

Article

Evaluating Stand Allocation Scenarios for Airport Ground Delay Mitigation Using Fast-Time Simulation

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Abstract

At airports where both contact and remote stands are operated, stand allocation may influence aircraft ground movement flow and delay occurrence. However, directly validating alternative stand allocation strategies in an actual operational environment involves operational risks and controllability limitations. This study addresses these issues by developing and validating a SIMMOD-based fast-time simulation model for Gimpo International Airport, incorporating actual operational data, airport layout information, aircraft fleet composition, runway operating configurations, and stand operation characteristics. Model validation was conducted by comparing the simulated and observed hourly departure and arrival throughput and by evaluating taxi-time errors using the root mean square error and mean absolute error. Three stand allocation scenarios with different contact and remote stand allocation ratios were designed, and their effects on departure and arrival aircraft ground delay were compared. Using hourly outputs averaged over ten independent simulation replications, S1 and S2 showed lower mean departure ground delay than S0, whereas the arrival response exhibited greater hourly variability. Within-day nonparametric comparisons, supplemented by temporal-dependence diagnostics, identified significant differences between the baseline and alternative scenarios for total departure ground delay. These findings indicate that stand allocation can be considered an operational strategy for reducing airport ground delay.

Keywords: airport ground operation; fast-time simulation; ground delay; stand allocation

1. Introduction

Airport ground operations are a key determinant of airport operational performance, and aircraft taxi time and ground delay are directly associated with overall airport efficiency, including punctuality, runway, stand capacity, and operational predictability. The ICAO Global Air Navigation Plan (GANP) performance framework identifies additional taxi-out and taxi-in times as key indicators for evaluating airport operational performance [1]. In addition, airport collaborative decision-making (A-CDM) is a core concept that supports information sharing and collaborative decision-making among stakeholders in the air traffic flow management process [2]. The primary objective of this procedure is to improve operational predictability and ground operation efficiency through information sharing among airport stakeholders [3–5].

Previous research relevant to airport ground-delay analysis can be grouped into two broad streams. The first stream evaluates taxi-time and airport surface-performance characteristics using observed operational data, simulation, and data-driven methods.



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Zhang and Wang [6] estimated unimpeded taxi time and evaluated airport taxiing performance using actual operational data. Lee et al. [7] combined fast-time simulation and machine-learning techniques for taxi-time prediction, while Wang et al. [8] examined the contribution of operational features to taxi-time prediction. Within the context of domestic airport operations, studies have addressed variable taxi-time prediction, airport-capacity estimation using aircraft-delay simulation, delay-calculation methods for capacity assessment, turnaround-time improvement, and the factors contributing to airport delays [9–13]. These studies provide an important basis for measuring taxi-time and delay performance, but their primary focus is prediction or performance assessment rather than the evaluation of stand-allocation interventions.

The second stream addresses stand and gate assignment as an airport planning and optimization problem. Bouras et al. [14] surveyed and classified the airport gate-assignment problem, and Daş et al. [15] reviewed single- and multi-objective approaches. Guépet et al. [16] developed exact and heuristic approaches to stand allocation, Dijk et al. [17] examined recoverable robust stand allocation, and Yao et al. [18] integrated stand allocation with ground-support-vehicle scheduling. These studies have considered objectives and constraints such as passenger walking distance, boarding-bridge utilization, stand conflicts, operational robustness, and ground-handling resources.

Beyond allocation algorithms, previous studies have directly linked stand or gate decisions with aircraft taxi operations and airport surface flow. Kim et al. [19] incorporated aircraft taxi time, taxi delay, and ramp congestion into gate assignment. Neuman and Atkin [20] considered potential taxiway conflicts around gates during the allocation process, while Yang and Gao [21] integrated stochastic ground-movement scheduling with taxiway routing and gate/stand allocation. Remote-stand operations additionally require coordinated apron-bus transportation [22], and the feasible use of apron stands depends on physical and operational capacity constraints, including aircraft-type and user-mix considerations [23]. From a methodological perspective, simulation models should be validated in accordance with their intended analytical purpose using complementary verification and validation techniques [24], and airport ground-movement models benefit from calibration using observed taxi-time data [25]. Despite these research streams, relatively few studies have used a validated fast-time simulation model based on actual airport operations to quantify how changes in the aggregate contact-to-remote stand assignment structure affect departure and arrival ground delay.

This study addresses the existing gap by evaluating the impact of stand allocation strategies on airport ground delay using a validated fast-time simulation model, with Gimpo International Airport as a case study. This was achieved by developing a SIMMOD-based ground operation simulation model incorporating actual operational data from 2023, airport layout information, aircraft-type data, runway operating directions, and stand operation characteristics. The reproducibility of the simulation model was verified by comparing the simulation outputs with actual operational data. Subsequently, scenarios with stepwise changes in the allocation ratios of contact and remote stands were designed to analyze variations in departure and arrival ground delay and their statistical significance.

2. Methodology

2.1. Research Framework

This study aims to develop and validate a fast-time simulation model that accurately reproduces the ground operation characteristics of Gimpo International Airport and to quantitatively evaluate the effects of changes in stand allocation ratios on ground delay reduction using a highly reproducible model that reflects actual operating conditions. As illustrated in Figure 1, the research procedure comprises three stages.

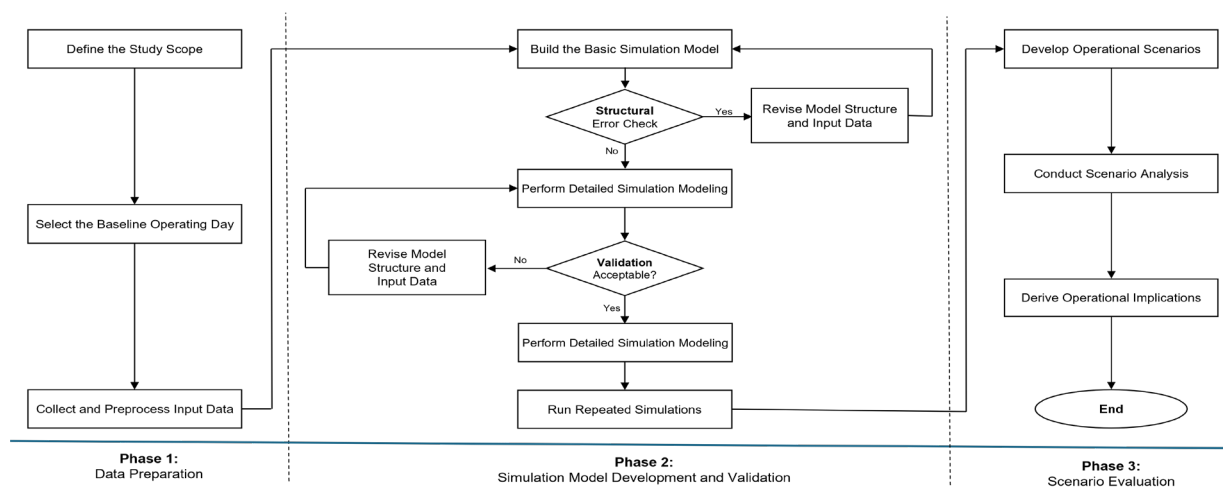


Figure 1. Framework for simulation scenario analysis.

First, input data, including aircraft operational data from 2023, airport layout information, and aircraft-type data, were collected from the aeronautical information management system, flight operation information system (FOIS), and A-CDM operational data. The baseline operating day was selected by comparing the runway direction stability, flight volume, on-time performance, and cancellation rates.

Second, simulation model development and validation were conducted. Based on the collected data, a SIMMOD-based node-link simulation network was constructed. The model comprised basic modeling, including runway-taxiway-stand connectivity, and detailed modeling involving parameter inputs such as aircraft-type-specific taxi speeds, separation minima, runway occupancy time, and pushback duration. The FAA REDIM-V4 model was used to estimate the runway exit taxiway usage ratios, which were applied as supplementary inputs. The model was validated and calibrated using actual hourly throughput and taxi-time data.

Third, operational scenario evaluation and result analysis were performed. Based on the validated baseline model, scenarios with different contact and remote stand allocation ratios were designed. The taxi time and ground delay under each scenario were calculated and comparatively analyzed. The scenario design and statistical testing procedures are presented in Figure 1.

2.2. Study Area and Input Data

The spatial scope of this study was defined as the airside area of Gimpo International Airport. The analysis included runways, taxiways, aprons, stands, and aircraft ground movement routes. Actual departure and arrival operational data from 2023 and airport layout information were used to reflect the actual airport operating environment as accurately as possible. As summarized in Table 1, most of the input data were constructed based on AIP, FOIS, and A-CDM data sources. The ICAO aerodrome reference code and wake turbulence category were applied to reflect the aircraft-type-specific operational characteristics [26]. These criteria were used to classify the aircraft categories and airport ground operation characteristics. In addition, the aircraft movement routes, runway and taxiway operational information, apron configurations, and stand operation information were incorporated to ensure that the input data could reproduce actual airport ground operation flows rather than simply predict the travel time.

Table 1. Input data used for the simulation model.

Data Type	Main Variables	Use in Simulation Model
Airport collaborative decision-making (A-CDM)/flight operation information system (FOIS) data	Flight number, scheduled time, arrival/departure, aircraft type	Traffic demand input, validation and performance comparison
Airport layout data	Runway, taxiway, apron, stand location	Airport network construction
Aircraft characteristics	Aircraft type, aerodrome reference code (ARC), wake turbulence category (WTC)	Aircraft movement parameter setting
Runway operation data	Arrival/departure runway direction	Runway configuration setting
Stand operation data	Contact stand, remote stand	Stand allocation scenario design

2.3. Baseline Operating Day Selection

The baseline operating day applied to the simulation model was selected as an actual representative normal-operation case rather than as a statistically synthesized average operating day. The purpose of selecting the baseline operating day was not to evaluate operational efficiency under a specific runway configuration, but to reproduce representative ground-operation flows at Gimpo International Airport under stable and non-abnormal operating conditions.

To quantitatively examine the traffic-demand level of the selected day, the daily aircraft movements for all 365 days of 2023 were analyzed. As shown in Figure 2, the annual mean was 372.38 aircraft movements per day, and the interquartile range was 364–386 movements per day. On 24 September 2023, a total of 380 aircraft movements were recorded, which was approximately 2.05% higher than the annual mean and within the interquartile range of the annual daily traffic distribution. Therefore, the traffic demand on the selected day was within the central range of normal airport operations rather than representing an exceptionally high- or low-demand condition.

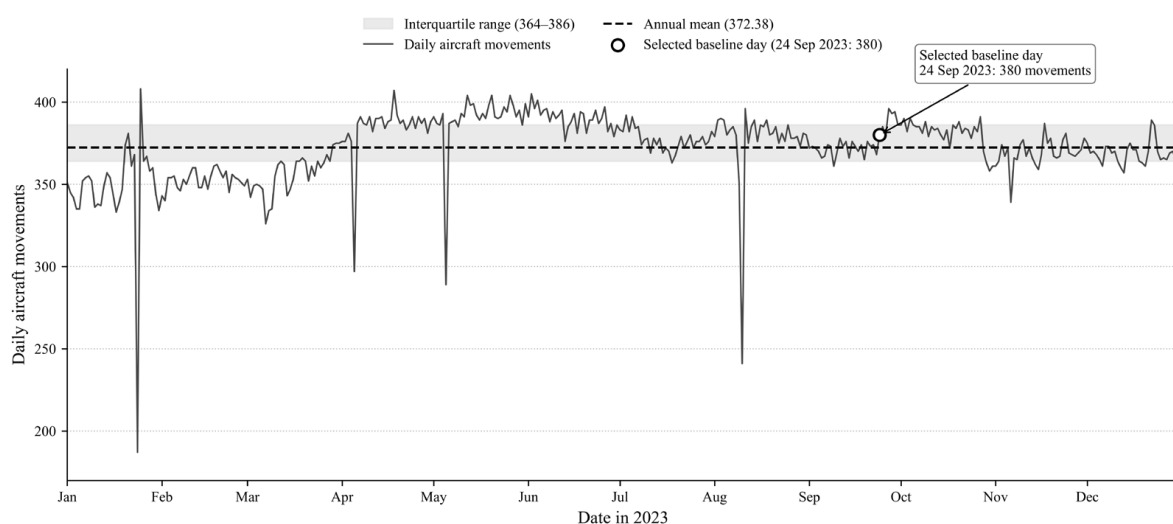


Figure 2. Daily aircraft movements at Gimpo International Airport in 2023 and the selected baseline operating day.

Candidate days were subsequently compared based on runway-direction stability, cancellation rate, delay rate, daily aircraft movements, and on-time performance. Days on which the runway operating direction remained unchanged throughout the analysis period were prioritized to minimize the influence of runway-configuration changes on aircraft ground movement. The effects of abnormal operations were further minimized by excluding days with cancellations, diversions, or other irregular operating conditions.

As summarized in Table 2, 24 September 2023 recorded 380 aircraft movements, with an on-time performance rate of 87.9%, a delay rate of 12.1%, and a cancellation rate of 0.0%. In addition to its traffic demand being within the central range of the annual distribution, the runway operating direction remained stable throughout the analysis period. Therefore, the date was selected as the representative baseline operating day for Gimpo International Airport. On that day, arrivals were operated on RWY 14R and departures on RWY 14L, and these conditions were applied as the operational schedule and runway configuration of the baseline simulation model. The actual stand utilization records for the selected day were also reflected in the baseline stand allocation configuration, thereby enabling the relative effects of stand allocation changes to be evaluated in the subsequent scenario analysis.

Table 2. Candidate days for baseline operating day selection.

Date	Number of Flights	On Time (%)	Delay (%)	Cancel (%)	Arrival RWY	Departure RWY
24 September 2023	380	87.9	12.1	0.0	14R	14L
21 November 2023	368	86.7	13.3	0.0	14R	14L
21 August 2023	400	78.5	21.5	0.0	14R	14L
4 December 2023	372	78.0	22.0	0.0	14R	14L
24 October 2023	390	71.0	29.0	0.0	14R	14L

2.4. Simulation Model Development

In this study, a SIMMOD-based fast-time simulation model was developed to reproduce the ground operations at Gimpo International Airport. SIMMOD is a discrete-event simulation model based on a node-link structure that represents runways, taxiways, aprons, stands, and aircraft movement routes as a network and calculates aircraft movement times and ground-delay-related indicators. Fast-time simulation tools are used to evaluate changes in airport and airspace operational efficiency using operational inputs such as airport capacity, traffic schedules, and operating conditions and producing outputs such as delay, throughput, and other performance measures [27,28].

The simulation model was developed in two stages: basic modeling and detailed modeling. In the basic modeling stage, the airport ground operation network was constructed by reflecting the runway, taxiway, apron, and stand configurations, as well as the aircraft movement routes at Gimpo International Airport. In the detailed modeling stage, operational parameters including the aircraft categories, taxi speeds, separation minima, runway occupancy time (ROT), pushback time, runway exit taxiway usage ratios, and exit taxiway occupancy time were incorporated. After the model was constructed, the connectivity of the aircraft movement routes, runway and taxiway occupancy conflicts, and occurrences of abnormal stops were examined and corrected to establish the baseline model shown in Figure 3.

However, some operational parameters were subject to limitations in obtaining direct observational data. In particular, owing to the lack of constraints in directly identifying runway exit taxiway usage ratios from actual surface surveillance data on the baseline operating day, this study employed the FAA Runway Exit Design Interactive Model Version 4 (REDIM-V4). The estimated values generated by REDIM-V4, reflecting the runway and exit taxiway geometry of Gimpo International Airport and the aircraft fleet composition on the baseline operating day, were applied as supplementary input data.

Figure 4 presents the runway exit taxiway usage ratios estimated using REDIM-V4. Each point represents the estimated result for a specific aircraft type, and the size of each circle indicates the operational proportion of the corresponding aircraft type on the baseline operating day. The vertical dashed lines represent the weighted average usage ratio for each exit taxiway based on the aircraft fleet composition. However, because these values

were generated by the REDIM-V4 model and not obtained from direct observations, they were applied as supplementary input variables for assigning runway exit locations to arriving aircraft.



Figure 3. Simulation model of the ground operations at Gimpo International Airport.

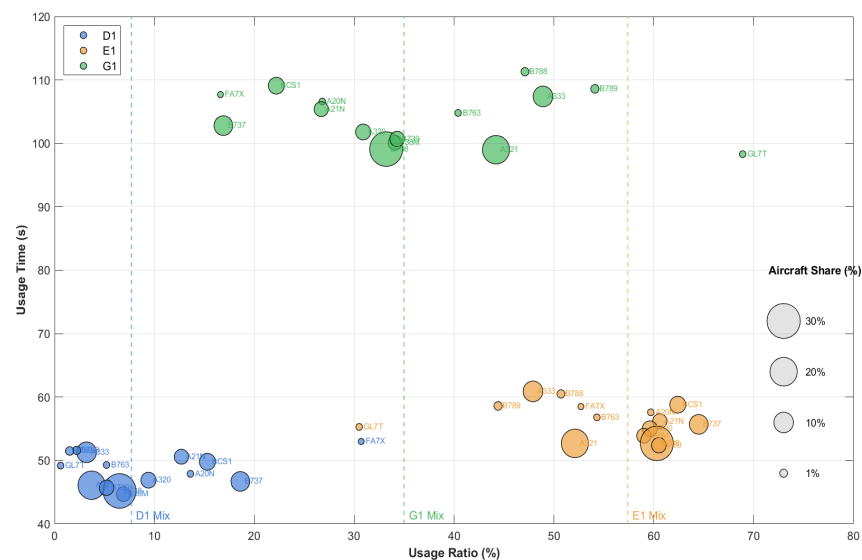


Figure 4. Runway Exit Design Interactive Model Version 4 (REDIM-V4)-based estimation of the runway exit usage ratios on the baseline operation day.

2.5. Model Calibration and Validation

Calibration and validation of the baseline model were performed to determine whether the model was sufficiently representative for the intended scenario-comparison purpose, consistent with established simulation verification and validation principles [24]. The validation model was developed under the RWY 14 operational configuration at Gimpo International Airport. Because several operational parameters were represented by probability distributions, ten independent simulation replications were conducted using different

random seeds. The hourly outputs were averaged across the replications to reduce dependence on any single random-seed realization and were subsequently used for model validation and scenario comparison. R^2 , RMSE, and MAE were used to assess agreement between the observed and simulated baseline operations, while the scenario analysis focused on the direction and magnitude of the mean response across the repeated runs. The validation indicators and model-calibration approach used in this study are summarized in Table 3.

Table 3. Model validation indicators and calibration approach.

Validation Component	Indicator	Purpose
Hourly arrival/departure throughput	Coefficient of determination (R^2) Root mean square error (RMSE), mean absolute error (MAE) slope, intercept	Reproducibility of aggregate traffic flow by time interval
Taxi-out and taxi-in time	Root mean square error (RMSE), mean absolute error (MAE)	Reproducibility of aircraft ground movement time
Repeated simulation	10 replications with different random seeds	Reduction in dependence on a single random-seed realization through output averaging
Calibration stages	Baseline, Calibrated Model 1, Calibrated Model 2	Evaluation of error reduction through model refinement
Outlier sensitivity check	RMSE, MAE after excluding upper 5%	Supplementary check of abnormal or special operational cases

Model validation was conducted in two stages. First, the simulation results were compared with actual observed data based on hourly arrival and departure aircraft throughput. Arrival and departure aircraft were analyzed separately, and the coefficient of determination (R^2) was used to verify the reproducibility of traffic distribution and hourly operational flow on the baseline operating day. Second, the simulation results were compared with actual values based on the aircraft taxi time.

The root mean square error (RMSE) and mean absolute error (MAE) were used for taxi-time validation. RMSE is calculated by averaging the squared differences between the predicted and observed values and then taking the square root. As such, it is sensitive to large errors. Conversely, MAE represents the average absolute difference between the predicted and observed values and indicates the average deviation of the simulation results from actual observations.

The simulation model was calibrated by adjusting the aircraft operating speeds, taxi routes, and selected operational parameters. After constructing the baseline model, discrepancies between the simulated and actual taxi times were identified. Subsequently, Calibrated Model 1 and Calibrated Model 2 were developed sequentially to evaluate the prediction error reductions. In addition, the RMSE and MAE were recalculated after removing the upper 5% of taxi-time outliers from the actual operational data to supplementarily analyze the influence of abnormal ground delays or special operational conditions on the model validation results.

In this study, model validation was not intended to reproduce the exact movement trajectory of each individual flight, but to verify whether the aggregated ground-operation flow and taxi-time characteristics of the baseline operating day could be reproduced at a level appropriate for scenario analysis. Accordingly, multiple complementary indicators were examined: hourly throughput was used to evaluate aggregate traffic-flow reproducibility, while RMSE and MAE were used to evaluate taxi-time agreement. This use of observed taxi-time data is consistent with airport ground-movement calibration approaches that distinguish operational movement characteristics from delay generated by traffic interactions [24,25].

2.6. Stand Allocation Scenario Design and Analytical Framework

The baseline scenario, S0, was established using the actual stand assignment records of the selected baseline operating day. Of the 380 flights operated on 24 September 2023, 36 flights were assigned to remote stands, corresponding to approximately 9.5% of the total flights. For consistency in scenario construction, this value was represented as a nominal remote-stand assignment share of 10%.

Let the set of stand assignment scenarios be defined as follows:

$$S = \{S0, S1, S2\} \quad (1)$$

Let N denote the total number of flights. Under scenarios, the numbers of flights assigned to remote and contact stands are represented in Equation (2), and the remote-stand assignment share is defined as:

$$q_s = \frac{N_{R,s}}{N}, \quad N_{C,s} = N - N_{R,s} \quad (2)$$

In Equation (2), q denotes the proportion of flights assigned to remote stands under scenario s . The target remote-stand assignment shares were set to 10%, 20%, and 30% for S0, S1, and S2, respectively, as summarized in Table 4.

Table 4. Stand allocation scenarios for Gimpo International Airport.

Scenario	Contact Stand (%)	Remote Stand (%)	Description
S0	90	10	Baseline scenario based on the observed remote stand usage on the reference operating day (36 out of 380 flights, constituting approximately 9.5%)
S1	80	20	Balanced scenario considering congestion mitigation and operational feasibility
S2	70	30	Aggressive scenario testing the upper-bound effect of remote stand utilization

To construct S1 and S2, flights assigned to contact stands in S0 were randomly selected without replacement and reassigned to remote stands until the target remote-stand assignment shares of 20% and 30%, respectively, were reached. No additional prioritization rule based on aircraft type, airline, scheduled operating time, or original contact-stand location was applied during this process, because the scenario design was intended to isolate the effect of changing the aggregate contact-to-remote stand assignment share rather than the effect of a specific flight-selection policy. The resulting flight-level assignment set for each scenario was fixed and maintained across all ten simulation replications.

Across all scenarios, the flight schedule, hourly traffic demand, aircraft fleet composition, runway operating configuration, airport ground network, aircraft performance parameters, and other simulation settings were held constant. Only the contact-to-remote stand assignment structure was changed. This controlled design enabled the effect of the aggregate remote-stand assignment share to be evaluated under identical baseline operating conditions.

Flight-level delay was indexed by flight, scenario, simulation replication, operation type, and delay component. The operation type was classified as departure or arrival, while the delay component was classified as GND, QUE, or TOT. GND represents the delay accumulated during aircraft movement within the airport surface network because of

operational interactions and conflicts, whereas QUE represents the waiting delay associated with the departure runway queue. For each flight, total ground delay was defined as the sum of ground-movement delay and queuing delay:

$$d_{i,s,k}^{o,TOT} = d_{i,s,k}^{o,GND} + d_{i,s,k}^{o,QUE} \quad (3)$$

For arrival aircraft, a separate queuing-delay component was not generated in the simulation output. Therefore, the arrival queuing delay was set to zero, and the total arrival ground delay was calculated as:

$$d_{i,s,k}^{arrival,TOT} = d_{i,s,k}^{arrival,GND} \quad (4)$$

For each operation type, the mean delay component obtained from simulation replication k was calculated across all corresponding flights as:

$$D_{s,k}^{o,m} = \frac{1}{N_o} \sum_{i=1}^{N_o} d_{i,s,k}^{o,m} \quad (5)$$

The average ground delay for each scenario was then calculated across the ten simulation replications:

$$\overline{D}_s^{o,m} = \frac{1}{K} \sum_{k=1}^K D_{s,k}^{o,m}, \quad K = 10 \quad (6)$$

The relative change in ground delay compared with the baseline scenario S0 was calculated as:

$$\Delta_s^{o,m} = \frac{\overline{D}_s^{o,m} - \overline{D}_{S0}^{o,m}}{\overline{D}_{S0}^{o,m}} \times 100 \quad (7)$$

A negative value of the relative change indicates a reduction in ground delay relative to S0, whereas a positive value indicates an increase. This analytical framework provides a consistent basis for evaluating how changes in the stand assignment structure affect aircraft taxi routes, apron congestion, departure flow after pushback, stand access for arriving aircraft, and the resulting departure and arrival ground delays.

2.7. Performance Indicators and Statistical Analysis

In this study, the hourly arrival and departure throughput, taxi time, and ground delay were established as the primary validation and evaluation indicators for verifying the reproducibility of the simulation model and assessing the effects of the stand allocation scenarios.

The hourly throughput was used as a model validation indicator to evaluate how accurately the simulation model reproduced the actual hourly traffic flow of the airport. The taxi time was used to evaluate the ground movement characteristics of aircraft, and the ground delay served as the key outcome variable for interpreting the effects of stand allocation scenarios on reducing airport ground delay. Taxi time and additional time have been widely used as major indicators for evaluating airport ground operation performance. This study compared the changes in the departure and arrival ground delay based on the simulation outputs. Scenario effects were compared using the average and total ground delay times. In addition, the hourly ground delay distributions were examined to determine whether the effects were concentrated during specific periods.

Because S0, S1, and S2 were generated by modifying only the stand allocation structure while maintaining the same traffic demand, runway operating conditions, and flight schedule, the hourly total ground-delay values averaged across the ten simulation replications were aligned by identical time intervals across the scenarios. The matched intervals from 06:00 to 22:00, during which aircraft operations were recorded, were used as blocks for the

within-day scenario comparison; the two subsequent zero-demand intervals were excluded from the statistical analysis.

Because consecutive hourly observations within a single operating day could potentially exhibit temporal dependence, serial correlation was assessed before conducting the nonparametric comparisons. Lag-1 autocorrelation coefficients and Ljung–Box tests at lags 1–3 were evaluated for the departure and arrival total ground-delay series under S0, S1, and S2. The same diagnostics were applied to the pairwise hourly difference series, defined as $\Delta t(a,b,o) = D_{a,t(o)} - D_{b,t(o)}$, where a and b denote two scenarios, o denotes departure or arrival operations, and t denotes the matched hourly interval.

Because arrival and departure operations share runway, taxiway, apron, and stand-access resources, contemporaneous correlations between departure and arrival total ground delay and one-period cross-lagged correlations between arrival delay at time t and departure delay at time $t + 1$, and vice versa, were also examined. In addition, a leave-one-period-out sensitivity check was performed by sequentially excluding each hourly interval and repeating the Friedman and Wilcoxon analyses to determine whether the statistical conclusions were driven by a specific period.

Considering the limited number of matched hourly observations and the difficulty of justifying the normality assumption, overall differences among S0, S1, and S2 were examined using the nonparametric Friedman test, with the 16 matched hourly intervals treated as blocks. When the Friedman test indicated a statistically significant overall difference, pairwise comparisons were conducted using the Wilcoxon signed-rank test. To account for the three pairwise comparisons, the Bonferroni-corrected significance level was set at 0.0167 (0.05/3). Kendall's W was calculated as $\chi^2/[N(k - 1)]$, where $N = 16$ denotes the number of matched hourly intervals and $k = 3$ denotes the number of scenarios, to quantify the effect size associated with each Friedman test.

The Friedman and Wilcoxon tests were applied to the hourly outputs averaged across the ten simulation replications. Accordingly, the results were interpreted as exploratory within-day comparisons of the mean scenario responses under the selected baseline operating conditions, rather than as population-level inferences across different operating days.

3. Results

3.1. Model Validation Results

The reproducibility of the simulation model was evaluated by comparing actual operational data from the selected baseline operating day with the simulation outputs. The simulation was repeated ten times using different random-number settings, and the averaged outputs were used to reduce the influence of any single random-seed realization. Model validation was conducted from two perspectives: the hourly arrival and departure throughput and the aircraft taxi time. The objective of this validation was not to reproduce the exact movement trajectory of each individual aircraft but to determine whether the ground operation flow and taxi-time characteristics of Gimpo International Airport under the baseline operating conditions could be reproduced at a level sufficient for scenario analysis.

Figure 5 presents the comparison between the simulation results and actual observed data for hourly departure and arrival aircraft throughput. The coefficient of determination (R^2) was 0.98 for departure aircraft and 0.99 for arrival aircraft. These results indicate that the simulation model successfully reproduced the hourly aircraft operation distribution on the baseline operating day, demonstrating that the input operational schedules, runway operating conditions, and airport ground network structure were appropriately implemented to represent hourly traffic flow. However, the hourly throughput comparison should be

interpreted as a verification of traffic flow reproducibility on the baseline operating day rather than a direct validation of the detailed movement routes or the actual taxi behavior of individual aircraft.

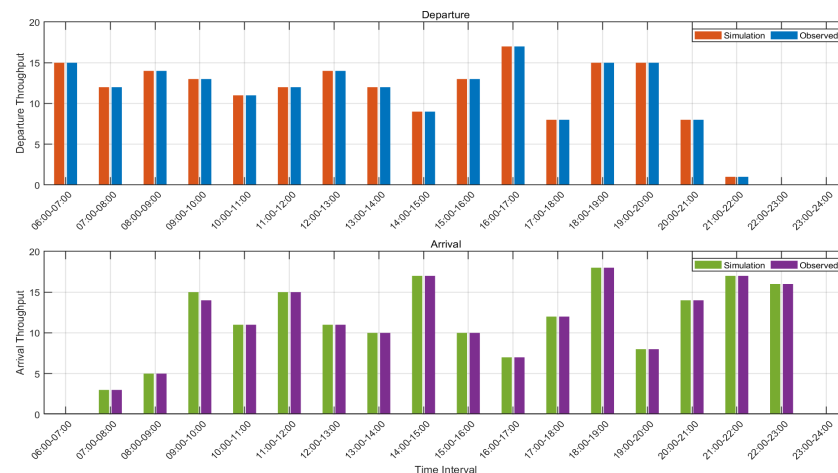


Figure 5. Comparison of the simulated and observed hourly throughputs at Gimpo International Airport.

To further examine the linear relationship underlying the reported R^2 values, Figure 6 presents scatter plots of the observed and simulated hourly throughput values together with linear regression and identity lines. For departure throughput, the regression slope was 1.000, the intercept was approximately 0, the MAE was 0.571 aircraft, and the RMSE was 0.708 aircraft. For arrival throughput, the regression slope was 1.000, the intercept was 0.004, the MAE was 0.414 aircraft, and the RMSE was 0.546 aircraft. In both cases, the regression lines closely overlapped the identity lines, indicating a strong linear relationship, limited systematic overestimation or underestimation, and relatively small hourly throughput errors. These supplementary results support the use of R^2 for evaluating the linear association between the observed and simulated hourly throughput values.

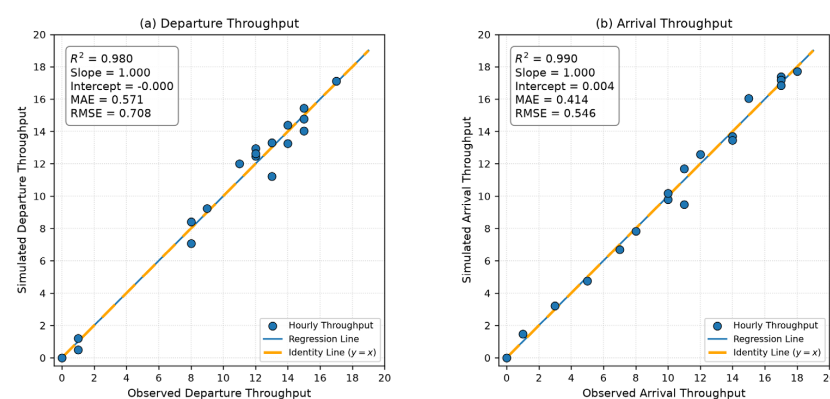


Figure 6. Linear relationship between observed and simulated hourly aircraft throughput: (a) departures; (b) arrivals.

The validation results for the taxi time are outlined in Tables 5 and 6. In the baseline model, the RMSE and MAE for departure aircraft were 3.56 min and 2.46 min, respectively, and 3.12 min and 1.98 min, respectively, for arrival aircraft. After two stages of model calibration, the final calibrated model exhibited reduced RMSE and MAE values of 2.52 min and 1.91 min, respectively, for departure aircraft. For arrival aircraft, the RMSE and MAE decreased to 3.06 min and 1.72 min, respectively. The reduction in the prediction error due to calibration was relatively distinct for the departure taxi time, whereas the reduction

in RMSE for the arrival taxi time was limited. This suggests that arrival aircraft taxi time may be more strongly influenced by factors that are difficult to fully reproduce within the simulation model, including runway exit taxiway selection, crossing flows within the apron area, stand access routes, and time-dependent operating environments.

Table 5. RMSE and MAE of the simulated taxi time by calibration stage.

Operation Type	Baseline		Calibrated Model 1		Calibrated Model 2	
	RMSE	MAE	RMSE	MAE	RMSE	MAE
Departure aircraft	3.56	2.46	2.86	2.27	2.52	1.91
Arrival aircraft	3.12	1.98	3.09	1.79	3.06	1.72

Table 6. RMSE and MAE of the simulated taxi time after removing the upper 5% of observations.

Operation Type	Baseline		Calibrated Model 1		Calibrated Model 2	
	RMSE	MAE	RMSE	MAE	RMSE	MAE
Departure aircraft	2.93	2.32	2.42	2.01	2.09	1.63
Arrival aircraft	1.89	1.67	1.78	1.35	1.72	1.29

In addition, a sensitivity analysis was conducted by excluding the upper 5% of the observed taxi-time values to examine the influence of abnormal ground delays or special operating conditions on the validation results. After excluding the upper 5% of observations, the RMSE and MAE for departure aircraft decreased to 2.09 min and 1.63 min, respectively, whereas those for arrival aircraft decreased to 1.72 min and 1.29 min, respectively. These results indicate that a small number of extreme taxi-time observations had a measurable influence on the error metrics and that the validation results for the arrival taxi time may be particularly sensitive to certain abnormal operational conditions.

The validation indicators and repeated simulations served distinct but complementary purposes: R^2 , RMSE, and MAE assessed agreement with observed operations, whereas the repeated runs reduced the influence of any single random-seed realization on the aggregate outputs.

3.2. Overall Effects of Stand Allocation Scenarios

The effects of stand allocation on ground delay were examined by comparing S0 (baseline), which reflected the actual remote stand utilization rate on the baseline operating day, with S1 (balanced) and S2 (aggressive), in which the remote stand utilization ratio was progressively increased. S0 was defined with a remote stand ratio of 10%, reflecting the 36 flights that used remote stands among the total 380 flights operated on the baseline operating day. Table 7 summarizes the mean ground-delay results across the ten simulation replications.

For arrival operations, mean total ground delay was 0.73 min/flight under S0, 0.49 min/flight under S1, and 0.51 min/flight under S2, corresponding to descriptive reductions of 32.9% and 30.1%, respectively, relative to S0. However, the arrival response was not monotonic: increasing the remote-stand assignment share from 20% in S1 to 30% in S2 did not produce an additional reduction, and the mean delay instead increased slightly by 0.02 min/flight. Therefore, the lower mean values under S1 and S2 should be interpreted as descriptive tendencies under the selected operating conditions rather than as evidence that progressively increasing remote-stand utilization consistently reduces arrival ground delay.

These results summarize the mean ground-delay response of the simulation model under the selected operating conditions. The hourly patterns and statistical significance of these differences are examined in the following sections.

Table 7. Mean ground-delay metrics and replication variability under different stand allocation scenarios (unit: min/flight).

Scenario	Contact (%)	Remote (%)	Dep GND	Dep QUE	Dep TOT, Mean $\pm$ SD	Dep TOT Δ vs. S0 (%)	Arr TOT, Mean $\pm$ SD	Arr TOT Δ vs. S0 (%)
S0	90	10	4.00	0.44	4.44 $\pm$ 0.37	–	0.73 $\pm$ 0.36	–
S1	80	20	3.43	0.43	3.87 $\pm$ 0.33	–12.8%	0.49 $\pm$ 0.28	–32.9%
S2	70	30	3.07	0.43	3.51 $\pm$ 0.22	–20.9%	0.51 $\pm$ 0.33	–30.1%

The validation errors reported in Tables 5 and 6 and the inter-scenario differences in Table 7 represent different aspects of model performance. RMSE and MAE quantify the absolute reproduction error between observed and simulated taxi times, whereas the scenario comparison evaluates relative differences under identical demand, model structure, and operational inputs. Therefore, the S0–S2 departure difference of 0.93 min/flight should not be interpreted as directly equivalent to the absolute validation error. Nevertheless, because this difference is smaller than the departure MAE (1.91 min) and RMSE (2.52 min), it should be interpreted as a relative model-based effect rather than an exact prediction of real-world delay reduction.

3.3. Hourly Ground Delay Patterns

The effects of stand allocation changes on ground delay reduction may vary depending on hourly traffic demand and ground operation flow. Therefore, hourly variations in the total ground delay were analyzed for each scenario to examine how increased remote stand utilization influenced departure and arrival ground delay patterns. This hourly analysis also provides supplementary evidence for interpreting the statistical differences among scenarios.

Figure 7 illustrates the hourly total departure ground delay under the three stand allocation scenarios. Overall, the total departure ground delay tended to decrease as the proportion of remote stand utilization increased. Larger absolute differences among the scenarios were observed during several periods with relatively high baseline departure delay.

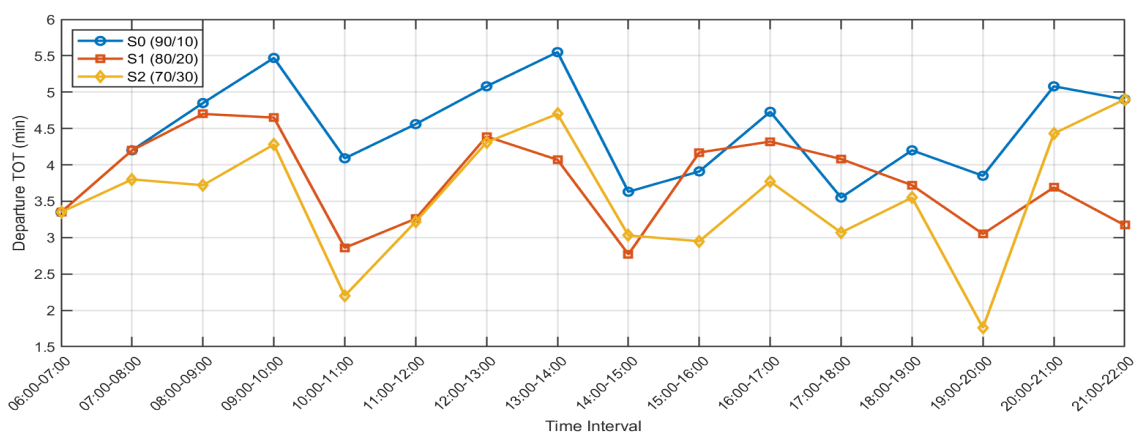


Figure 7. Hourly departure ground delay under different stand allocation scenarios.

Figure 8 presents the hourly total arrival ground delay under the same three stand allocation scenarios. Although the total arrival ground delay was generally lower than the total departure ground delay, differences were still observed among scenarios and hourly

fluctuations. On average, S1 and S2 reduced arrival ground delay compared with the baseline scenario. However, during certain periods, increasing the remote stand utilization ratio resulted in increased arrival ground delay. This suggests that arrival aircraft ground delay is not determined solely by the remote stand utilization ratio but is also influenced by the complex interactions between the stand access routes after runway exit, arrival concentration, crossing flows within the apron area, and stand locations.

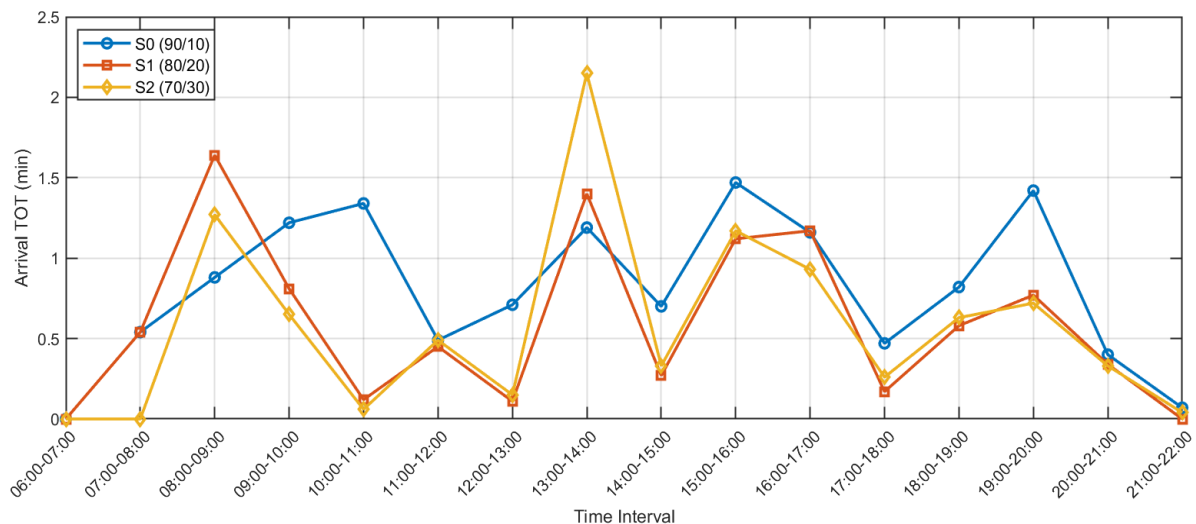


Figure 8. Hourly arrival ground delay under different stand allocation scenarios.

These hourly analyses demonstrate that the effects of stand allocation changes may differ for departure and arrival operations. Departure ground delay responded relatively consistently to increased remote stand utilization, whereas arrival ground delay exhibited greater variability depending on hourly operational conditions. Therefore, scenario effects should not be interpreted solely based on the average ground delay results. In addition, the hourly ground delay distributions must be considered together with statistical significance.

The hourly results show that the arrival response was not uniform across operating periods. Accordingly, the mean scenario differences were evaluated together with the statistical comparisons presented in Section 3.4.

3.4. Statistical Comparison of Scenarios

Before the scenario comparisons, temporal-dependence diagnostics were applied to the 16 matched hourly intervals. For the six scenario-specific departure and arrival total ground-delay series, the lag-1 autocorrelation coefficients ranged from -0.212 to 0.113 , and none of the Ljung–Box tests at lags 1–3 was statistically significant at the 5% level. For the six pairwise inter-scenario difference series, the lag-1 coefficients ranged from -0.292 to 0.485 , and all corresponding Ljung–Box results also remained above the 5% significance level. The departure S1–S0 difference series showed the highest lag-1 coefficient ($r = 0.485$), but its Ljung–Box result was not statistically significant ($p = 0.068$). Thus, statistically detectable serial correlation was not identified in the analyzed hourly series. The detailed serial-correlation diagnostics for the scenario-specific total ground-delay series and pairwise inter-scenario differences are summarized in Table 8. The departure–arrival cross-dependence assessment did not identify a statistically significant one-period cross-lagged relationship under any scenario. A moderate contemporaneous relationship was observed under S1 (Pearson $r = 0.575$, $p = 0.020$); however, it did not remain statistically significant after applying the Bonferroni-adjusted criterion of 0.0167 for the three scenario comparisons.

These results indicate that a systematic hourly carryover between departure and arrival ground delay was not statistically detectable in the analyzed data.

Table 8. Serial-correlation diagnostics for hourly total ground-delay series and pairwise differences.

Series	Lag-1 Coefficient	Ljung–Box <i>p</i> -Value	Interpretation
S0 departure TOT	0.063	0.823	Not significant
S1 departure TOT	0.063	0.783	Not significant
S2 departure TOT	−0.067	0.785	Not significant
S0 arrival TOT	0.113	0.652	Not significant
S1 arrival TOT	−0.122	0.647	Not significant
S2 arrival TOT	−0.212	0.395	Not significant
Departure S1–S0	0.485	0.068	Not significant
Departure S2–S0	0.184	0.472	Not significant
Departure S2–S1	0.223	0.452	Not significant
Arrival S1–S0	−0.105	0.653	Not significant
Arrival S2–S0	−0.292	0.208	Not significant
Arrival S2–S1	0.281	0.219	Not significant

Note: The Ljung–Box *p*-values shown in the table correspond to lag 1; the tests at lags 2 and 3 were also non-significant for all series. The analysis used the 16 operating intervals from 06:00 to 22:00.

The leave-one-period-out sensitivity check further showed that the overall departure comparison remained statistically significant regardless of which hourly interval was excluded. The S0–S1 and S0–S2 departure comparisons also remained significant under the Bonferroni-corrected criterion in every case, whereas the S1–S2 comparison remained non-significant. The arrival pairwise results were less stable across the exclusions, supporting a more conservative interpretation of the arrival-delay findings.

Based on these diagnostics, the matched hourly intervals were retained as blocks for the within-day Friedman and Wilcoxon comparisons. The tests were used to assess whether scenario differences were consistently distinguishable across the hourly operating periods of the selected baseline day, rather than to generalize the findings to independent operating days.

For the total departure ground delay, the Friedman test indicated statistically significant differences among the three scenarios ($\chi^2 = 17.6897$, $p = 0.000144$). The post hoc Wilcoxon signed-rank test showed that both S1 and S2 significantly reduced the total departure ground delay compared with the baseline scenario S0, and the significance remained valid after Bonferroni correction. The *p*-values were 0.002319 for the comparison between S0 and S1 and 0.000122 for the comparison between S0 and S2. By contrast, the difference between S1 and S2 was not statistically significant ($p = 0.207764$). These results indicate that increasing remote stand utilization effectively reduces the departure ground delay compared with the baseline scenario; however, further expansion from 20 to 30% cannot be conclusively interpreted as providing an additional statistically significant improvement. These findings are interpreted as within-day evidence for the selected baseline operating conditions.

For the total arrival ground delay, the Friedman test also indicated a significant overall difference among the three scenarios ($\chi^2 = 8.3793$, $p = 0.015152$). However, none of the pairwise comparisons conducted using the Wilcoxon signed-rank test remained statistically significant after Bonferroni correction. The *p*-values for S0 versus S1, S0 versus S2, and S1 versus S2 were 0.035278, 0.049438, and 0.772766, respectively, all of which exceeded the

corrected significance level of 0.0167. The significant Friedman result indicates that the hourly rank patterns were not identical across all three scenarios when considered jointly; it does not establish that either S1 or S2 individually provided a statistically confirmed reduction relative to S0. Because none of the pairwise comparisons remained significant after Bonferroni correction, the lower mean arrival delays under S1 and S2 should be interpreted as descriptive tendencies rather than statistically confirmed pairwise effects. This distinction explains why a lower aggregate mean can coexist with hourly reversals and the slightly higher mean delay in S2 than in S1. The overall Friedman test results and corresponding Kendall's W effect sizes are summarized in Table 9, while the post hoc Wilcoxon signed-rank test results are presented in Table 10.

Table 9. Friedman test results and Kendall's W effect sizes.

Metric	Scenario Comparison	χ^2	df	p-Value	Kendall's W	Interpretation
Departure TOT	S0 vs. S1 vs. S2	17.6897	2	0.000144	0.553	Significant
Arrival TOT	S0 vs. S1 vs. S2	8.3793	2	0.015152	0.262	Significant

Table 10. Wilcoxon signed-rank test results.

Metric	Scenario Comparison	p-Value	Adjusted α	Interpretation
Departure TOT	S0 vs. S1	0.002319	0.0167	Significant
Departure TOT	S0 vs. S2	0.000122	0.0167	Significant
Departure TOT	S1 vs. S2	0.207764	0.0167	Not significant
Arrival TOT	S0 vs. S1	0.035278	0.0167	Not significant
Arrival TOT	S0 vs. S2	0.049438	0.0167	Not significant
Arrival TOT	S1 vs. S2	0.772766	0.0167	Not significant

Overall, the pairwise statistical evidence was confirmed for the departure comparisons with S0, whereas the corresponding arrival comparisons were not significant after Bonferroni correction.

4. Discussion

4.1. Operational Interpretation of Scenario Effects

For departures, increased remote-stand assignment may disperse aircraft concentration around contact stands and alter pushback and apron movement flows before aircraft enter the departure queue.

By contrast, the arrival results did not show a monotonic or consistently significant response to increased remote-stand assignment. Although S1 and S2 exhibited lower mean arrival ground delay than S0, S2 did not improve upon S1, and higher arrival delays were observed during some hourly periods. None of the pairwise comparisons remained significant after Bonferroni correction. These findings indicate that the aggregate remote-stand assignment share alone does not determine arrival performance. Depending on the assigned stand, reassignment may shorten or lengthen the post-runway-exit route and change interactions with apron crossing flows and concentrated arrival traffic. Because S1 and S2 were controlled aggregate-share scenarios rather than optimized flight-to-stand plans, the results should not be interpreted as evidence of a uniform arrival-delay benefit from progressively increasing remote-stand utilization.

4.2. Practical Implications for the Stand Allocation Strategy

This study presents stand allocation not merely as a means of determining aircraft parking positions, but as an operational variable that can influence airport ground delay. Increasing the remote-stand assignment share reduced departure ground delay, whereas the improvement in arrival ground delay was relatively limited. These findings indicate that the operational value of remote stands depends not only on the proportion assigned, but also on how the allocation structure interacts with airport surface traffic and stand-access conditions.

S1 represents a scenario in which the observed remote-stand assignment share of approximately 9.5% on the baseline operating day was increased to a nominal target of 20%. This scenario produced a substantial reduction in departure ground delay, while maintaining a moderate level of remote-stand assignment. S2, with a target share of 30%, resulted in a further reduction in departure ground delay, although the incremental improvement over S1 was relatively limited. These results suggest that an intermediate level of remote-stand assignment may provide a useful basis for further operational assessment.

In practice, stand allocation decisions are influenced by a broader set of operational and service considerations. These include stand-use charges, airport-airline contractual arrangements, airline-specific stand preferences, passenger bus capacity, ground handling personnel and equipment, turnaround requirements, and transfer or connection constraints. The balance among these factors may differ according to the objectives of airport operators, airlines, and ground handling organizations. Therefore, stand allocation strategies should be evaluated by considering both airside delay performance and the operational resources required to support remote-stand operations.

Actual airport operations also require dynamic stand allocation strategies that account for hourly traffic flows and real-time operational constraints. The European A-CDM specification identifies stand and gate planning as a key responsibility of airport operators and emphasizes the continuous updating of allocation plans based on predicted stand occupancy, operational constraints, and information shared among stakeholders. Accordingly, stand allocation planning can be further enhanced by incorporating flight schedules, aircraft types, stand capacity, airline requirements, passenger transportation resources, and ground handling availability into a dynamically updated decision process.

4.3. Limitations and Future Research

This study quantitatively evaluated the effects of stand allocation changes on ground delay reduction using a validated fast-time simulation model. However, several limitations remain. First, because the analysis was conducted using a single baseline operating day, various operational variabilities, such as seasonal changes, day-of-week traffic fluctuations, peak-period demand patterns, and weather-related effects, could not be sufficiently reflected. Second, it was not confirmed whether similar effects would appear under different runway operating configurations. Because runway direction and runway-use patterns can influence runway exit selection, taxi routes, apron entry flows, and departure sequencing, the effects of stand allocation strategies may vary under different operating conditions. Third, some parameters, including runway exit taxiway usage ratios and push-back duration, relied on model-based estimates or assumed values owing to limitations in directly observed surface movement data. Fourth, the alternative scenarios were generated through random reassignment and evaluated primarily in terms of airside ground-delay performance. Consequently, S1 and S2 should be interpreted as controlled experimental configurations rather than as optimized operational stand plans. Therefore, the results should be interpreted as scenario-based evidence under the selected baseline operating conditions rather than as a universal operational rule applicable to all operating days.

Although no statistically detectable serial correlation or systematic one-period departure–arrival cross-lagged relationship was identified in the averaged hourly delay series, the temporal-dependence tests were based on only 16 operating intervals from a single baseline day. Failure to reject the serial-correlation tests does not prove complete independence, particularly with a limited number of observations. Accordingly, the Friedman and Wilcoxon results should be interpreted as supplementary within-day evidence under the selected baseline conditions, and multi-day validation remains necessary for broader statistical generalization.

The present analysis reports replication-level standard deviations for mean total ground delay across the ten simulation runs. Future studies should determine the required number of replications based on a predefined confidence-interval precision and examine stochastic uncertainty across multiple representative operating days.

Future studies should analyze the output from each replication separately, report run-level standard deviations and confidence intervals, and determine the required number of simulation runs based on a predefined confidence-interval precision. This extension would provide a more detailed characterization of stochastic uncertainty in the estimated scenario effects.

Future research should examine the generalizability of the results by incorporating multiple operating days and diverse operational conditions, including different runway configurations, traffic-demand levels, seasonal characteristics, and weather conditions. In addition, high-resolution surface-surveillance data, such as airport surface detection equipment (ASDE), ADS-B, or comparable airport surface-surveillance sources, should be utilized to more accurately extract taxi events, identify waiting time during taxiing, and reproduce aircraft movement trajectories and queuing delays. Surveillance-based taxi-event extraction has been shown to support airport surface-performance evaluation by identifying taxiing delay and delay-prone locations on the airport surface [29]. Incorporating such data would improve the calibration of runway-exit selection, taxi-route assignment, pushback behavior, apron crossing flows, and aircraft waiting patterns.

Furthermore, stand-allocation research should be extended toward a simulation–optimization framework capable of developing dynamic allocation algorithms that simultaneously consider multiple objectives, including aircraft-type-specific stand compatibility, turnaround time, ground-handling resources, passenger movement, stand-use costs, airline preferences, airport–airline contractual arrangements, and transfer or connection constraints. Integrated ground-movement studies have demonstrated the value of jointly considering taxiway routing and gate/stand allocation under operational uncertainty [21], while broader airport-surface optimization research has shown that integrated routing and scheduling can improve resource use and reduce taxi and gate waiting times [30]. Future stand-allocation models should therefore incorporate uncertainty-aware and dynamically updated operational constraints rather than relying solely on fixed contact-to-remote stand allocation ratios. Such extensions would support the joint evaluation of airside traffic flow, passenger service, ground-handling resource utilization, and operating costs.

5. Conclusions

This study evaluated the effects of contact and remote stand allocation ratios on aircraft ground delay at Gimpo International Airport using a fast-time simulation model. A SIMMOD-based ground operation model was developed using actual operational data from 2023, airport layout data, and aircraft-type information. The baseline model was validated using hourly throughput and taxi-time error indicators. The baseline scenario was established with a remote stand utilization ratio of 10%, reflecting the actual operating condition on the selected baseline day, in which 36 of 380 flights used remote stands. Based

on this configuration, two alternative scenarios with remote stand utilization ratios of 20% and 30% were designed, and their effects on departure and arrival ground delays were comparatively analyzed.

Under the selected baseline operating conditions, the alternative stand-allocation scenarios exhibited lower departure ground delay than S0, whereas the arrival response was less consistent across scenarios and operating periods. The additional departure-delay reduction from S1 to S2 was not statistically significant, and the pairwise arrival comparisons were not significant after Bonferroni correction. These findings remain conditional on the selected operating day and should not be generalized across different operating conditions without further validation.

These findings support considering stand allocation as an operational variable in airport ground-flow management. S1, with a 20% target remote-stand share, may serve as a reference scenario for further operational assessment; however, it should not be interpreted as an optimized or universally applicable allocation plan. Future research should incorporate multiple operating days, varying runway configurations, high-resolution surface surveillance data, and passenger and ground-handling resource constraints. Future evaluations should determine the required number of simulation runs based on predefined confidence-interval precision and assess stochastic uncertainty across multiple representative operating days.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

A-CDM	Airport Collaborative Decision-Making
ADS-B	Automatic Dependent Surveillance–Broadcast
AIP	Aeronautical Information Publication
ARC	Aerodrome Reference Code
ASDE	Airport Surface Detection Equipment
FAA	Federal Aviation Administration
FOIS	Flight Operation Information System
GANP	Global Air Navigation Plan
ICAO	International Civil Aviation Organization
MAE	Mean Absolute Error
REDIM	Runway Exit Design Interactive Model
RMSE	Root Mean Square Error
ROT	Runway Occupancy Time
RWY	Runway
WTC	Wake Turbulence Category

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