aerospace

MDPI

Article

Evaluating Third-Sector Apron Operations: Radio Occupancy and Interface Tasks

Changcheng Li [1,2,*], Huabo Bao [3], Yuxin Hu [2], Minghua Hu [1,2], Zheng Zhao [1,2], Bin Jiang [1,2,*], Saiwen Zhang [1,2] and Jiamei Wang [1,2]

[1] College of Civil Aviation, Nanjing University of Aeronautics and Astronautics, No. 29 Jiangjun Avenue, Nanjing 211106, China; minghuahu@nuaa.edu.cn (M.H.); zheng_zhao@nuaa.edu.cn (Z.Z.); seven_z@nuaa.edu.cn (S.Z.); wang_jiamei@nuaa.edu.cn (J.W.)
[2] State Key Laboratory of Air Traffic Management System, No. 8 Yongzhi Road, Nanjing 210014, China; helenhuyuxin@gmail.com
[3] Heilongjiang Airport Management Group Co., Ltd., Harbin 150079, China; baohuabo@163.com
* Correspondence: lichangcheng@nuaa.edu.cn (C.L.); jiangbin_sq@nuaa.edu.cn (B.J.)

Abstract

Opening a third apron-control sector adds a command and support pair, yet a lower average radio occupancy may conceal busy hours during its operation. We evaluated 30 completed openings at Beijing Daxing International Airport using channel records, exact configuration times and two-sector references. The 114 clock-hour records covered 112.36 h of operation and 224.71 additional position-hours. Extending the reference pool from 1008 to 1454 airport hours provided traffic-composition-matched comparisons for every opening hour. Eight summer Plan 1 hours exceeded the local 70% reference, all on the third responsibility area's channel. In two lower-average openings, the respective busy-hour contrasts were +7.64 and +4.98 percentage points. Neither hour had a reference with identical recorded context in the full candidate pool; six other busy hours retained positive contrasts. Plan 1's busiest-channel share was lower in all 21 openings, while total radio use was higher in 13. Expanded summer mean differences were −5.54 and +1.45 percentage points for Plans 1 and 2, with both conditional intervals spanning zero. Interface-task rates and actual staffing coverage described the activity accompanying the added pair. The findings support evaluating the complete opening through its hourly radio profile, the available comparisons for busy hours and the associated interface activity.

Keywords: apron control; sector configuration; radio occupancy; opening episodes; interface tasks; resource evaluation

Check for updates

Academic Editor: Miroslav Kelemen

Received: 6 October 2026
Revised: 24 October 2026
Accepted: 26 October 2026
Published: 28 October 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

Opening a third apron-control sector adds a command position and a monitoring or coordination position. The operating unit then needs to judge what the additional team achieved. An average reduction in occupancy at the busiest radio channel offers one answer, yet individual hours may remain heavily occupied and responsibility transfers may increase. Evaluating the opening therefore requires both its comparison with two-sector operation and the sequence of conditions encountered by the team. Comparable reference hours support the first judgment; the complete operating record reveals busy hours that an average can hide.

Traffic counts alone give an incomplete account of controller demand. Capacity models represent tasks generated by traffic, while complexity studies distinguish situations with

similar volumes but different handling demands [1,2]. Dynamic-density research incorporated traffic interactions and compared them with observed controller activity [3]. Li and Hu's track-based assessment separates monitoring, coordination and conflict-related activities [4]; EUROCONTROL's capacity-analysis methodology estimates hourly task time using locally weighted radio, coordination and radar tasks [5]. Airport ground studies similarly relate operational events to task demands and controllers' experience of apron work [6,7]. Modeled task time, recorded radio use and perceived workload each capture a different part of the operation.

The activity encountered during operation can also differ from the planned division of work. Event-based real-time simulations distinguish an exercise's designed taskload from the events participants actually encounter [8]. In an exploratory flight-based human–autonomy experiment, controllers often changed the initial allocation as the exercise developed [9]. An apron-sector opening likewise spans changing traffic and coordination conditions. Keeping its hourly sequence makes those changes visible alongside the average outcome.

Radio occupancy measures the time used for communication on a channel. Tower capacity research has included radio time among controller activities [10], and a Schiphol ground-control study used channel recordings to assess a taskload model [11]. Communication frequency and duration have also been used to predict aircraft counts within an airspace sector [12]. Radio time itself covers only part of controller work. A Federal Aviation Administration (FAA) study found that task activity improved workload predictions based on communication variables [13], consistent with Hilburn's distinction between visible actions and planning, monitoring and decision making [14]. Here the object is communication use at the busiest channel. Its occupancy depends on both the airport's total radio use and the share carried by that channel. These quantities allow us to distinguish a change in total communication from a change in its distribution.

Brunia's ground-sector splitting study provides the closest comparison. It evaluated North and North–Center models under the same historical Schiphol traffic and found that the benefit of a Center split depended on the traffic handled there, particularly relevant arrival flows [11]. The model included handoff-related features and used recorded radio communications as its reference. This common-flow design evaluates candidate splits. Completed openings raise a complementary question: what conditions occurred while the additional team actually operated? A lower group average can conceal higher-average openings, and a lower opening average can conceal individual busy hours. An opening-level evaluation connects those hourly conditions to the period for which the team was provided.

Sectorization research shows why this evaluation involves more than balancing traffic counts. Flight-centric designs consider task balance, trajectory segmentation and boundary changes together [15]. Cell-based optimization incorporates traffic complexity into boundary construction [16], and multilayer-graph approaches combine traffic vectors with network structure [17]. Dynamic-programming configuration models include future traffic, reconfiguration costs and required positions [18]. These approaches connect responsibility design to demand and resource provision. Field records can then show how an existing configuration performed under the circumstances for which operators selected it.

Changing a configuration also changes the responsibilities that must be transferred. Dynamic-sectorization simulations identify naming, responsibility transfer and handoff timing as practical concerns [19]. Jung et al. separately assessed workload during and after boundary changes, relating transition demands to sector-volume changes and handoffs [20]. European airspace-design guidance connects sector development to coordination, qualified staffing and adjacent interfaces [21]. Capacity planning further distinguishes the provision of sector hours from constructing staff rosters [22]. In the present setting, the additional

command position operates with monitoring or coordination support. Radio use and interface tasks therefore need to be interpreted in relation to the team that handles them.

The same link between resources and operating conditions appears elsewhere in airport research. Apron queuing at Beijing Daxing has been represented through a network of control positions and traffic directions [23]. Runway capacity depends on operating direction and separation requirements [24], and its response to demand changes varies with traffic composition [25]. For an added apron-control team, the corresponding question is whether the opening average adequately describes the communication conditions it encountered.

We examine this question using winter and summer channel records for two existing third-sector plans at Beijing Daxing International Airport. All 30 openings are included. Each plan is compared with selected two-sector hours within its own period, and its average comparison is examined alongside actual busy hours and interface-task rates. An extended two-sector record allows strict traffic-composition matching to cover the busy hours as well as the quieter ones. Configuration times and channel-to-area correspondence locate the communication within the period of additional staffing. The comparisons distinguish a smaller busiest-channel share from lower occupancy and connect each opening's hourly conditions to the additional team provided. Because plan choice followed anticipated demand, the comparisons support review of those operations rather than a causal ranking of the layouts.

2. Materials and Methods

2.1. Study Setting and Operating Configurations

The baseline configuration divided apron-control responsibility between two sectors. Plan 1 and Plan 2 each opened a third sector using a different predefined responsibility layout. The boundaries indicate who handles an aircraft or vehicle within an area; they are not radio-propagation contours. Figure 1 presents the study-area context and the two third-sector layouts with fine identifiers and coordinates removed. The supplied channel-to-area table links anonymous channels CH_E, CH_W and CH_N to responsibility areas 1, 2 and 3 within each plan. This correspondence locates a busy channel in the active layout; it does not identify the effect of moving a boundary.

Two-sector operation used two command and two monitoring/coordination positions; three-sector operation used three of each. Opening the third sector therefore added one operating pair. Interface counts describe activity under that configuration, since the summaries do not identify the individual performing each task or whether support staff also transmitted. The comparison concerns simultaneously staffed positions, excluding the larger workforce available for rotation and rest.

Operators selected the plans under different demand circumstances. Summer decision summaries associate Plan 1 with one anticipated high-demand area and Plan 2 with another; no recorded hotspot was observed under both plans. Each plan is therefore compared with two-sector reference hours within its own period. This preserves the operating context while leaving demand and layout jointly associated with the observed differences.

2.2. Channel-Hour Radio Occupancy

The original winter period covered 20 January–2 February 2025 and the summer period 25 August–21 September 2025, supplying 1008 airport hours. An additional 446 two-sector hours extended the reference pool: 308 winter hours on 6–19 January and 3–16 February, from 07:00 to 17:00, and 138 summer hours on 11–24 August and 22–30 September, from 16:00 to 21:00. Times denote clock-hour starts. The combined record contains 1454 airport hours and 3022 active channel-hours; the extensions are selected daytime/evening coverage rather

than continuous additional days. Hours follow Asia/Shanghai (UTC+08:00), excluding the endpoint. The provider supplied channel radio durations, airport traffic, operating context and interface-task summaries. Channel-hour durations are non-missing and refer to a 3600-s observation window.

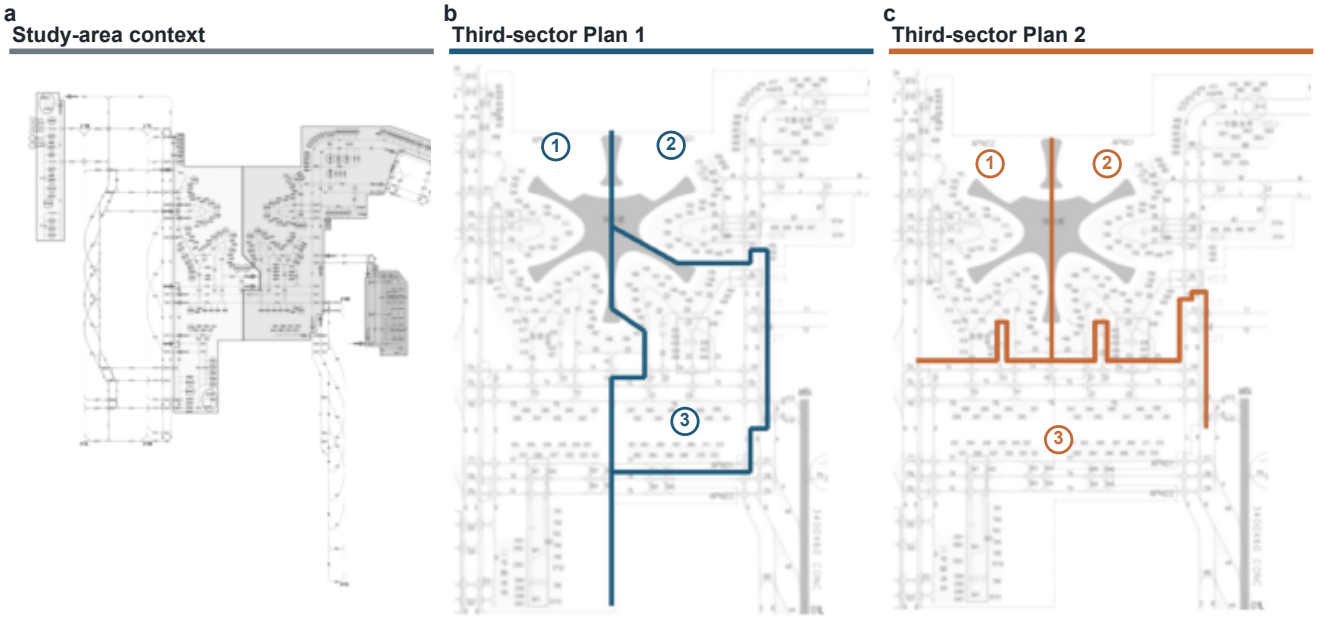


Figure 1. Study-area context and third-sector responsibility layouts: (**a**) context of the airport apron-control area; (**b**) third-sector Plan 1; and (**c**) third-sector Plan 2. Panel (**a**) is not a map of the two-sector baseline. Numbers in panels (**b**,**c**) identify responsibility areas, corresponding to anonymous channels CH_E (1), CH_W (2) and CH_N (3) in the supplied channel table. The layouts retain the operating boundary topology while suppressing fine stand and taxiway identifiers, internal annotations and exact coordinates. Boundaries indicate responsibility rather than radio coverage.

Let r_{ih} denote recorded radio seconds for active sector channel i in clock hour h. It includes transmissions by controllers, aircraft and vehicles, including transfers spoken on the same radio channel. Telephone, internal-line and other non-radio coordination are excluded. Sector-channel occupancy and its hourly maximum are

$$o_{ih} = \frac{r_{ih}}{3600}, \qquad y_h = \max_{i=1,\ldots,n_h} o_{ih}, \tag{1}$$

where n_h is the number of active sectors. The maximum identifies the most occupied channel in that hour; it is not an instantaneous within-hour peak. The busiest channel may change between hours of an opening.

According to the provider, transmissions crossing an hour boundary are divided between the hours occupied, and duplicate or overlapping intervals within a channel are merged. Missing-record intervals are flagged. We used the supplied durations and checked that $R_h = \sum_i r_{ih}$ reconciled with the airport radio total within rounding; the recording equipment was not independently calibrated. Interface tasks are counted separately, without adding a second duration for transfers already included in radio timing.

The busiest-channel share is $p_h = \max_i r_{ih}/R_h$ for $R_h > 0$, giving the hourly identity $y_h = R_h p_h/3600$. Concurrent use of different channels can make R_h exceed 3600 s. We report total, share and maximum for all 30 openings using identical matched hours, references and averaging order. The hourly products are averaged directly; Supplementary Section S12 gives the covariance term separating that mean from the product of component means. A zero total has zero occupancy and an undefined share. With two and three channels, the fea-

sible minimum shares are 1/2 and 1/3, respectively, so the change in channel count must also be considered when interpreting a lower share.

The hourly maximum measures use of the busiest channel while retaining changes in which channel is busiest. Silent monitoring, planning and other cognitive demands fall outside this radio-use measure.

2.3. Matched References and Opening-Level Aggregation

An opening episode is a continuous recorded use of one third-sector plan. Exact start and end times define its operating duration, while clock-hour labels identify the original 30 episodes and 114 hourly observations. The original analysis uses 1008 airport hours and the original selection rule. The expanded analysis adds 446 two-sector hours and applies stricter traffic-composition limits to every candidate. Both analyses concern the same third-sector openings.

Both analyses select up to three two-sector references from the same period and local clock hour, requiring an absolute difference no greater than 10 in the combined number of arrivals, departures and towing activities. The expanded rule additionally limits the respective component gaps to 5, 5 and 2 activities (composition B). Ranking uses standardized component differences and penalties for runway, weather, low-visibility and deicing mismatches, followed by total-activity difference and earlier reference time. The original period-specific scales and penalties remain fixed when the candidate pool expands. Occupancy and interface outcomes enter neither eligibility nor ranking. Supplementary Sections S4 and S15 give the complete rules and achieved comparability.

For a third-sector hour h, let $\mathcal{M}_h$ be its selected two-sector references. Its comparison is

$$d_h = y_h - \frac{1}{|\mathcal{M}_h|} \sum_{c \in \mathcal{M}_h} y_c. \tag{2}$$

For opening e, let $\mathcal{H}_e$ contain its matched hours and let E_g count openings in period–plan group g. We average hourly differences within openings, then weight openings equally:

$$d_e = \frac{1}{|\mathcal{H}_e|} \sum_{h \in \mathcal{H}_e} d_h, \qquad \bar{d}_g = \frac{1}{E_g} \sum_{e \in g} d_e. \tag{3}$$

Equal opening weights prevent longer episodes from dominating the group mean. Differences are reported in percentage points; one point corresponds to 0.6 occupied minutes per hour in this maximum-channel measure. Total speaking time and staff labor are separate quantities.

The original references had mean absolute total-traffic gaps of 3.61–4.40 activities per hour, but individual arrival or departure gaps reached 19. Component restrictions address that count imbalance while leaving unrecorded routes, conflicts and local restrictions uncontrolled.

The original-period checks also use composition A (10/10/5), composition B, the nearest single reference and all eligible references. When coverage changes, comparisons on common hours separate the effect of new reference choices from restored hours and aggregation weights. Supplementary Sections S10 and S15 retain the original and expanded results, including hours without references. No analysis assigns zero to an undefined comparison.

Two recorded-context sensitivities require agreement on runway configuration, weather, low visibility and deicing. One filters the 337 selected expanded pairs. The other applies these conditions to the full two-sector candidate pool before ranking, retaining the original traffic limits, scales and tie order. Both select up to three references per actual hour. Remaining references are equal within hours, with hour and opening weights recalculated after any loss of comparisons. Repeating the original expanded comparison on the same retained hours separates sample and weight changes from reference changes (Supplementary Section S19).

The original rule matched 112 of the 114 opening-hour labels through 284 pairs. Two Plan 2 hours, one per period, lacked eligible references. Expanded composition matching supplies 337 pairs for all 114 hours (Table 1). Actual busy-hour counts always retain the complete 114 h record, independently of reference availability.

Table 1. Operating and comparison coverage. Airport-hour totals include the added two-sector references and are repeated by plan within a period. Match columns give matched/actual clock-hour labels, distinct from elapsed operating time.

Period	Airport Hours	Plan	Openings	Original Match	Expanded Match
Winter	644	1	11	28/28	28/28
Winter	644	2	3	13/14	14/14
Summer	810	1	10	42/42	42/42
Summer	810	2	6	29/30	30/30
Total	1454	–	30	112/114	114/114

References could be reused between hours and openings. We report unique reference hours and dates, their weight concentration, and the effects of deleting individual reference hours, dates or openings. A further check removes each real date from both actual and reference records before averaging the remaining comparisons, without rematching. Hours that lose all references leave the relative comparison, and an opening with none remaining is undefined. These deletion ranges measure the influence of the recorded units, separately from the model-conditional intervals below.

We estimated the precision of each opening-equal mean contrast conditional on the recorded operating conditions, selected references and comparison weights. Reused references enter once as unique airport hours with accumulated coefficients, and actual and reference records from the same date belong to one dependence block. The fitted model preserves the opening-equal mean contrast, and a full-design small-sample cluster adjustment with a Satterthwaite approximation provides its interval [26]. Single-date intervals provide a common summary; two alternating partitions of adjacent two-day blocks assess sensitivity to the dependence assumption. The intervals require a suitable conditional mean and independent errors between blocks. Variation among observed openings is described separately by their individual results. Supplementary Sections S13 and S17 give the full method, assumptions and diagnostics; the original-reference winter offset analysis remains in Section S14.

2.4. Absolute High Occupancy and Comparison with Proportional Estimates

An absolute high-occupancy hour satisfies $y_h > 0.70$, or more than 2520 occupied seconds on the busiest channel. This strict 70% line is local expert guidance supplied for the study, not an estimated capacity or a universal safety threshold. All actual third-sector hours enter the count, including hours without a selected reference. High-hour counts describe observed channel conditions during an opening. They do not estimate how many high hours opening the third sector prevented.

Sensitivity counts use strict 60%, 65% and 75% lines on unrounded occupied seconds. Original endpoint-omission checks remain in Supplementary Section S11. Exact switching times identify 54 hours fully covered by the configuration and 60 boundary hours. For the latter, supplied within-hour radio intervals split at the switch allow channel totals to be integrated over the active portion. The active density is the largest channel total over that portion divided by its duration; it is not a sum of minute-by-minute maxima. Comparing this density with full-hour references is a time-scale sensitivity analysis because reference-minute traffic and radio records are unavailable. A separate check retains only full-configuration

hours (Supplementary Section S16). The local hourly review line is not redefined as a validated threshold for short fragments.

To show the effect of replacing the earlier measurement, we compare channel-derived results with the former proportional estimate $\hat{r}_{ih} = R_h C_{ih} / \sum_j C_{jh}$, where C_{ih} is the supplied sector communication total including radio and non-radio coordination. The earlier cap-constrained allocation ranges are retained in Supplementary Section S1 as a totals-only comparison. They describe distributions permitted by the combined totals, not uncertainty intervals for the supplied channel measurements. The residual $C_{ih} - r_{ih}$ is an accounting difference; it is not independently timed non-radio coordination.

2.5. Interface Tasks and Staffed-Position Coverage

We calculate a reported interface-task rate for each hour as

$$q_h = 100 \frac{T_h}{A_h + D_h + W_h}, \tag{4}$$

where T_h is the supplied interface count, and A_h, D_h and W_h are arrivals, departures and towing activities. Treatment-minus-reference differences in q_h follow Equations (2) and (3). Two airport hours had no traffic activities, so their rates were undefined rather than zero; neither entered an opening or its matches. Averaging hourly rates is distinct from dividing total tasks by total activities across an opening.

Winter counts represent sending and receiving endpoint tasks. The original winter record contains 16,010 endpoint tasks and 8049 event-table rows; repeated coordination and endpoint coverage mean that simply halving the task count would not recover the number of distinct events. The original summer summaries provide 30,334 endpoint tasks without an independent event table. The provider confirmed that summer two- and three-sector configurations used the same task definition, interface scope and repeated-coordination rules. An internal apron transfer contributes one sending and one receiving task. A transfer involving an outside unit contributes only the apron-side task within the study. Additional coordination is counted when it creates another task; duplicate exports of the same record are not counted again. Tasks are assigned to the request hour. We retain period-specific rates without converting counts to communication duration, net labor or cognitive workload.

Recorded command and monitoring/coordination start and end times synchronously cover the actual configuration in all 30 episodes. Their intersections with the opening intervals give 224.71 additional position-hours over 112.36 elapsed hours. The earlier 228 position-hours assume full coverage of all 114 clock-hour labels and are retained as that conditional calculation. Coverage hours are distinct from additional headcount, roster requirements and payroll. Hourly task counts are not divided in proportion to active minutes because task times within those hours are unobserved.

3. Results

3.1. Average Occupancy Varies Between Opening Episodes

Expanded composition matching retained all 30 openings and all 114 hourly records. Plan 1 had lower mean hourly maximum occupancy than its references in 19 of 21 openings: all 11 winter openings and eight of ten summer openings. Plan 2 had higher means in all three winter openings and four of six summer openings. The other two summer Plan 2 openings were lower by 3.22 and 4.61 percentage points (Figure 2).

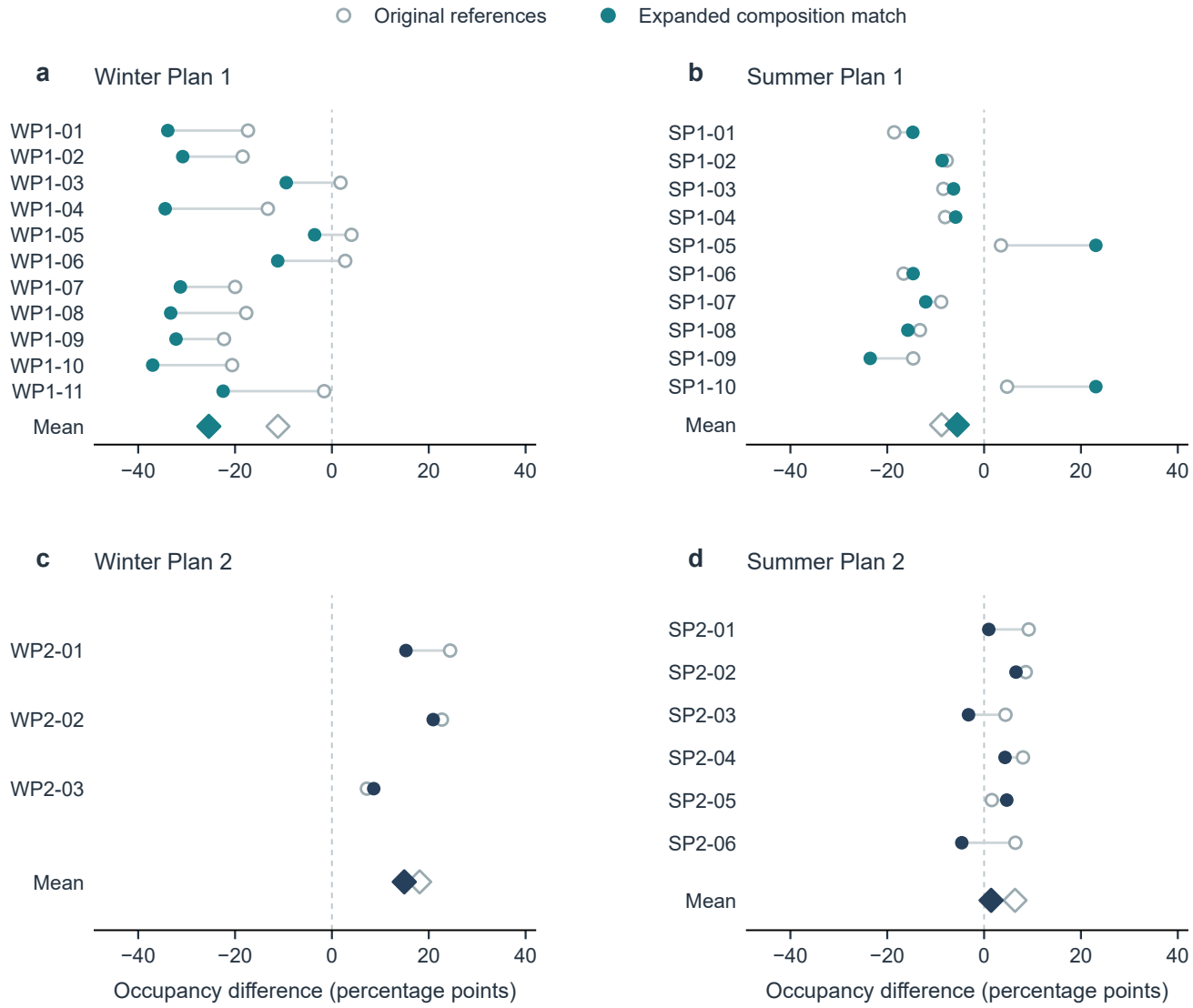


Figure 2. Mean occupancy comparisons for all 30 openings under original and expanded composition-matched references. Hollow gray symbols show original estimates; filled teal/navy symbols show expanded Plan 1/Plan 2 estimates. Circles denote openings and diamonds their opening-equal group means. Dashed vertical lines mark zero. Lines connect two comparisons for the same observed opening, not confidence limits. Negative values indicate lower occupancy than the selected two-sector references. The expanded rule retains every hourly label; the original rule lacks one Plan 2 hour in each period. Table 2 reports single-date conditional intervals; Supplementary Sections S13 and S17 give all block schemes.

Group contrasts changed with the references (Table 2). Winter Plan 1 changed from −11.14 under the original rule to −25.41 percentage points under expanded composition matching; winter Plan 2 changed from +18.12 to +14.95. The corresponding summer contrasts moved toward zero, from −8.79 to −5.54 for Plan 1 and from +6.39 to +1.45 for Plan 2. Each group compares its own demand circumstances with its own references.

Table 2 gives approximate 95% single-date conditional intervals for all four expanded mean contrasts. Both summer intervals cross zero, as do both adjacent-two-day partitions, leaving the summer mean directions uncertain under these models. Winter Plan 1's interval remains below zero. Winter Plan 2's positive interval is exploratory: its three openings occurred on only two dates, with approximately 1.7 effective degrees of freedom. Winter Plan 1's linear model produced one fitted occupancy of 100.34% at a recorded value of 98.61%. Supplementary Section S17 retains this slight fitted extrapolation as a model di-

agnostic alongside all winter conditional intervals. These intervals describe precision in the fixed comparison means; Figure 2 shows the variation among observed openings. All original and expanded calculations are retained in Supplementary Sections S13 and S17.

Table 2. Occupancy comparisons, conditional mean intervals and additional pair coverage.

Period	Plan	Original Diff. (pp)	Expanded Diff. (95% Cond. CI, pp)	Lower Mean Openings	High/Actual Hour Labels	Expanded Task Diff.	Actual Added Position-Hours
Winter	1	−11.14	−25.41 [−33.76, −17.07]	11/11	1/28	+29.98	54.71
Summer	1	−8.79	−5.54 [−13.13, +2.06]	8/10	8/42	+14.84	82.83
Winter	2	+18.12	+14.95 [+5.71, +24.18]	0/3	11/14	+5.14	27.72
Summer	2	+6.39	+1.45 [−3.83, +6.74]	2/6	16/30	+5.69	59.45

CI, confidence interval; pp, percentage points. Expanded comparisons use composition B and all 114 labels; original comparisons use 112. Means weight openings equally. Brackets give approximate 95% single-date model-conditional intervals for the fixed expanded comparison means. Winter Plan 2 is exploratory (three openings on two dates, effective degrees of freedom 1.73); winter Plan 1 has one fitted value of 100.34% at an observed value of 98.61%. Lower mean counts and task differences use expanded references. High hours exceed 70% in the complete actual-hour record. Task differences are endpoint tasks per 100 activities. Position-hours sum recorded command and monitoring/coordination coverage, without estimating net labor savings.

The original comparison matched 112 hours and classified 16 of 21 Plan 1 openings as lower and all nine Plan 2 openings as higher. Figure 2 retains those estimates beside the expanded comparisons. Supplementary Sections S2 and S8 retain the original opening profiles and their comparison with proportional measurements; the measurement comparison and the change of reference pool are separate analyses.

3.2. Lower Opening Averages Coexist with Busy Hours

Summer Plan 1 contained eight high-occupancy hours among 42 hourly records (Figure 3a). Each busy hour had a positive contrast under expanded composition matching, ranging from +4.98 to +50.06 percentage points. SP1-03 and SP1-08 had opening means of −6.31 and −15.75, yet their respective busy-hour contrasts were +7.64 and +4.98 (Figure 3b). Thus, these two opening averages concealed a higher relative occupancy at the busy hour. SP1-05 and SP1-10 had higher opening means of +23.08 and +23.08 and three busy hours each. Supplementary Table S34 gives every busy-hour comparison.

Full-pool identical-context selection returned the same references as fixed-pair filtering. Six busy-hour comparisons remained, all in SP1-05 and SP1-10 and all positive. For each busy hour in SP1-03 and SP1-08, seven candidates met the traffic limits, but every candidate used the south-flow runway configuration while the actual hour used north flow. Neither hour therefore had a same-context reference in the supplied record (Supplementary Table S37). The check retained 38 of 42 summer Plan 1 hours and all ten openings, giving −6.93 percentage points. This mean describes the retained hours; the two omitted busy hours still lack same-context comparisons. Supplementary Tables S35 and S36 separate the effects of the retained sample, its weights and reference choices.

Reference coverage also explains the earlier mean change. Composition B within the original dates retained only two busy hours and 35 hours overall, giving −13.31 percentage points. Expanded matching restored all 42 hours and eight busy-hour comparisons, each restored busy hour using three reference dates. Its complete-record mean was −5.54; Supplementary Section S15 separates reference changes from restored hours and weights.

The eight busy hours are selected by their observed occupancy, so their contrasts describe those records without a separate significance test.

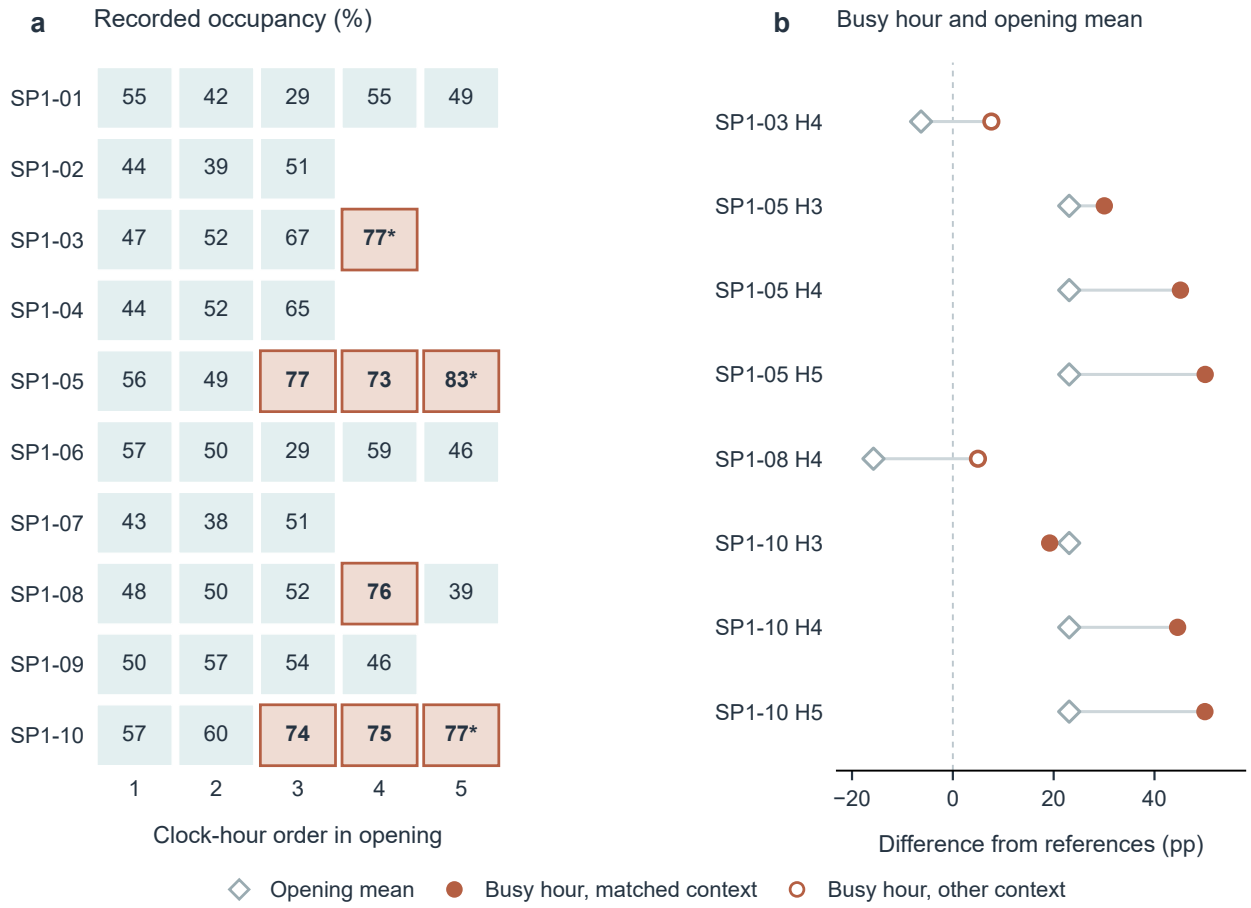


Figure 3. Busy-hour and opening-average contrasts in summer Plan 1. (**a**) Natural-hour maximum occupancy for all 42 records; blank cells indicate shorter openings. Rounded values are displayed, with counts based on unrounded seconds. Outlines mark hours above 70%; asterisks identify busy boundary hours. (**b**) Each circle gives a busy hour's expanded-reference contrast in percentage points (pp); the diamond gives its opening's mean, repeated when that opening has several busy hours. H in panel (**b**) labels denotes the numbered hour order in panel (**a**). Filled circles retain identical-context references; hollow circles have no identical-context reference in the supplied full candidate pool. Connecting lines are not uncertainty intervals; the vertical dashed line marks zero. The primary expanded comparison remains defined for every circle.

All eight busy hours had CH_N, serving responsibility area 3, as their busiest active-portion channel. CH_N was also busiest in 32 of the 34 other hours, or 40 of 42 records overall. This correspondence locates communication across the opening rather than identifying a cause specific to busy hours. Five busy records were full configuration hours. The other three covered 3441–3519 s of actual operation, with active densities of 78.46%, 85.91% and 80.96%; these remain distinct from natural-hour classifications (Supplementary Section S16).

The remaining groups contained one high hour among 28 winter Plan 1 labels, 11 among 14 winter Plan 2 labels and 16 among 30 summer Plan 2 labels. The two Plan 2 hours unmatched by the original rule were high; both now have expanded references.

Summer Plan 1 had 10, 10, 8 and 6 high hours at the 60%, 65%, 70% and 75% lines, respectively. Winter Plan 1 had 6, 3, 1 and 0. The persistence of summer busy hours therefore extends across the specified lines, whereas winter's single hour above 70% does not persist at 75% (Supplementary Table S18).

3.3. Radio Use Can Increase as the Busiest-Channel Share Falls

The busiest-channel share was lower than its expanded-reference mean in all 21 Plan 1 openings (Figure 4). Total radio use was higher in 13: four of 11 winter openings and nine of ten summer openings. Mean hourly maximum occupancy was lower in 19. The lower share therefore persisted more widely than an increase in total communication.

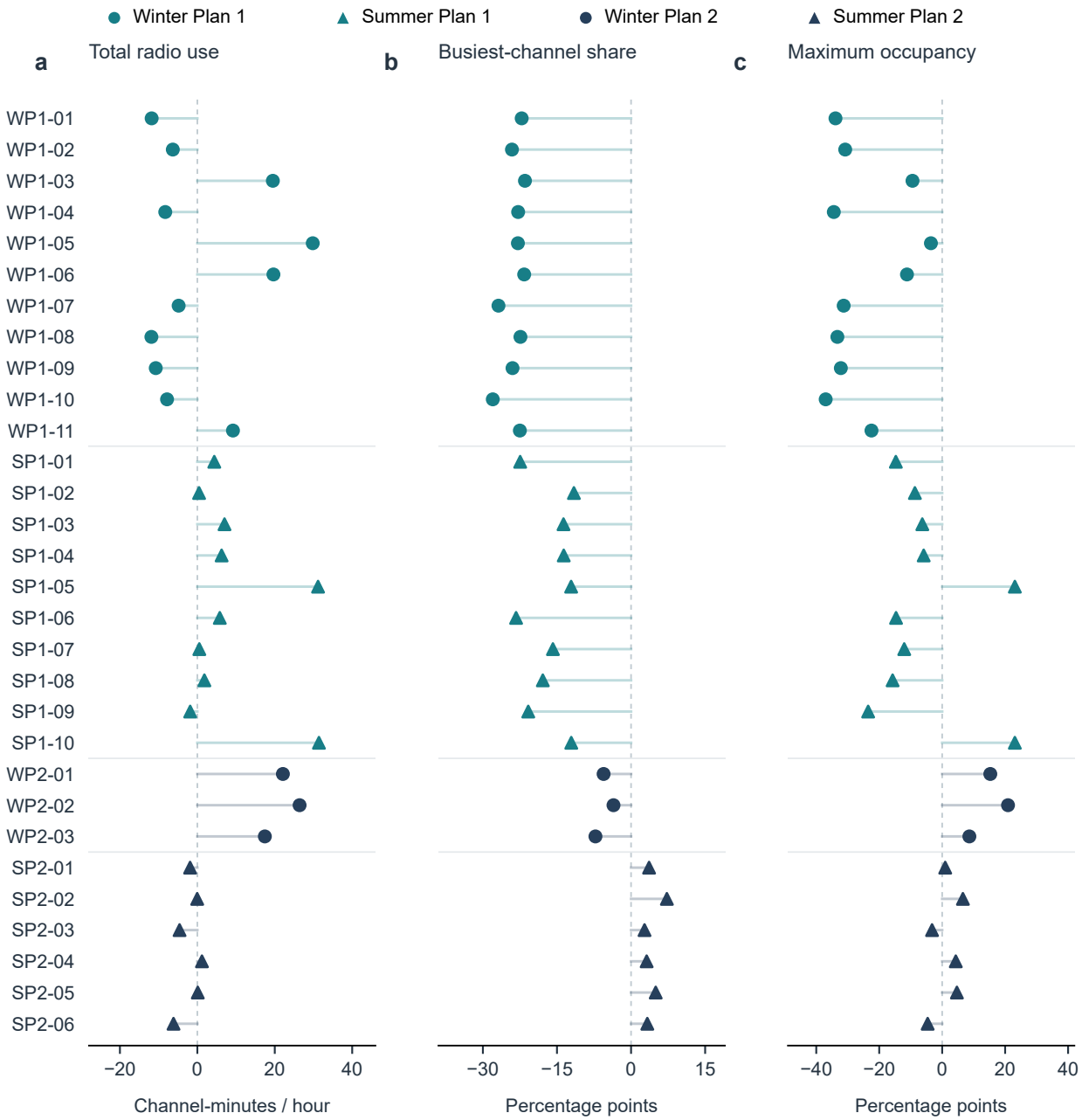


Figure 4. Radio use and its distribution across all 30 openings and 114 matched hourly labels under expanded composition matching. (**a**) Total radio use in summed channel-minutes per hour; (**b**) busiest-channel share in percentage points; (**c**) mean hourly maximum occupancy in percentage points. Each point is an actual-minus-reference mean using the same hours and weights across components. Teal/navy denote Plans 1/2; circles/triangles denote winter/summer. Dashed lines mark zero. W/S prefixes identify the period. These are descriptive contrasts, without episode-level sampling intervals. Occupancy averages hourly products; Supplementary Section S12 defines the covariance identity. The feasible minimum share changes with channel count.

All three winter Plan 2 openings had lower busiest-channel shares but higher totals and maxima. In summer Plan 2, all six shares were higher, while total radio use was higher in two openings and lower in four. Two of those openings also had lower maximum occupancy. These combinations show how the busiest channel's share and the airport total jointly determine its occupancy; neither component alone identifies the result.

Under the original references, 20 of 21 Plan 1 openings had higher total radio use and 16 had lower maximum occupancy. The corresponding expanded counts were 13 and 19. The smaller busiest-channel share persisted across reference pools, while the accompanying total and occupancy contrasts depended on the comparisons available (Supplementary Sections S12 and S18).

3.4. Interface Activity and Sensitivity to Comparison Hours

Interface-task rates were higher than their expanded references in all 21 Plan 1 openings, all three winter Plan 2 openings and five of six summer Plan 2 openings. Group differences were +29.98, +14.84, +5.14 and +5.69 tasks per 100 activities for winter Plan 1, summer Plan 1, winter Plan 2 and summer Plan 2, respectively (Table 2). Winter Plan 2's original rate difference of −4.30 became positive under expanded matching. The earlier combination of higher occupancy and fewer tasks therefore depended on its original references; it is not a persistent configuration characteristic.

Actual added-pair coverage totaled 224.71 position-hours: 54.71 and 27.72 in winter Plans 1 and 2, and 82.83 and 59.45 in summer. Command and monitoring/coordination positions covered each opening synchronously. Exact starts and ends account for the difference from the earlier 228-position-hour calculation based on complete coverage of all 114 labels.

Expanded references reduced winter Plan 1's concentration. Reference dates increased from eight to 30; the original dominant date's weight fell from 84.34% to 5.05%, and the largest remaining date weight was 10.35%. The more negative mean reflects these different reference levels as well as broader coverage. All 131 expanded real-date deletion contrasts retained their group point direction, although some left sharply reduced actual samples (Supplementary Section S17).

Using active-fragment densities preserved all four expanded group directions (Supplementary Table S30). Restricting the comparisons to full configuration hours changed both the retained hours and opening membership. Winter Plan 1 then contained only six hours in five openings, giving −19.05 percentage points and a task-rate difference of −0.48 per 100 activities. Its original-reference endpoint result, −1.03 percentage points and −5.13 tasks, remains in Supplementary Section S11. Table S30 reports every group's natural-hour, active-density and full-hour comparison.

4. Discussion

The additional team operated through communication conditions that were obscured by opening averages. Two lower-average openings contained busy hours whose occupancy exceeded selected references, but their traffic-eligible references used a different runway configuration. Six busy hours in two higher-average openings retained identical-context references. The complete opening record therefore shows both the communication encountered by the team and which periods support a closer relative comparison.

This finding complements Brunia's comparison of alternative ground-sector splits under common historical traffic [11]. That analysis relates the modeled benefit of a Center split to the demand it handles. The present records concern the subsequent operating question: how the additional team performed throughout an actual opening. The channel-to-area correspondence and configuration times place observed busy communication within

that operation. Comparing complete openings then connects the hourly conditions to the period of additional staffing, while retaining the distinct demand circumstances for which operators chose each plan.

4.1. Interpreting Total Radio Use and Channel Share

The radio components explain why a smaller busiest-channel share could accompany either occupancy direction. Every Plan 1 opening had a smaller share under both reference analyses, whereas the frequency of greater total use changed with the reference pool. Winter Plan 2 combined smaller shares with greater totals and higher maxima. The additional channel changes the feasible distribution of radio use, while demand can change its total. A lower share describes how communication was divided; interpreting it as relief at the busiest channel requires the accompanying total and hourly profile.

Relative occupancy and actual busy hours answer different operating questions. An opening may have a lower average because its references are busier, while one of its own hours still has heavy radio use. Summer Plan 1 retained busy hours after the expanded comparison restored its strict reference coverage. A related concern arises in potable-water-truck allocation, where longer service durations remain relevant even when the mean service time is known [27]. For apron control, the hourly profile makes these busy periods visible but leaves shorter bursts of communication congestion unresolved. Independent timing calibration would establish recording accuracy. Assessing cognitive workload and safety would require observations beyond radio and interface activity.

Several processes could contribute to the observed radio totals. Concentrated traffic or local restrictions can change communication at a given activity count, and a configuration may itself generate additional exchanges. Operators also selected plans in anticipation of different hotspots. The mean differences therefore reflect the layout and demand circumstances together. Comparing the layouts causally would require comparable demand under both plans, which these records do not provide. Optimization studies define demand and candidate layouts explicitly [16,17]; the present comparisons show the communication outcomes of the combinations actually chosen.

4.2. Interface Activity Belongs to the Operating Team

Responsibility transfers add an operational dimension to the radio results. Sectorization research connects task balance to trajectory segmentation and boundary changes [15], and human-in-the-loop work emphasizes clear transfers when configurations change [19]. Summer Plan 1 had higher task rates under both reference analyses, alongside openings with either mean-occupancy direction. Winter task contrasts were more reference- and sample-dependent. Operational burden would additionally depend on which tasks were prolonged, repeated or handled by the support position.

The accompanying support position is important to this interpretation. It can take part in monitoring and coordination while the command position handles radio traffic. Task-based assessments distinguish those activities [4], but the present summaries identify only the operating configuration. Assigning a burden to individual controllers would require their task roles and durations. Such accounting would also need to recognize that radio transfers are already included in channel timing, so an endpoint count adds information about activity without adding another measured duration.

The 224.71 command/support position-hours quantify the additional coverage provided during these openings. Converting coverage into a workforce requirement also involves rosters, as capacity planning distinguishes sector-hour budgets from staffing schedules [22]. FAA research uses recorded task activity to inform staffing provision while

distinguishing it from workload [28]. Net staffing efficiency would require task durations and the arrangements for rotation, rest and leave alongside the radio and interface results.

4.3. Operational Use and Transfer to Other Airports

SP1-03 and SP1-05 both had smaller busiest-channel shares and greater total radio use than their selected references, yet their opening-average occupancy contrasts were −6.31 and +23.08 percentage points. The first used 7.95 additional position-hours and contained one busy hour; the second used 9.87 and contained three. Interface-task rates were higher in both.

An operating review can begin with the complete opening average and then examine its busy hours. If the review objective is lower occupancy at the busiest channel, SP1-03 has a lower opening average than its selected references, while its busy hour remains above the local review line without an identical-context reference. SP1-05 has a higher opening average, and its three busy-hour contrasts remain positive with identical-context references. Radio totals and channel shares distinguish communication volume from its distribution. The associated interface rates and measured command/support coverage identify the activity and staffing commitment accompanying these radio conditions.

These operating judgments depend on the references available for each hour. The expanded winter pool reduced concentration but changed reference levels and the resulting mean. Summer intervals include both higher and lower mean occupancy. Those models describe precision in the selected comparisons. Estimating performance in future openings requires independent operating repetitions, for which winter Plan 2's three-opening sample provides particularly limited information.

Exact switching times locate communication within the active configuration, while the selected references still describe full hours at the endpoints. Closer comparisons of those portions would require reference communication and traffic measured over the same fractions of an hour.

The calculation can be repeated at another airport once its channels, responsibility interfaces and staffed positions are defined. Common timing and endpoint-counting rules are necessary for comparable radio and task measures. Differences in support ratios change the required position-hours, while differences in channel arrangements change the possible shares. Reference availability also depends on local traffic and operating practice. The repeatable element is therefore the link between a complete opening, its available comparisons and its staffing arrangement. Local plan rankings and the 70% review line require their own evidence at another site.

A prospective opening decision requires evidence from before the choice is made. The 24 summer decision entries cover ten Plan 1 openings, six Plan 2 openings and eight instances retaining two sectors, but registration followed the decision and coverage of all eligible opportunities is unknown. An exploratory comparison found higher planned sector shares in all eight busy hours than in same-clock, non-high Plan 1 hours from other openings; six busy hours had only one such reference (Supplementary Section S5, Table S7). These observations motivate recording anticipated demand and feasible configurations at the decision time. Dynamic configuration models include future demand, active positions and reconfiguration costs [18]. A prospective apron study could use those quantities to compare predefined opening rules under documented demand and full paired-position availability, including unsuccessful openings.

5. Conclusions

A lower opening-average occupancy can conceal busy hours encountered by an additional apron-control team. Expanded traffic-composition matching covered all 114 hourly

records. In two lower-average openings, busy-hour occupancy exceeded the selected references. Neither hour had an identical-context reference in the supplied full candidate pool, while six other busy hours retained positive contrasts. The openings used 224.71 additional command/support position-hours.

Group means changed materially with the reference pool, and the expanded summer conditional intervals crossed zero. Reviewing an opening through its hourly communication profile, comparable reference hours, radio distribution and interface activity relates the added team to the conditions it handled. The calculation can be repeated at other airports after their channels, tasks, staffing and references are defined.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/aerospace13110991/s1. The supporting information preserves the original 1008 h comparisons and all earlier sensitivity results (Sections S1–S14, Tables S1–S24 and Figures S1 and S2). Sections S15–S18 give expanded comparisons, actual timing and coverage, all conditional intervals and radio components (Tables S25–S33). Section S19 gives busy-hour contrasts, fixed-pair and full-pool identical-context checks for all openings, and the hours without comparable references (Tables S34–S37). The conditional-interval calculations use Reference [26].

Author Contributions: Conceptualization, C.L. and M.H.; methodology, C.L. and Z.Z.; software, C.L.; validation, C.L., Y.H. and Z.Z.; formal analysis, C.L.; investigation, H.B.; resources, H.B., M.H. and B.J.; data curation, C.L. and Y.H.; writing—original draft preparation, C.L. and H.B.; writing—review and editing, C.L., H.B., S.Z., Y.H., M.H., Z.Z. and B.J.; visualization, C.L. and J.W.; supervision, M.H.; project administration, C.L.; funding acquisition, C.L., M.H. and Z.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 52472345; the Key Program of the National Natural Science Foundation of China, grant number 52532010; and the National Key Research and Development Program of China, grant number 2022YFB2602401. The funders had no role in the design of the study; in the collection, analysis or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Institutional Review Board Statement: Not applicable. The study used de-identified operational aggregates and configuration and staffed-position coverage times, without individual-level human-subject measurements.

Informed Consent Statement: Not applicable.

Data Availability Statement: The analysis uses de-identified operational aggregates and configuration and staffed-position coverage times. Underlying operational records are not publicly available because of operational confidentiality and data-owner restrictions. De-identified aggregate results and figures are included in the article and Supplementary Materials with data-owner permission. Requests for additional materials should be directed to the corresponding authors and remain subject to data-owner approval. Analysis code and de-identified derivative data may be shared only where separately authorized by the data owner.

Acknowledgments: During the preparation of this work, the authors used ChatGPT (GPT-6.1 Sol) to improve language and readability. After using this tool, the authors reviewed and edited the text and take full responsibility for the content.

Conflicts of Interest: Author Huabo Bao was employed by Heilongjiang Airport Management Group Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Janić, M. A Model of Air Traffic Control Sector Capacity Based on Air Traffic Controller Workload. *Transp. Plan. Technol.* **1997**, *20*, 311–335. [CrossRef]
2. Djokic, J.; Lorenz, B.; Fricke, H. Air Traffic Control Complexity as Workload Driver. *Transp. Res. Part C Emerg. Technol.* **2010**, *18*, 930–936. [CrossRef]
3. Laudeman, I.V.; Shelden, S.G.; Branstrom, R.; Brasil, C.L. *Dynamic Density: An Air Traffic Management Metric*; Technical Memorandum NASA/TM-1998-112226; NASA Ames Research Center: Moffett Field, CA, USA, 1998. Available online: https://ntrs.nasa.gov/citations/19980210764 (accessed on 24 October 2026).
4. Li, C.; Hu, Y. Controller's Workload and Sector Capacity Assessment Based on 4D Track. In *Artificial Intelligence in China*; Lecture Notes in Electrical Engineering; Springer: Singapore, 2021; Volume 653, pp. 285–295. [CrossRef]
5. EUROCONTROL. Capacity Analysis Methodology (CAPAN). Available online: https://www.eurocontrol.int/methodology/capacity-analysis-methodology (accessed on 4 October 2026).
6. Chua, Z.; Causse, M.; Cousy, M.; Andre, F. Modulating Workload for Air Traffic Controllers during Airport Ground Operations. *Proc. Hum. Factors Ergon. Soc. Annu. Meet.* **2015**, *59*, 16–20. [CrossRef]
7. Müller, A.; Petru, R.; Angerer, P. Cognitive Demands and the Relationship between Age and Workload in Apron Control. *Aviat. Space Environ. Med.* **2011**, *82*, 26–33. [CrossRef] [PubMed]
8. Zamarreño Suárez, M.; Arnaldo Valdés, R.M.; Pérez Moreno, F.; Delgado-Aguilera Jurado, R.; López de Frutos, P.M.; Gómez Comendador, V.F. Methodology for Determining the Event-Based Taskload of an Air Traffic Controller Using Real-Time Simulations. *Aerospace* **2023**, *10*, 97. [CrossRef]
9. de Rooij, G.; Tisza, A.B.; Borst, C. Flight-Based Control Allocation: Towards Human–Autonomy Teaming in Air Traffic Control. *Aerospace* **2024**, *11*, 919. [CrossRef]
10. Di Mascio, P.; Carrara, R.; Frasacco, L.; Luciano, E.; Ponziani, A.; Moretti, L. How the Tower Air Traffic Controller Workload Influences the Capacity in a Complex Three-Runway Airport. *Int. J. Environ. Res. Public Health* **2021**, *18*, 2807. [CrossRef] [PubMed]
11. Brunia, S. Task Load Estimation for ATC Ground Control: A Dynamic Density-Based Analysis. Master's Thesis, Delft University of Technology, Delft, The Netherlands, 2023.
12. Muñoz-de Escalona, E.; Leva, M.C.; Gianini, G.; Lopez de Frutos, P.; Jadronova, M. Air Traffic Controllers Communication Analysis as a Proxy of Task Demand and Mental Workload: Using Voice Recording Markers for Safety Critical Task. *Saf. Sci.* **2025**, *191*, 106928. [CrossRef]
13. Manning, C.A.; Mills, S.H.; Fox, C.M.; Pfleiderer, E.M.; Mogilka, H.J. *Using Air Traffic Control Taskload Measures and Communication Events to Predict Subjective Workload*; Final Report DOT/FAA/AM-02/4; Federal Aviation Administration, Office of Aerospace Medicine: Washington, DC, USA, 2002. Available online: https://www.faa.gov/sites/faa.gov/files/data_research/research/med_humanfacs/oamtechreports/0204.pdf (accessed on 24 October 2026).
14. Hilburn, B. *Cognitive Complexity in Air Traffic Control: A Literature Review*; Technical Report EEC Note No. 04/04; EUROCONTROL Experimental Centre: Brétigny-sur-Orge, France, 2004. Available online: https://www.eurocontrol.int/sites/default/files/library/007_Cognitive_Complexity_in_ATC.pdf (accessed on 24 October 2026).
15. Gerdes, I.; Temme, A.; Schultz, M. Dynamic Airspace Sectorisation for Flight-Centric Operations. *Transp. Res. Part C Emerg. Technol.* **2018**, *95*, 460–480. [CrossRef]
16. Gómez Arnaldo, C.; Arroyo López, J.M.; Delgado-Aguilera Jurado, R.; Zamarreño Suárez, M.; Pérez Castán, J.A.; Pérez Moreno, F. Cell-Based Optimization of Air Traffic Control Sector Boundaries Using Traffic Complexity. *Aerospace* **2026**, *13*, 101. [CrossRef]
17. Zhao, T.; Escribano, J.; Majumdar, A.; Ochieng, W.Y. Robust 3D Dynamic Airspace Sectorization: A Multilayer Graph-Based Approach. *J. Air Transp. Manag.* **2026**, *132*, 102953. [CrossRef]
18. Bloem, M.; Gupta, P. Configuring Airspace Sectors with Approximate Dynamic Programming. In Proceedings of the International Council of the Aeronautical Sciences Congress (ICAS 2010), Nice, France, 19–24 September 2010; NASA NTRS 20100036788; ARC-E-DAA-TN1935. Available online: https://ntrs.nasa.gov/citations/20100036788 (accessed on 24 October 2026).
19. Ahrenhold, N.; Gerdes, I.; Mühlhausen, T.; Temme, A. Validating Dynamic Sectorization for Air Traffic Control Due to Climate Sensitive Areas: Designing Effective Air Traffic Control Strategies. *Aerospace* **2023**, *10*, 405. [CrossRef]
20. Jung, J.; Lee, P.U.; Kessell, A.M.; Homola, J.R.; Zelinski, S. Effect of Dynamic Sector Boundary Changes on Air Traffic Controllers. In Proceedings of the AIAA Guidance, Navigation, and Control Conference, Toronto, ON, Canada, 2–5 August 2010. [CrossRef]
21. EUROCONTROL. European Route Network Improvement Plan, Part 1: European Airspace Design Methodology Guidelines—General Principles and Technical Specifications for Airspace Design. Edition 3.3. 2026. Available online: https://www.eurocontrol.int/sites/default/files/2026-07/eurocontrol-ernip-part1-airspace-design-methodology-v3-3.pdf (accessed on 4 October 2026).
22. Starita, S.; Strauss, A.K.; Fei, X.; Jovanović, R.; Ivanov, N.; Pavlović, G.; Fichert, F. Air Traffic Control Capacity Planning under Demand and Capacity Provision Uncertainty. *Transp. Sci.* **2020**, *54*, 882–896. [CrossRef]

23. Li, N.; An, J.; Peng, J.; Olive, X.; Liu, X.; Gao, Z. Prediction of Apron Queue Length Based on a Single-Server Queueing Network Model. *Aerospace* **2026**, *13*, 156. [CrossRef]
24. Li, C.; Hu, M.; Zhao, Z.; Hu, Y.; Peng, Y. Non-Intersecting Diverging Runways Separation under Emergency Avoidance Situation. *Aerospace* **2023**, *10*, 131. [CrossRef]
25. Du, M.; Li, C.; Hu, Y.; Hu, M.; Zhao, Z.; Peng, Y.; Jiang, B. Runway–Corridor Composition Shapes Capacity Responses to Multi-Airport Demand Reallocation. *Aerospace* **2026**, *13*, 766. [CrossRef]
26. Pustejovsky, J.E.; Tipton, E. Small-Sample Methods for Cluster-Robust Variance Estimation and Hypothesis Testing in Fixed Effects Models. *J. Bus. Econ. Stat.* **2018**, *36*, 672–683. Correction in *J. Bus. Econ. Stat.* **2023**, *41*, 650–652. https://doi.org/10.1080/07350015.2023.2174123. [CrossRef]
27. Li, C.; Hu, M.; Hu, Y.; Zhao, Z.; Wang, Y. Enhancing Airport Resource Efficiency through Statistical Modeling of Heavy-Tailed Service Durations: A Case Study on Potable Water Trucks. *Aerospace* **2025**, *12*, 643. [CrossRef]
28. Manning, C.A.; Pfleiderer, E.M. *Relationship of Sector Activity and Sector Complexity to Air Traffic Controller Taskload*; Final Report DOT/FAA/AM-06/29; Federal Aviation Administration, Office of Aerospace Medicine: Washington, DC, USA, 2006. Available online: https://www.faa.gov/sites/faa.gov/files/data_research/research/med_humanfacs/oamtechreports/200629.pdf (accessed on 24 October 2026).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.