuristic algorithms [12, 6, 23] for global optimization. However, these deterministic frameworks often lack the responsiveness to handle real-world disruptions like unexpected delays [4]. To mitigate operational uncertainty, dynamic control methods monitor real-time traffic to detect conflicts and replan immediate movements [46, 7, 5]. Yet, these systems often evaluate local conflicts in isolation. They struggle to synthesize the multi-faceted, dynamic information characteristic of airport ground environments such as cascading delays across intersecting taxiways and varying aircraft taxi speeds. Recently, reinforcement learning and multi-agent methods have improved scheduling efficiency and adaptability [22, 11, 33]. Despite addressing key challenges like multi-aircraft coordination, their "black-box" decision-making obscures the underlying risk distribution and rationale, making it difficult for controllers to understand and trust the system.

Building upon these automated algorithms, we integrate real-time conflict resolution recommendations with visual analytics to contextualize spatio-temporal traffic dynamics, ultimately supporting transparent, human-centric decision-making.

2.2 spatio-temporal Visual Analytics for Traffic Decision-Making

spatio-temporal visual analytics is instrumental in traffic decision-making, with extensive applications in bus route planning [28, 36, 37], trip planning [44, 14], road traffic planning [13], and facility location [45]. Similarly, aircraft ground taxiing scheduling is a critical domain that benefits from these approaches.

One stream of research supports decision-making by revealing spatio-temporal traffic patterns. These tools aid comprehension but defer actual decisions to users. Approaches range from map-centered traffic overlays [27] to combined temporal–spatial views showing dynamic dependencies [1, 25, 39, 16]. Although some methods attempt to integrate spatial and temporal dimensions, they often rely on "one-way" or "loose" coupling. For instance, embedding discrete temporal glyphs in maps (e.g., [27]) fragments the continuity of timelines, while projecting spatial paths onto timeline charts (e.g., [1]) often discards critical geographical topology. Consequently, users must still constantly cross-reference disjointed views to map abstract schedules back onto physical layouts.

Another stream integrates decision-making into visual workflows. For example, systems like ShuttleVis [28], BNVA [36], and BRPVis [37] support bus route planning via multi-level visualizations. TriPlan [44] and CT3 [14] enable flexible itinerary design, while TraSculptor [13] assesses roads. These systems cover the "intelligence-design-choice" stages of decision-making [31], supporting problem identification and solution generation. However, they often rely on static snapshots or post-hoc diagnostic paradigms (as seen in [34]), offering limited support for maintaining holistic awareness of rapidly evolving spatio-temporal dynamics.

To this end, we introduce a bidirectional integration design that mutually embeds spatial and temporal dimensions within each other's visual representation. Tailored to the safety-critical constraints of airport taxiing, this approach synthesizes temporal separations and spatial bottlenecks into a unified interface. By combining predictive simulation with optimized recommendations, our framework enables operators to preview cascading impacts and make proactive, context-aware decisions.

3 FORMATIVE STUDY

To inform our design, we conducted semi-structured interviews with domain experts in aircraft taxiing scheduling, identifying key workflow challenges of ground controllers and deriving corresponding design goals.

3.1 Interviewees

All the experts (denoted as E1, E2, E3) are affiliated with a civil aviation research institute and specialize in Air Traffic Management, possessing over five years of professional experience in the domain. E1, a co-author of this study, is a senior researcher with 15 years of experience in airport surface operation control and has participated in the surface operation design for multiple large-scale airports. E2 has extensive experience in the research and development of the Advanced Surface Movement Guidance and Control System, and E3 specializes in airport surface conflict detection systems.

3.2 Procedure

We conducted one-on-one online interviews with each expert after obtaining informed consent, with each session lasting approximately 45 minutes. Each interview was structured into three parts: (1) understanding the participant's professional background and daily responsibilities in airport surface operations; (2) identifying pain points and bottlenecks encountered in current aircraft taxiing scheduling workflows; and (3) envisioning potential improvements and desired capabilities for intelligent decision support tools.

All sessions were audio-recorded and transcribed. We analyzed the transcripts using thematic analysis [8, 26], iteratively coding and grouping recurring challenges into overarching themes that directly informed our design goals.

3.3 Findings

We summarize the experts' feedback into key operational challenges, focusing on the taxiing workflow and three conflict types.

Workflow of aircraft taxiing scheduling. Based on the collected feedback, the ground scheduling process comprises three core tasks: (1) Situation Monitoring: Controllers must maintain constant awareness of the evolving operational environment. This entails tracking dynamic aircraft states (e.g., position, speed) against designated routes, and monitoring critical resources (runways, taxiways, stands) to detect deviations or emerging constraints. (2) Pushback Decision: For every flight, controllers determine specific taxi routes and assign departure pushback times, grounding these decisions in flight schedules and real-time ground conditions. (3) Conflict Resolution: Triggered by potential conflicts or sudden state changes, this reactive task requires controllers to rapidly evaluate situations and formulate resolution strategies by analyzing the systemic impacts of potential adjustments. To ensure safe separation, primary options involve replanning the taxi route to bypass the area or implementing temporary delays (e.g., holding).

Executing these iterative tasks with current fragmented tools, such as separate radar screens and tabular schedules, is cognitively demanding. Experts highlighted that mentally aligning disjointed spatial and temporal data is highly error-prone, emphasizing the need for a unified platform that seamlessly links spatial routes, temporal schedules, and conflict alerts. This consensus directly motivates our coordinated multi-view design and shapes the design goals detailed in Section 3.4.

Conflict Types. Experts defined conflicts as scenarios where aircraft compete for spatio-temporal resources, breaching safety standards. Three primary patterns were identified: Following Conflict, where a trailing aircraft approaches a leader; Head-on Conflict, involving opposite movements on the same path; and Crossing Conflict, where aircraft routing paths converge at an intersection with close arrival times.

3.4 Design Goals

Guided by the identified challenges, we formulate two overarching design principles that guide our system design. First, responding to the limited holistic awareness in **C1**, we propose *Spatio-Temporal Structural Alignment*, bridging disjoint dimensions by spatializing temporal schedules and temporalizing spatial maps. Second, to target the insufficient decision support in **C2**, we introduce *Prospective Action-Impact Coupling*, which projects cascading consequences of adjustments, transforming error-prone mental simulation into an interactive, forward-looking process. Together, these principles serve as the conceptual foundation, directly shaping and organizing our specific design goals (**G1**–**G6**).

G1: Contextualize Temporal Dimension with Spatial Dynamics. Aircraft taxiing scheduling requires constant monitoring of dynamic spatio-temporal traffic (**E1-E3**). Currently, controllers must mentally bridge static spatial snapshots with detached temporal schedules. To reduce this burden, the system should fuse spatial layouts with temporal progressions, enhancing holistic awareness of evolving spatio-temporal dynamics (**E2**, **E3**) and facilitating schedule judgment (**E1**).

G2: Overlay Planning Outcomes onto Dynamic Surface Situations. Blindly following algorithm-recommended schedules or routes is insufficient (**E1-E3**). Controllers currently perform demanding mental simulations to envision how planned aircraft will interact with ongoing traffic. To bridge this gap, the system must visually integrate planned aircraft into the real-time surface situation, reducing cognitive load.

G3: Facilitate Detailed Verification for Imminently Scheduled Aircraft. For aircraft approaching their scheduled times, controllers must verify operational readiness (**E1-E3**). This includes checking planned times, routes, gates, and runways for both departures and arrivals. The system must clearly present these comprehensive, context-specific attributes, ensuring immediate access to necessary data for individual upcoming flights.

G4: Enable Interactive Pushback Adjustment with Situation Preview. When surface situations change, controllers frequently adjust departure pushback times to mitigate conflicts or reduce wait times (**E2**). To support proactive management, the system must allow users to interactively modify pushback schedules and seamlessly preview the resulting traffic situation.

G5: Support Rapid Detection and Analysis of Potential Conflicts. Monitoring conflicts in dynamic environments is cognitively demanding and time-critical (**E1-E3**). The system must support early detection and assist users in analyzing conflict types and severity. Crucially, it should incorporate uncertainty into the detection mechanism to provide robust safety margins, moving beyond immediate, short-sighted assessments (**E1**).

G6: Facilitate Conflict Resolution with Impact Assessment. To accelerate decision-making, the system should recommend optimal conflict resolution strategies (**E1-E3**). Since resolving a single conflict can cause cascading delays or trigger new conflicts (**E2**, **E3**), the system must support detailed impact analysis for different strategies. Furthermore, it must allow controllers to simulate and preview a solution's global outcome before application.

In summary, these six design goals (**G1**–**G6**) are systematically anchored in our two core design principles, collectively reinforcing the system's decision-support capabilities. Specifically, *DP1* (*Spatio-Temporal Structural Alignment*) shapes how the system visually unifies disjoint dimensions, guiding the contextualization of temporal schedules within spatial layouts (**G1**), the overlay of planning outcomes onto live surface situations (**G2**), and the verification of imminent flights (**G3**). Conversely, *DP2* (*Prospective Action-Impact Coupling*) establishes the forward-looking interactive mechanisms, empowering controllers to adjust pushback times with instant previews (**G4**), analyze potential taxi conflicts (**G5**), and assess the cascading impacts of resolution strategies before application (**G6**). This explicit mapping provides a structured foundation that directly guides the visualization design and system implementation in the following sections.

4 Simulation Framework for Aircraft Ground Taxiing

Due to restricted access to live airport data, we developed a custom simulation framework grounded in real-world flight statistics to generate the realistic trajectory and event data driving our visual system. The routing and conflict algorithms serve as backend infrastructure to support our visualization, rather than standalone algorithmic contributions.

To support the workflow in Section 3.3, our backend simulation is structured into two functional modules, each corresponding to a core scheduling task. Specifically, Simulation and Route Optimization (Section 4.2) simulates real-time taxiing states for ongoing *Situation Monitoring*, generating optimized baseline trajectories that establish proactive schedules for *Pushback Decision*. Conflict Risk Assessment Section 4.3 identifies potential risks using a probabilistic model to facilitate real-time *Conflict Resolution*.

4.1 Data Description

Our system utilizes two data categories: airport roadway networks and aircraft schedules. (1) Roadway Network: To faithfully simulate the surface environment, we constructed a topological representation of Beijing Capital International Airport (PEK) using open-source data. The network comprises 2,084 nodes, 3,033 taxiway segments, and 3 runways, providing the structural foundation for routing and simulation. (2) Aircraft Schedules: We collected 1,107 historical flight records from November 2, 2023. Each record contains key operational attributes, including flight ID, aircraft type, assigned gate, runway gate, and scheduled times, which serve as initial constraints for generating taxiing trajectories.

4.2 Simulation and Route Optimization

Due to the lack of direct access to real-time airport operational data streams, we developed a simulation environment to generate the requisite trajectory and event data. To simplify the kinematic model while maintaining realism, aircraft are assumed to taxi at constant speeds, randomized within standard operational limits.

To facilitate the generation of schedules and routes for upcoming flights (**G3**), we implement route optimization through a Dual-Layer Spatio-temporal Optimizer[24], which tackles the problem with a hierarchical structure: the upper layer handles route allocation, and the lower layer manages temporal scheduling. An Iterated Neighborhood Search (INS) algorithm [29] iteratively refines the solution. The optimization objective is to minimize a comprehensive cost consisting of taxi distance, departure delay, and conflict penalties. For the set of optimized flights S, the global objective function is defined as:

$$J(S) = c\sum_{f\in S} L_f(P_f) + \sum_{f\in S}\max(0, s_f - s_f^0) + \alpha\sum_{n\in V}\Bigg(\sum_{\{f,g\}\in\mathscr{C}(S)} I_{f,g,n} + 1.5\sum_{(f,p)\in\mathscr{C}_P} I_{f,p,n} + 2\sum_{(f,a)\in\mathscr{C}_A} I_{f,a,n}\Bigg). \quad (1)$$

The first term represents total taxi distance, the second term penalizes any departure delay, and the remaining terms represent conflict penalties between the optimized flights.

4.3 Conflict Risk Assessment

In response to **G5** , we propose a probabilistic assessment model to quantitatively assess conflict risks during taxiing. Given that taxiing is subject to potential speed fluctuations and unexpected disruptions, we prioritize safety by moving beyond deterministic snapshots. Unlike traditional methods that focus solely on immediate, deterministic states, this model accounts for the operational variability highlighted by the experts. Following experts' insights on realistic taxiing dynamics, we define a feasible speed range $[v_{\min}, v_{\max}]$ anchored to the instantaneous velocity v of each aircraft. Based on this range, we derive a *temporal occupancy interval* $[t_{\text{in}}(x), t_{\text{out}}(x)]$ for each aircraft at a potential conflict point x, representing the earliest possible arrival time and the latest possible departure time at that location. Let $I(x)$ denote the temporal intersection (overlap duration) between the occupancy intervals of two aircraft at position x, and let $U(x)$ denote their temporal union (total exposure duration). The **conflict probability** is defined as the ratio between the overlap duration and the total exposure duration:

$$P(x) = \frac{I(x)}{U(x)} = \frac{\max\left(0,\ \min\left(t_{\text{out}}^A(x), t_{\text{out}}^B(x)\right) - \max\left(t_{\text{in}}^A(x), t_{\text{in}}^B(x)\right)\right)}{\left(t_{\text{out}}^A(x) - t_{\text{in}}^A(x)\right) + \left(t_{\text{out}}^B(x) - t_{\text{in}}^B(x)\right) - I(x)} \quad (2)$$

where $t_{in}^k(x)$ and $t_{out}^k(x)$ denote the earliest arrival time and latest departure time of aircraft $k \in \{A, B\}$ at conflict point x under the feasible speed range, respectively. This formulation ensures $P(x) \in [0,1]$, where $P(x) = 0$ indicates complete temporal separation (no conflict risk) and $P(x) = 1$ indicates full temporal overlap (maximum conflict risk).

Based on this formulation, we assess conflict severity (classified as High, Medium, or Low) using the conflict type, the peak conflict probability $P_{\max} = \max_x P(x)$, and the estimated time to conflict, facilitating subsequent decision support.

To validate our simulation's operational realism, domain experts qualitatively reviewed a sample of generated trajectories and conflict scenarios. They confirmed that simulated movements and bottleneck dynamics capture essential real-world characteristics, demonstrating operational plausibility for decision support. Nonetheless, we acknowledge that our model simplifies certain micro-level real-world dynamics, such as variable pilot speed profiles and communication latencies.

5 ActSoon

As illustrated in Figure 1, ActSoon coordinates three views to address our design goals through the workflow in Section 3.3: **The *Temporal Dynamics Panel* (A)** handles temporal scheduling and path validation (*Pushback Decision*), embedding spatial context for spatio-temporal reasoning (**G1**, **G2**) and interactive adjustments (**G3**, **G4**) (*Situation Monitering*). **The *Spatial Dynamics Panel* (C)** monitors conflict detection (**G1–G3**), projecting temporal progressions onto spatial trajectories(**G5**) (*Situation Monitering* and *Conflict Resolution*). **The *Conflict Resolution Panel* (B)** facilitates conflict resolution and impact assessment by presenting strategy cards with global previews (**G6**) to assess severity and prevent cascading delays (**G5**) (*Conflict Resolution*).

5.1 *Temporal Dynamics Panel*

The *Temporal Dynamics Panel* (as shown in Figure 2) comprises a time schedule (A), a time slider (C), and a timeline (D). It visualizes the taxiing schedule while **integrating spatial relationships into a temporal layout**, allowing users to perceive potential spatial interactions directly along the timeline for aircraft that are currently taxiing or scheduled to begin taxiing within a certain period (typically a window of 10 minutes). Through this representation, users can continuously monitor the real-time situations and spatio-temporal states of aircraft (*Situation Monitoring*) to make informed and timely pushback decisions (*Pushback Decisions*).

To facilitate detailed verification for imminently scheduled aircraft (**G3**), the time schedule (Figure 2 (A)) presents comprehensive attributes (e.g., aircraft ID, expected departure time, origin and destination) for upcoming departures and arrivals. We distinguish between aircraft statuses using color coding: blue represents **pending flights** (planned but not yet taxiing), while green indicates **active flights** (currently taxiing). This color mapping is consistent throughout the entire system. An icon to the left of the aircraft ID distinguishes departure and arrival flights(Figure 2 (A1)).

The timeline visualizes the aircraft in different rows, with time progressing from left to right (Figure 2 (D)). The starting point of the timeline always represents the current time. As shown in the legend of Figure 2 (D2),the taxiing timeline is visualized with a green dashed line for taxiing aircraft and a blue dashed line for scheduled aircraft. For scheduled aircraft, we display their estimated start and end taxiing times. For taxiing aircraft, we show the estimated remaining time until they complete taxiing.

Unlike arriving aircraft immediately routed to the apron, departing flights require flexible taxi start times to meet runway schedules. To support interactive pushback adjustment with situation preview (**G4**), we designed a time slider (Figure 2 (C, E)). The slider positions encode the estimated taxi duration relative to the scheduled departure window. Controllers can drag the slider to adjust taxi start times at a one-minute resolution (arrivals remain locked as ground controllers do not dictate landing times), or perform direct numeric inputs. These adjustments instantly update predicted traffic across the timeline, enabling proactive conflict management.

To support conflict detection (**G5**) and spatial awareness (**G1**), we vertically arrange aircraft using a graph-based layout. We construct a graph where edges represent spatio-temporal overlaps and weights capture conflict intensity. A two-level sequencing strategy then orders aircraft: at the macro level, independent conflict clusters (connected components) are prioritized by aggregate severity; at the micro level, a greedy algorithm sequences flights within each cluster to place strongly associated neighbors adjacently. Correspondingly, vertical spacing dynamically scales with conflict intensity, placing tightly coupled flights in close proximity while separating unrelated clusters with wider gaps (Figure 2 D1). To handle high traffic volumes, scrollable views are provided, pinning high-priority or conflicted aircraft to the top to preserve situational awareness.

To support controllers' focus on conflict timing and locations (**G5**), we visualize three types of spatio-temporal conflicts (following, head-on, and crossing identified in 3.3). **Alternative Design Considerations.** During our iterative design, we initially considered mapping conflict probability to color gradients. However, expert feedback revealed that this approach caused severe visual clutter and failed to clearly communicate conflict types, timing, or precise locations. Consequently, we abandoned color-coded probability in favor of distinct structural metaphors. As shown in Figure 2 (F), a potential conflict is flagged whenever two aircraft share a spatial intersection within a temporal safety buffer. We represent these spatial overlaps using three visual metaphors: a single directed arrow for following conflicts showing sequence; two opposing arrows for converging head-on conflicts (Figure 2 F2); and an intersecting semi-circle for crossing conflicts depicting the taxiway junction (Figure 2 F3). This structural mapping ensures that critical spatial intersections remain distinct even without direct schedule overlap, aligning with conservative real-world safety margins.

We added connecting bands between corresponding aircraft entries in the table and the timeline (Figure 2 (C)), allowing users to intuitively perceive the correlation between temporal dynamics and spatial relationships (**G1**).

5.2 *Spatial Dynamics Panel*

To complement the *Temporal Dynamics Panel* and address the core challenge of contextualizing temporal dimensions with spatial dynamics (**G1**), the *Spatial Dynamics Panel* provides a geographically faithful representation of ground taxiing while embedding critical temporal data directly into the spatial layout. This design allows users to continuously perform *Situation Monitoring* by analyzing the spatio-temporal states of multiple aircraft simultaneously. As shown in (Figure 1 (C3)), to distinguish different operational states, scheduled aircraft are denoted by dashed lines in the corresponding color, whereas currently taxiing aircraft utilize solid lines in shades of green. Crucially, to bridge the cognitive gap between space and time, the color intensity of each segment reflects temporal proximity: darker green segments indicate immediate positions, fading to lighter green for future locations. This encoding serves as an intuitive cue for potential route conflicts, as intersecting trajectories displayed in similar color intensities signal a high probability of collision. Furthermore, to support the rapid detection and analysis of potential conflicts (**G5**), we overlay a "risk ribbon" along the taxiway surface (Figure 1 (C2)). The width of this ribbon dynamically encodes the likelihood of a conflict occurring at that specific point, as calculated in Section 4.3, visually directing ground controllers' attention to these high-risk areas. To facilitate exploration, users can pan and zoom the map to inspect the global traffic situation or focus on specific aircraft and their potential interactions.

To assist controllers in prioritizing immediate threats over future ones, these potential conflicts are color-coded: prominent orange ribbons highlight risks involving currently taxiing aircraft, while blue ribbons indicate potential conflicts between aircraft that have not yet started taxiing.

5.3 *Conflict Resolution Panel*

Designed to support the rapid analysis of potential conflicts (**G5**) and facilitate conflict resolution with impact assessment (**G6**), the *Conflict Resolution Panel* serves as a dedicated decision-support interface to achieve conflict resolution (*Conflict Resolution*). Specifically, upon detecting a potential conflict, the system immediately contextualizes the threat by displaying its severity level, type, involved aircraft, and taxiway locations (Figure 1 (B1)). This direct presentation of conflict attributes aids users in quickly gauging the urgency of the situation (**G5**). Beyond mere detection, the view directly addresses the need for rapid decision-making (**G6**) by generating recommended resolutions, such as modifying a route or instructing an aircraft to hold. To enable controllers to select the optimal strategy that balances safety with efficiency, each resolution is presented as a card-based summary containing key evaluation metrics (Figure 1 (B3)). Visual bar (Figure 1 (B5)) encodings quantify the cost of each solution, such as the additional route length or time delay required for the rerouted aircraft. Crucially, to help users mitigate cascading delays (**G6**), each card features an impact diagram (Figure 1 (B6)) that visualizes the potential downstream effects of the solution on other aircraft. In the view, aircraft are color-coded consistently with other views, and the width of connecting lines encodes the magnitude of the impact, allowing controllers to preview the global consequences of a local resolution before applying.

Users can interact with solution cards to preview simulated outcomes or apply resolutions directly. Activating a simulation triggers a synchronized update across both views to project potential impacts. In the *Temporal Dynamics Panel*, the aircraft's original schedule is rendered semi-transparently alongside the simulated timeline to facilitate comparison, with directional links indicating cascading propagation effects (Figure 1 (A2)). Simultaneously, the *Spatial Dynamics Panel* overlays the new predicted trajectory onto the airport layout to verify spatial feasibility (Figure 1 (C3)).

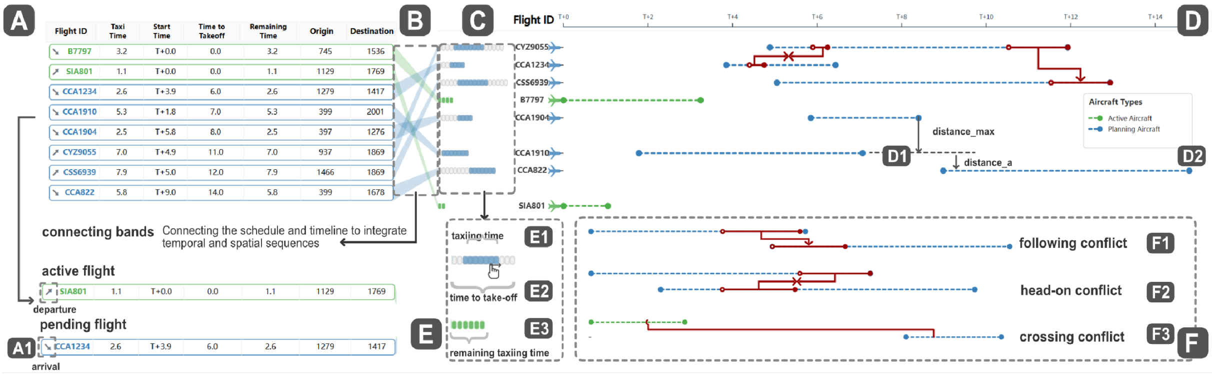

Figure 2: **Visual design of the *Temporal Dynamics Panel***: (A) a time schedule, (B) connecting bands, (C) a time slider, (D) a timeline, aircraft separation (D1), and the legend (D2), (E) the encoding of time slider and (F) to show three types of conflict encoding, following conflict (F1), head-on conflict (F2) and crossing conflict (F3).

6 Case Study

To evaluate how ActSoon supports systemic decision-making in high-density operations, we conducted a case study with U1, a senior air traffic controller, analyzing a rush hour window with 14 active flights (Figure 3). It demonstrates how a localized schedule adjustment propagates downstream risks, and how ActSoon helps controllers visualize, simulate, and resolve cascading conflicts.

Phase I: Localized Multi-Aircraft Conflict Resolution. Initially, active arrival and departure streams converge near the central runway (Figure 3 (B1)). The predictive engine flags an upcoming, complex conflict corridor on the timeline in *Temporal Dynamics Panel* (Figure 3 (A1)), primarily involving departing flight MSR956 and arriving flight CCA1910, with secondary pressure from CCA822 and SIA801. The opposing arrows suggest a potential head-on conflict, which is a relatively risky type. U1 intervenes by advancing MSR956's start time by 2.5 minutes on the timeline. The system dynamically updates (Figure 3 (A2)(B2)): **MSR956** clears the critical intersections earlier, significantly reducing its conflict probability with **CCA1910** and dispersing the spatial bottleneck around the central runway corridor. Several new potential conflicts are emerging, but none are pressing(Figure 3 (B3)).

Phase II: Cascading Risk Propagation.

However, ground transit is highly coupled; local changes propagate across the spatio-temporal network. As traffic flows progress, ActSoon recalculates trajectories. Advancing MSR956 shifts its downstream occupancy, compressing available buffer times for other flights including CCA1910, and SIA801. This shift creates a secondary bottleneck (Figure 3 (A3, B4, B5)), generating new overlapping timeline projections and spatial warning bands.

Phase III: Multi-Criteria Trade-offs and Simulation. Subsequently, the cascading effect triggers a major head-on conflict between CCA1910 and MSR956, and a parallel conflict between MSR956 and SIA801(Figure 3 (C1)). After prioritizing the more urgent conflicts, instead of forcing manual, high-pressure calculations, ActSoon generates optimized alternatives in *Conflict Resolution Panel* (Figure 3 (C2)): **Option 1 (Waiting/Holding)** holds MSR956 temporarily to let CCA1910 pass; while simple (Path Delta = 0.00), the impact graph reveals a significant time delay that propagates downstream, queuing trailing departures (SIA801, CCA822, CCA975) and degrading runway throughput. In contrast, **Option 2 (Rerouting)** reroutes CCA1910 via an alternative segment, completely eliminating the head-on conflict, bypassing the parallel bottleneck, and keeping downstream runway queues clear despite minor path deviation. U1 utilizes interactive simulation to preview Option 2's spatial-temporal outcomes (Figure 3 (B6)). The system projects the rerouted **CCA1910** (blue). The preview confirms perfect separation and a balanced network load, with no secondary conflicts.

7 Expert Interview

We conducted semi-structured interviews with 5 airport ground controllers to assess the effectiveness and usability of our system. Specifically, we asked these controllers to use ActSoon to simulate aircraft taxi scheduling and collected their feedback for the system. Due to the proprietary nature of operational ground control systems and the absence of publicly available benchmarks for taxiing scheduling, direct comparative experiments with deployed solutions were not feasible. This section begins by outlining the experimental design, including participants' background, interview procedure, and tasks, and concludes with a summary of the feedback obtained from the participants.

7.1 Participants

We recruited five target users (denoted as U1-U5) through social media platforms to join our interview (2 female and 3 male, $Age_{mean} = 27.60$, $Age_{sd} = 0.8$). All participants are experienced ground controllers with 4 to 5 years of experience at major international airports with high traffic volumes. They are responsible for managing complex high-intensity flight operations, including takeoffs, landings, and airport surface movement.

7.2 Task and Data

As detailed in Section 4.1, we utilized the real-world flight schedule data from Beijing Capital International Airport (PEK) for the year 2023 to construct realistic scenarios for our interviews. The dataset reflects an hourly landing and takeoff rate of approximately 50, consistent with the peak-hour operational capacity reported for major hub airports in recent studies [35]. This alignment with real-world traffic intensity ensures the practical relevance of our setup.

Specifically, we extracted two segments from the full dataset, each containing 30 consecutive flight records. The first segment served as a tutorial for participant training, while the second was used in the formal task, where participants utilized ActSoon to simulate real-world aircraft taxiing scheduling. To illustrate, this formal task segment spanned a roughly 42-minute window on November 2, 2023 (07:01:26 to 07:43:59), comprising 16 arriving and 14 departing flights.

We asked participants to schedule aircraft to minimize transit times while proactively detecting and resolving conflicts. To experience the workflow of ActSoon, they followed a structured protocol: identifying spatio-temporal conflicts across coordinated views, adjusting timelines, and evaluating simulated recommendations.

7.3 Procedure

After obtaining informed consent, we conducted online user studies via virtual meeting platforms. Although participants accessed ActSoon on individual laptops rather than actual multi-monitor control tower setups, this environment deliberately focused their attention

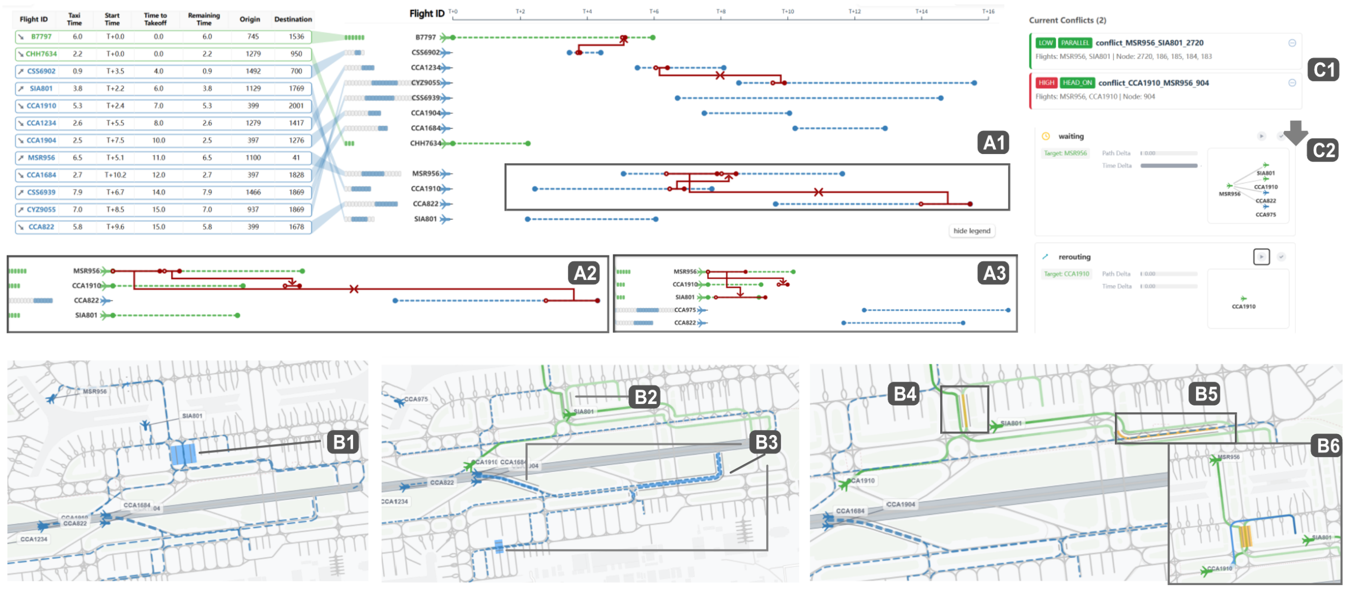

Figure 3: The continuous case study of cascading taxiing conflict detection and resolution in ActSoon: (A1–A3) Temporal evolution in *Temporal Dynamics Panel*: the initial bottleneck (A1), schedule update after advancing MSR956 (A2), and the downstream cascading state during final resolution (A3). (B1) Initial spatial layout in *Spatial Dynamics Panel* with flights converging near the central runway. (B2, B3) Downstream propagation where the local adjustment shifts traffic pressure and compresses buffer times. (B4–B6) Simulation preview of rerouting CCA1910, showing clear physical separation for MSR956 (green), SIA801 (light green), and CCA1910 (blue). (C1, C2) Decision support in *Conflict Resolution Panel* listing current conflicts (C1) and presenting optimization cards (C2) with global impact previews.

on evaluating the core visual encodings and workflow. The session began with a briefing on system features, followed by a 15-minute training phase using tutorial data. Participants then spent approximately 15 minutes completing the evaluation tasks. Subsequently, they completed a 16-item questionnaire (Figure 4) adapted from prior studies [40, 9]: Q1–Q6 assessed task-specific workflow effectiveness; Q7–Q10 evaluated detailed visual designs and interactions; Q11–Q14 measured usability using the UMUX scale [20] (with Q13 and Q14 reverse-coded); and Q15–Q16 collected open-ended feedback on system strengths and limitations. Each session lasted approximately 60 minutes, and participants were compensated $15/hour. All data were anonymized.

7.4 Results

We summarize the participants' responses to the questionnaire in Figure 4. Overall, the system received positive feedback from the participants. The majority of participants consistently agreed that the system was highly effective in supporting aircraft ground taxi scheduling, providing intuitive visual aids that streamline the decision-making process for ground controllers. Additionally, they all expressed willingness to use this system in their future work. Detailed feedback from the participants is summarized as follows. (Detailed representative qualitative quotes are compiled in Section A of the Supplementary Material.)

Workflow Effectiveness. As illustrated in Figure 4, the consistently positive ratings for Q1 through Q6 demonstrate the system's effectiveness in supporting taxiing decisions. Participants highly praised the system's proactive capabilities, noting that the predictive visualizations and automated recommendations successfully help controllers anticipate conflicts and reduce the cognitive workload compared to traditional multi-screen configurations (U1, U3, U4). While the feedback was largely enthusiastic, U2 raised a caution regarding scalability under extreme peak hours (Q5), suggesting that time and cognitive resources to evaluate multiple recommended options might be limited during high-density operations. Nevertheless, ActSoon successfully enabled all participants to rapidly identify and resolve unexpected conflict events.

Visual Design and Interactions. Feedback on the visual design was positive (Q7–Q10), with almost all ratings exceeding the neutral threshold. Specific components received detailed praise: participants found the *Spatial Dynamics Panel*'s spatial trajectories and dynamic conflict ribbons highly intuitive for immediate conflict localization (U1, U3). The *Temporal Dynamics Panel* was highlighted as an coordination tool for sequencing (U2). For the *Conflict Resolution Panel*, participants appreciated its rich metadata (U3) but offered improvements, such as overlaying the comparative impact diagrams onto the geographic map (U3) and simplifying the selection workflow to directly present key options (U5).

Usability. Overall, participants confirmed that ActSoon met their operational needs (Q11) and was intuitive and easy to learn without external manuals (Q12–Q14), reducing the manual thinking time required for routine coordination (U2, U4, U5).

Improvements. Participants suggested prioritizing spatial map cues over the time-centric *Temporal Dynamics Panel* to better match controllers' workflows (U4), allowing manual aircraft priority weighting to increase decision flexibility (U1), and adopting a radar-aligned "dark mode" to enhance visual ergonomics (U2). Furthermore, to prevent change blindness under high-pressure scenarios, future designs must enhance transition feedback, as visual differences before and after applying a strategy in *Spatial Dynamics Panel* and *Temporal Dynamics Panel* can sometimes be subtle.

8 Discussion

In this section, we further discuss the lessons we learned in Section 8.1, following by limitations and future work in Section 8.2.

8.1 Lessons Learned

Cognitive Lightness over Functional Completeness. Real-time decision support in high-pressure environments must prioritize cognitive lightness over functional completeness. While conventional interfaces offer granular control through complex parameters, our

Workflow Effectiveness:
Q1. I can determine an appropriate pushback time based on ActSoon.
Q2. I can identify potential conflicts using ActSoon.
Q3. I can effectively resolve conflicts using ActSoon.
Q4. I find the recommended solutions provided in ActSoon to be effective.
Q5. I can analyze the potential impacts of a solution using ActSoon.
Q6. This system aids me in decision-making for aircraft ground taxiing scheduling
Visual Design and Interactions:
Q7. The visual design of the temporal dynamics panel is intuitive.
Q8. The visual design of the spatial dynamics panel is intuitive.
Q9. The visual design of the conflict resolution panel is intuitive.
Q10. The interactions are smooth and easy to use.
Usability:
Q11. The system's functionality meets my needs well.
Q12. The system is good to use.
Q13. The system's user experience is poor and frustrating.
Q14. I need to spend excessive time correcting errors on this system.
Open-ended Questions:
Q15. What are the advantages and disadvantages of the system?
Q16. How can the system be improved in the future?

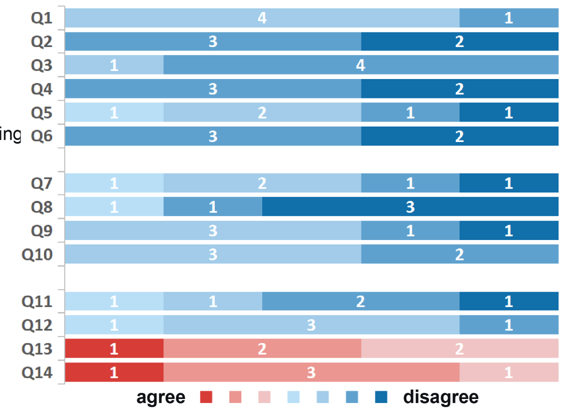

Figure 4: The results of the questionnaire in the user interview. Q1-Q14 are close-ended questions designed to evaluate the workflow effectiveness (Q1-Q6), visual design and interactions (Q7-Q10), and usability (Q11-Q14) of ActSoon. Q15-Q16 are open-ended questions to gain the pros and cons of ActSoon from participants. Q1-Q14 should be rated by 1-7, representing "strongly disagree" to "strongly agree" on each statement. The number of participants on each rating is represented by a horizontally stacked bar chart.

formative study indicated that such complexity overwhelms controllers. Consequently, we streamlined ActSoon by hiding secondary variables (e.g., precise taxi speeds and cost weights), presenting only critical conflicts alongside curated candidate solutions. User evaluation validated this design, confirming that reduced complexity freed cognitive resources for critical decision-making. Broadly, this suggests that time-critical systems should focus on distilling information to facilitate rapid, confident choices rather than maximizing user options.

Blending Spatial and Temporal Information. A core challenge in STVA is integrating geographic network topologies with continuous temporal schedules. To support controllers' dual need for spatial anchoring and temporal projection, we adopt a bidirectional integration approach, mutually embedding temporal cues in the *Spatial Dynamics Panel* and spatial relationships in the *Temporal Dynamics Panel*. Coupled with cross-view linking, this design reduces cognitive view-switching: experts successfully anchored immediate conflict detection in the spatial view while reserving the temporal view for sequencing. Ultimately, tightly integrated encodings that support at-a-glance reasoning outperform isolated, side-by-side designs in safety-critical tasks. Beyond airport taxiing, this bidirectional integration offers a reusable design pattern for other network-constrained trajectory domains, such as drone delivery, train scheduling, and logistics routing.

Collaborative Workflow Between Automation and Human. ActSoon demonstrates that effective decision support relies on a clear division of labor: algorithms handle structured computation (routing, conflict detection, recommendation), while controllers apply contextual judgment to evaluate and select resolutions. This synergy is essential because unpredictable operational variables (e.g., weather and cascading delays) exceed algorithmic capabilities, making human verification indispensable. Thus, instead of replacing human oversight, automation should alleviate routine cognitive burdens while preserving human agency for decisions requiring contextual flexibility and ultimate accountability. This division is validated by qualitative feedback comparing ActSoon to current practices: U3 highlighted that it "filled a gap in the current tools," and U4 observed it reduces cognitive demand relative to manual coordination, supporting this cooperative human-automation synergy.

8.2 Limitations and Future Work

First, while our system design successfully covers most typical traffic scenarios encountered in daily operations, extreme traffic densities (≥ 20 active aircraft) challenge both visual and computational scalability. On the visual level, high crowding degrades usability. Although our automatic offset algorithm prevents route overlap, dense offset lines increase visual complexity, and overlapping semi-transparent risk ribbons can accumulate opacity, obscuring map details. To enhance visual scalability, future work will integrate dynamic filtering and localized focus-plus-context views (e.g., minimaps) to mitigate clutter while preserving global awareness. On the computational level, while ActSoon maintains 60 FPS and sub-second latency (routing < 1.0 s, manual updates < 100 ms for 20 aircraft), extreme peak traffic at ultra-large hubs remains challenging. Future work will implement spatial network partitioning and localized re-computation to sustain performance.

Second, we acknowledge a simulation realism gap. As discussed in Section 4, despite qualitative validation by experts, our framework lacks micro-level calibration. Due to data constraints, we lacked high-fidelity trajectories to model micro-dynamics like varying pilot speeds or communication delays. Future work could leverage real-time ground movement data to calibrate these behaviors and narrow this gap.

Third, regarding visual design, we acknowledge limitations in feedback salience and system flexibility reflected in expert feedback. Specifically, while the current visual design successfully supports interactive scheduling, future work could optimize transition feedback to make state changes more salient during rapid adjustments. Additionally, experts suggested enhancing visual comfort through radar-aligned aesthetics (U2) and supporting manual priority weighting (U1). Future iterations will address these gaps by refining transition feedback and interactive control logic.

9 Conclusion

This study presents ActSoon, a visual analytics approach that empowers ground controllers to dynamically manage airport surface traffic. Grounded in a formal abstraction of network-constrained spatio-temporal scheduling, we develop a coordinated interface aligning spatial topologies with temporal timelines and an interactive decision-support workflow. By coupling proactive human adjustments with predictive cascading consequences, ActSoon enables controllers to anticipate risks and resolve conflicts, ultimately paving the way for safer and more efficient airport operations.

Acknowledgments

This work was supported by the National Key R&D Program of China (No.2023YFB2604100).

References

[1] S. Agarwal, G. Wallner, J. Watson, and F. Beck. Spatio-temporal analysis of multi-agent scheduling behaviors on fixed-track networks. In *Proceedings of the 2022 IEEE 15th Pacific Visualization Symposium (PacificVis)*, pp. 21–30, 2022. doi: 10.1109/PacificVis53943.2022.00011 2

[2] M. Al-Ghzawi and K. El-Rayes. Machine learning and multi-objective optimization methodology for planning construction phases of airport expansion projects. *Journal of Air Transport Management*, 115:102550, 2024. doi: 10.1016/j.jairtraman.2024.102550 1

[3] J. A. D. Atkin, E. K. Burke, and S. Ravizza. The airport ground movement problem: past and current research and future directions. In *Proceedings of the 4th International Conference on Research in Air Transportation (ICRAT)*, pp. 131–138. Budapest, Hungary, 2010. 2

[4] J. Bao, J. Kang, J. Zhang, Z. Zhang, and J. Han. A dynamic control method for airport ground movement optimization considering adaptive traffic situation and data-driven conflict priority. *Journal of Air Transport Management*, 124:102753, 2025. doi: 10.1016/j.jairtraman.2025.102753 2

[5] J. Bao, J. Kang, J. Zhang, Z. Zhang, and J. Han. A dynamic control method for airport ground movement optimization considering adaptive traffic situation and data-driven conflict priority. *Journal of Air Transport Management*, 124:102753, 2025. doi: 10.1016/j.jairtraman.2025.102753 2

[6] L. Beke, L. Uribe, A. Lara, C. Artemio Coello Coello, M. Weiszer, E. K. Burke, and J. Chen. Routing and scheduling in multigraphs with time constraints—a memetic approach for airport ground movement. *IEEE Transactions on Evolutionary Computation*, 28(2):474–488, 2024. doi: 10.1109/TEVC.2023.3262743 2

[7] S. G. Borjigin and M. A. Austin. Multi-domain semantic model and real-time planning approach to safe and efficient airport taxiway operations. *IEEE Transactions on Intelligent Transportation Systems*, 25(7):7738–7750, 2024. doi: 10.1109/TITS.2024.3354242 2

[8] V. Braun and V. Clarke. Using thematic analysis in psychology. *Qualitative Research in Psychology*, 3(2):77–101, 2006. doi: 10.1191/1478088706qp063oa 3

[9] Q. Chen, Y. Wang, Y. Yu, X. Zhu, X. Yu, and R. Wang. Conch: Competitive debate analysis via visualizing clash points and hierarchical strategies. *IEEE Transactions on Visualization and Computer Graphics*, 32(1):944–954, 2026. doi: 10.1109/TVCG.2025.3634629 7

[10] T. Chen and S. Hanaoka. Improvement of airport surface operation at tokyo international airport using optimization approach. *Aerospace*, 9(3):145, 2022. doi: 10.3390/aerospace9030145 2

[11] M. Dahanayaka, D. Prak, and M. Mes. From gate to runway: A systematic review of airport ground operations optimization. *Journal of Air Transport Management*, 135:103013, 2026. doi: 10.1016/j.jairtraman.2026.103013 2

[12] W. Deng, L. Zhang, X. Zhou, Y. Zhou, Y. Sun, W. Zhu, H. Chen, W. Deng, H. Chen, and H. Zhao. Multi-strategy particle dwarm and ant colony hybrid optimization for airport taxiway planning problem. *Information Sciences*, 612:576–593, 2022. doi: 10.1016/j.ins.2022.07.018 2

[13] Z. Deng, Y. Liu, M. Zhu, D. Xiang, H. Yu, Z. Su, Q. Lu, T. Schreck, and Y. Cai. Trasculptor: Visual analytics for enhanced decision-making in road traffic planning. *IEEE Transactions on Visualization and Computer Graphics*, 31(10):6899–6914, 2025. doi: 10.1109/TVCG.2025.3532498 2

[14] Z. Deng, D. Weng, and Y. Wu. You are experienced: Interactive tour planning with crowdsourcing tour data from web. *Journal of Visualization*, 26(2):385–401, 2022. doi: 10.1007/s12650-022-00884-1 2

[15] P. Di Mascio, M. V. Corazza, N. R. Rosa, and L. Moretti. Optimization of aircraft taxiing strategies to reduce the impacts of landing and takeoff cycle at airports. *Sustainability*, 14(15):9692, 2022. doi: 10.3390/su14159692 1

[16] J. Dong, H. Zhang, M. Cui, Y. Lin, H.-Y. Wu, and C. Bi. TCEVis: Visual analytics of traffic congestion influencing factors based on explainable machine learning. *Visual Informatics*, 8(1):56–66, 2023. doi: 10.1016/j.visinf.2023.11.003 2

[17] K. Dönmez. Airport Ground Optimizer (AGO): A decision support system initiative for air traffic controllers with optimization and decision-aid algorithms. *Journal of Air Transport Management*, 119:102648, 2024. doi: 10.1016/j.jairtraman.2024.102648 2

[18] K. Dönmez. Airport ground optimizer (ago): A decision support system initiative for air traffic controllers with optimization and decision-aid algorithms. *Journal of Air Transport Management*, 119:102648, 2024. doi: 10.1016/j.jairtraman.2024.102648 2

[19] K. Dönmez. The operational dynamics of end-around taxiways: Insights from istanbul airport. *Case Studies on Transport Policy*, 18:101303, 2024. doi: 10.1016/j.cstp.2024.101303 1

[20] K. Finstad. The usability metric for user experience. *Interacting with computers*, 22(5):323–327, 2010. 7

[21] P. He and W. Pan. Collaborative optimization model and algorithm for airport capacity and traffic flow allocation. *PLoS ONE*, 19(3):e0298540, 2024. doi: 10.1371/journal.pone.0298540 1

[22] X. Huang, Y. Tian, J. Li, N. Zhang, X. Dong, Y. Lv, and Z. Li. Joint autonomous decision-making of conflict resolution and aircraft scheduling based on triple-aspect improved multi-agent reinforcement learning. *Expert Systems with Applications*, 275:127024, 2025. doi: 10.1016/j.eswa.2025.127024 2

[23] Y. Jiang, Y. Wang, M. Liu, Q. Xue, H. Zhang, and H. Zhang. Bilevel spatial-temporal aircraft taxiing optimization considering carbon emissions. *Sustainable Energy Technologies and Assessments*, 58:103358, 2023. doi: 10.1016/j.seta.2023.103358 2

[24] Y. Jiang, Y. Wang, M. Liu, Q. Xue, H. Zhang, and H. Zhang. Bilevel spatial–temporal aircraft taxiing optimization considering carbon emissions. *Sustainable Energy Technologies and Assessments*, 58:103358, 2023. doi: 10.1016/j.seta.2023.103358 4

[25] S. Jin, H. Lee, C. Park, H. Chu, Y. Tae, J. Choo, and S. Ko. A visual analytics system for improving attention-based traffic forecasting models. *IEEE Transactions on Visualization and Computer Graphics*, 29(1):1102–1112, 2022. doi: 10.1109/TVCG.2022.3209462 2

[26] J. Lazar, J. H. Feng, and H. Hochheiser. *Research methods in human-computer interaction*. Morgan Kaufmann, 2017. 3

[27] C. Lee, Y. Kim, S. Jin, D. Kim, R. Maciejewski, D. Ebert, and S. Ko. A visual analytics system for exploring, monitoring, and forecasting road traffic congestion. *IEEE Transactions on Visualization and Computer Graphics*, 26(11):3133–3146, 2019. doi: 10.1109/TVCG.2019.2922597 2

[28] Q. Liu, Q. Li, C. Tang, H. Lin, X. Ma, and T. Chen. A visual analytics approach to scheduling customized shuttle buses via perceiving passengers' travel demands. In *2020 IEEE Visualization Conference (VIS)*, pp. 76–80, 2020. doi: 10.1109/VIS47514.2020.00022 2

[29] Q. Liu, X. Li, H. Liu, and Z. Guo. Multi-objective metaheuristics for discrete optimization problems: A review of the state-of-the-art. *Applied Soft Computing*, 93:106382, 2020. doi: 10.1016/j.asoc.2020.106382 4

[30] M.-J. Lobo, C. Hurter, and M. Cousy. A LIDAR interactive data visualization for ground aircraft detection at small airports. In *SID 2019, 9th SESAR Innovation Days*. Athens, Greece, 2019. 2

[31] E. Oral, R. Chawla, M. Wijkstra, N. Mahyar, and E. Dimara. From information to choice: A critical inquiry into visualization tools for decision making. *IEEE Transactions on Visualization and Computer Graphics*, 30(1):359–369, 2024. doi: 10.1109/TVCG.2023.3326593 2

[32] G. G. D. Santos and G. H. d. A. Correia. A flow-based integer programming approach to design an interurban shared automated vehicle system and assess its financial viability. *Transportation Research Part C: Emerging Technologies*, 128:103092, 2021. doi: 10.1016/j.trc.2021.103092 1

[33] M. von der Burg, J. Kamphof, J. Soomers, and A. Sharpanskykh. Towards next-generation airport surface movement operations using hierarchical-distributed multi-agent planning. *Transportation Research Part C: Emerging Technologies*, 2026. doi: 10.1016/j.trc.2026.105583 2

[34] G. Wang, X. Wen, F. Wang, L. Yang, Q. Wang, and M. Zhu. Aircascades: A visual analytics system for cascading taxiway interaction patterns. *Visual Informatics*, p. 100335, 2026. doi: 10.1016/j.visinf.2026.100335 2

[35] C. Wen, J. Lang, Y. Fu, et al. Refined aircraft landing-takeoff activ-

ity modeling to improve the sstimation of aviation co2 and pollutants emissions. *npj Climate and Atmospheric Science*, 8(1):316, 2025. doi: 10.1038/s41612-025-01195-6 6

[36] D. Weng, C. Zheng, Z. Deng, M. Ma, J. Bao, Y. Zheng, M. Xu, and Y. Wu. Towards better bus networks: A visual analytics approach. *IEEE transactions on visualization and computer graphics*, 27(2):817–827, 2021. doi: 10.1109/TVCG.2020.3030458 2

[37] Q. Xia, H. Zhang, D. Qu, J. Bai, and C. Lv. Brpvis: Visual analytics for bus route planning based on perception of passenger travel demand. *IEEE Computer Graphics and Applications*, 44(6):118–131, 2024. doi: 10.1109/MCG.2024.3454645 2

[38] Z. Xia, M.-H. Hsieh, and C.-H. Chen. A review on human-AI hybrid systems in air traffic management. In J. Wei, G. Margetis, H. Degen, and S. Ntoa, eds., *HCI International 2025 – Late Breaking Papers*, vol. 16346, pp. 284–295. Springer Nature Switzerland, 2026. doi: 10.1007/978-3-032-13187-4_19 2

[39] H. Xu, A. Berres, S. A. Tennille, S. K. Ravulaparthy, C. Wang, and J. Sanyal. Continuous emulation and multiscale visualization of traffic flow using stationary roadside sensor data. *IEEE Transactions on Intelligent Transportation Systems*, 23(8):10530–10541, 2022. doi: 10.1109/TITS.2021.3094808 2

[40] L. Ying, A. Wu, H. Li, Z. Deng, J. Lan, J. Wu, Y. Wang, H. Qu, D. Deng, and Y. Wu. VAID: Indexing view designs in visual analytics system. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*, 2024. doi: 10.1145/3613904.3642237 7

[41] L. Yuan, D. Fang, H. Chen, and J. Liu. Prediction of airport surface potential conflict based on gnn-lstm. *IET Intelligent Transport Systems*, 19(1):e12611, 2025. doi: 10.1049/itr2.12611 2

[42] S. Zaninotto, J. Gauci, and B. Zammit. An autonomous tow truck algorithm for engineless aircraft taxiing. *Aerospace*, 11(4):307, 2024. doi: 10.3390/aerospace11040307 1

[43] T. Zhang, L. Beke, S. Liu, M. Weiszer, and J. Chen. An extended memetic algorithm for multiobjective routing and scheduling of airport ground movements with intermediate holding. In *2022 IEEE Congress on Evolutionary Computation (CEC)*, pp. 1–8, 2022. doi: 10.1109/CEC55065.2022.9870239 2

[44] X. Zhang, X. Pang, X. Wen, F. Wang, C. Li, and M. Zhu. Triplan: an interactive visual analytics approach for better tourism route planning. *Journal of Visualization*, 26(1):231–248, 2023. doi: 10.1007/s12650-022-00861-8 2

[45] Y. Zhang, L. Xu, S. Tao, Q. Guan, Q. Li, and H. Zeng. Cslens: Towards better deploying charging stations via visual analytics — a coupled networks perspective. *IEEE Transactions on Visualization and Computer Graphics*, 31(1):251–261, 2025. doi: 10.1109/TVCG.2024.3456392 2

[46] N. Zhao and S. Cui. Study on 4D taxiing path planning of aircraft based on spatio-temporal network. *Mathematical Biosciences and Engineering*, 20(3):4592–4608, 2023. doi: 10.3934/mbe.2023213 2

[47] J. Zhuge, H. Liang, Y. Zhang, S. Li, X. Yang, and J. Wu. Aircraft ground taxiing deduction and conflict early warning method based on control command information. *Transportation Research Record*, 2678(11):684–704, 2024. doi: 10.1177/03611981241242360 2