# Aircraft Boarding: When the Fastest Method Changes

An Agent-Based Simulation of Boarding Strategies Under Different Operating Conditions

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# 1 Executive Summary

Aircraft boarding is a moving congestion problem inside one of the narrowest spaces encountered in routine transport operations.

Passenger walking, luggage stowage, seat interference, boarding order, non-compliance, travel groups and aircraft-door configuration interact to determine the total boarding time.

The final experiment contained **66,000 simulation runs**: 11 boarding policies × 3 operating scenarios × 2,000 Monte Carlo trials. Across the audited model-development history, **523,460 simulation rows** were actually written to result workbooks.

**Single door**

CRBF
**13 min 55 sec**

**Dual door**

Steffen-Lug
**16 min 05 sec**

**Operational stress**

CRBF
**29 min 43 sec**

The primary result is therefore not simply that one strategy won.

**The optimal boarding strategy changed when operating conditions changed.**

# 2 Explore the Boarding Process

The visualization below uses representative deterministic runs from the same V3.1.2 simulation engine used in the final experiment.

The animation is illustrative. The reported statistical conclusions are based on 2,000 Monte Carlo trials per strategy-scenario combination.

The HTML edition includes an interactive aircraft-cabin explorer where the reader can switch between boarding strategies and operating scenarios and observe passenger movement, luggage stowage and seating.

# 3 1. Introduction

Aircraft boarding appears simple from the passenger perspective: enter the aircraft, find a seat, store luggage and sit down.

Operationally, however, each passenger becomes part of a dynamic queue inside a narrow single aisle.

The effectiveness of a boarding strategy therefore depends on how well it distributes passenger activity through the aircraft while preventing local bottlenecks.

# 4 2. Why Boarding Strategy Matters

Common sources of delay include:

- walking through the aisle,
- luggage stowage,
- limited aisle width,
- simultaneous use of nearby overhead bins,
- passengers blocking one another,
- seat interference,
- travel groups,
- deviations from the prescribed boarding order,
- and front/rear door infrastructure.

The optimization objective is not simply to create an orderly queue.

It is to maximize useful parallel activity inside the cabin.

## 5 3. Boarding Strategies

The final comparison included seven academic or optimization-oriented methods:

- CRBF
- Steffen
- Steffen-Lug
- Reverse Pyramid (adapted)
- WilMA
- Random
- Back-to-Front

and four simplified airline-like structures:

- Ryanair-like
- easyJet-like
- Lufthansa-like
- US Network-like

The airline-like policies are structural approximations for comparative simulation and are not exact reconstructions of every real-world boarding procedure.

## 6 4. Model Development

The project contains **19 named simulation script files representing 18 unique executable versions**. `boarding_simulation_v3.py` and `boarding_simulation_v3_0.py` are byte-identical aliases and share the same V3.0 result workbook, so they are counted once rather than double-counted.

The counts below were audited against each script's loop structure and the row count of the corresponding `All Runs` worksheet. They are recorded executions, not estimates.

| Version | Main change / research question | Trials and design | Simulations | Cumulative |
|---|---|---|---|---|
| V1.0 | Baseline 26-row, 156-passenger agent model; Random, Back-to-Front, WilMA and Steffen. | 100 per strategy | 400 | 400 |
| V1.1 | Diagnostic validation: distributions, stowing, blocking, seat interference, throughput and experimental comparison. | 100 per strategy | 400 | 800 |

| Version | Main change / research question | Trials and design | Simulations | Cumulative |
|---|---|---|---|---|
| V1.2 | Cabin-length replication test: 26-row baseline versus the 12-row, 72-passenger experimental geometry. | 100 × 2 geometries × 4 strategies | 800 | 1,600 |
| V1.3 | Movement-realism sensitivity: entry headway, aisle spacing, restart delay and combined configurations. | 100 × 2 geometries × 12 configs × 4 | 9,600 | 11,200 |
| V1.4 | Exact literature-oriented Steffen order and luggage-stowing footprint sensitivity. | 100 × 2 geometries × 2 footprints × 5 | 2,000 | 13,200 |
| V1.5 | Concurrent luggage-stowing sensitivity across seven proximity/penalty configurations. | 100 × 2 geometries × 7 configs × 4 | 5,600 | 18,800 |
| V1.6 | Final calibration and robustness validation of continuous nearby-stower interference. | 500 × 23 calibration configs × 4 | 46,000 | 64,800 |
| V2.0 | Operational experiment begins: load-factor and carry-on-luggage intensity scenarios. | 500 × 7 scenarios × 4 | 14,000 | 78,800 |
| V2.1 | Passenger compliance and travel-group cohesion added as behavioural dimensions. | 500 × 9 scenarios × 4 | 18,000 | 96,800 |

| Version | Main change / research question | Trials and design | Simulations | Cumulative |
|---|---|---|---|---|
| V2.2 | First dual-door infrastructure model with front and rear passenger streams. | 500 × 2 door scenarios × 4 | 4,000 | 100,800 |
| V2.3 | Deterministic paired infrastructure validation and balanced front/rear assignment. | 500 × 3 infrastructure modes × 4 | 6,000 | 106,800 |
| V2.4 | Full load-factor × cabin-occupancy × door-infrastructure factorial sensitivity. | 500 × 3 × 3 × 3 × 4 | 54,000 | 160,800 |
| V3.0 | Frozen physical engine and six final production scenarios (v3.py is an identical alias). | 5,000 × 6 scenarios × 4 | 120,000 | 280,800 |
| V3.0.1 | Targeted validation of entry release, walking/spacing and seat-interference overlap. | 1,000 × 10 configs × 4 | 40,000 | 320,800 |
| V3.0.2 | External replication of the 72-passenger Steffen–Hotchkiss experiment. | 1,000 × 4 strategies | 4,000 | 324,800 |
| V3.1 | Seven academic and four airline-like policies compared in three final scenarios. | 2,000 × 3 scenarios × 11 | 66,000 | 390,800 |
| V3.1.1 | Methodological audit corrected CRBF, Reverse Pyramid and Steffen-Lug implementations. | 2,000 × 3 scenarios × 11 | 66,000 | 456,800 |

| Version | Main change / research question | Trials and design | Simulations | Cumulative |
|---|---|---|---|---|
| V3.1.2 | Final policy definitions; verified smoke run followed by the final 2,000-trial experiment. | 20 smoke + 2,000 final; each × 3 × 11 | 66,660 | 523,460 |

The cumulative total is **523,460 simulations**. This includes the V3.1.2 smoke test (660 runs) and its separate final run (66,000 runs).

The development path moved from baseline mechanics, through experimental replication and sensitivity analysis, into behavioural and infrastructure scenarios. V3.0 froze the physical engine; V3.1–V3.1.2 then concentrated on policy breadth and literature-correct definitions. Reverse Pyramid remains reported as **Reverse Pyramid (adapted)** because its published A320 zones were proportionally adapted to a 26-row all-economy cabin.

# 7 5. Experimental Design

| Scenario | Doors | Luggage | Compliance | Travel groups |
|---|---|---|---|---|
| Single door | Front | Baseline | 100% | 0% |
| Dual door | Front + rear | Baseline | 100% | 0% |
| Operational stress | Front | High | 75% | 25% |

Each strategy was evaluated with **2,000 Monte Carlo trials per scenario**.

The final dataset therefore contains **66,000 simulations**. `TRIALS_PER_SCENARIO` is a single explicit builder parameter. Setting it to 5,000 is prepared for a future matching result workbook, but this builder never reruns the simulation automatically.

# 8 6. Statistical Analysis

Because policies within each trial were evaluated using matched passenger realizations, strategy comparisons were paired.

The statistical analysis included:

- paired t-tests,
- Wilcoxon signed-rank tests,
- Holm multiple-comparison correction,
- Cohen's dz,
- 95% confidence intervals,
- win probabilities,
- P95 boarding times,
- and variability measures.

With 2,000 trials, small effects can become statistically significant.

Operational interpretation therefore prioritizes:

1. absolute time difference,
2. percentage difference,

3. effect size,
4. win probability,
5. P95 performance.

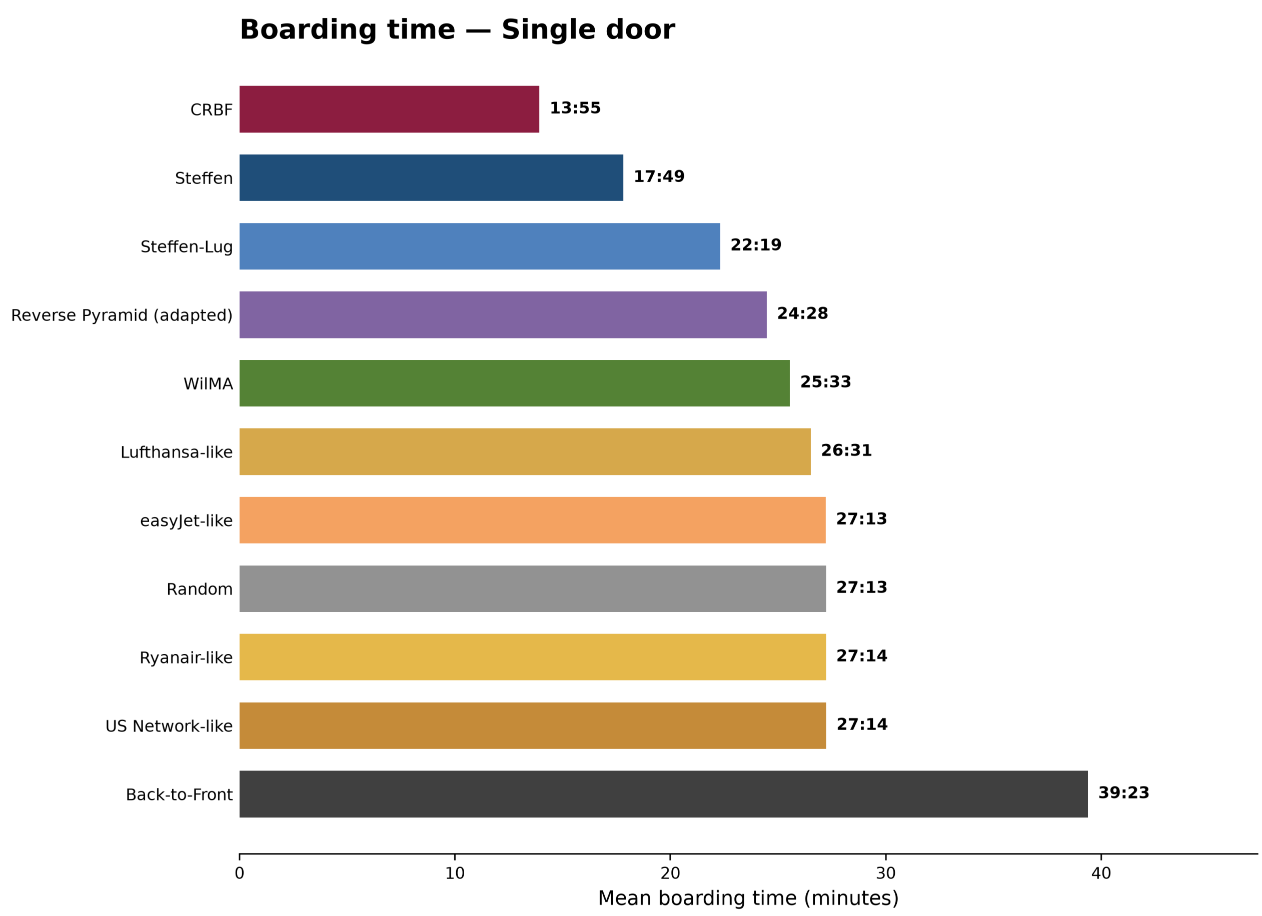
## 8.1 6.1 Convergence check from the existing final runs

A post-hoc running-mean check used the existing 66,000 `All Runs` rows; no simulation was rerun. Across all 33 scenario × policy groups, the median absolute change from 500 to 2,000 trials was **1.59 seconds** and the largest was **7.48 seconds**. From 1,500 to 2,000 trials, the median change was **1.18 seconds** and the largest was **9.04 seconds**.

At 2,000 trials, the median Monte Carlo 95% half-width for a mean was **4.14 seconds**; the maximum was **7.26 seconds**. These diagnostics support the stability of the reported mean estimates at the seconds-to-low-tens-of-seconds scale. A 5,000-trial run would reduce Monte Carlo standard errors to about 63.2% of their present size, but it is not required to reinterpret the existing results as valid.

# 9 7. Results

## 9.1 7.1 Single-door scenario



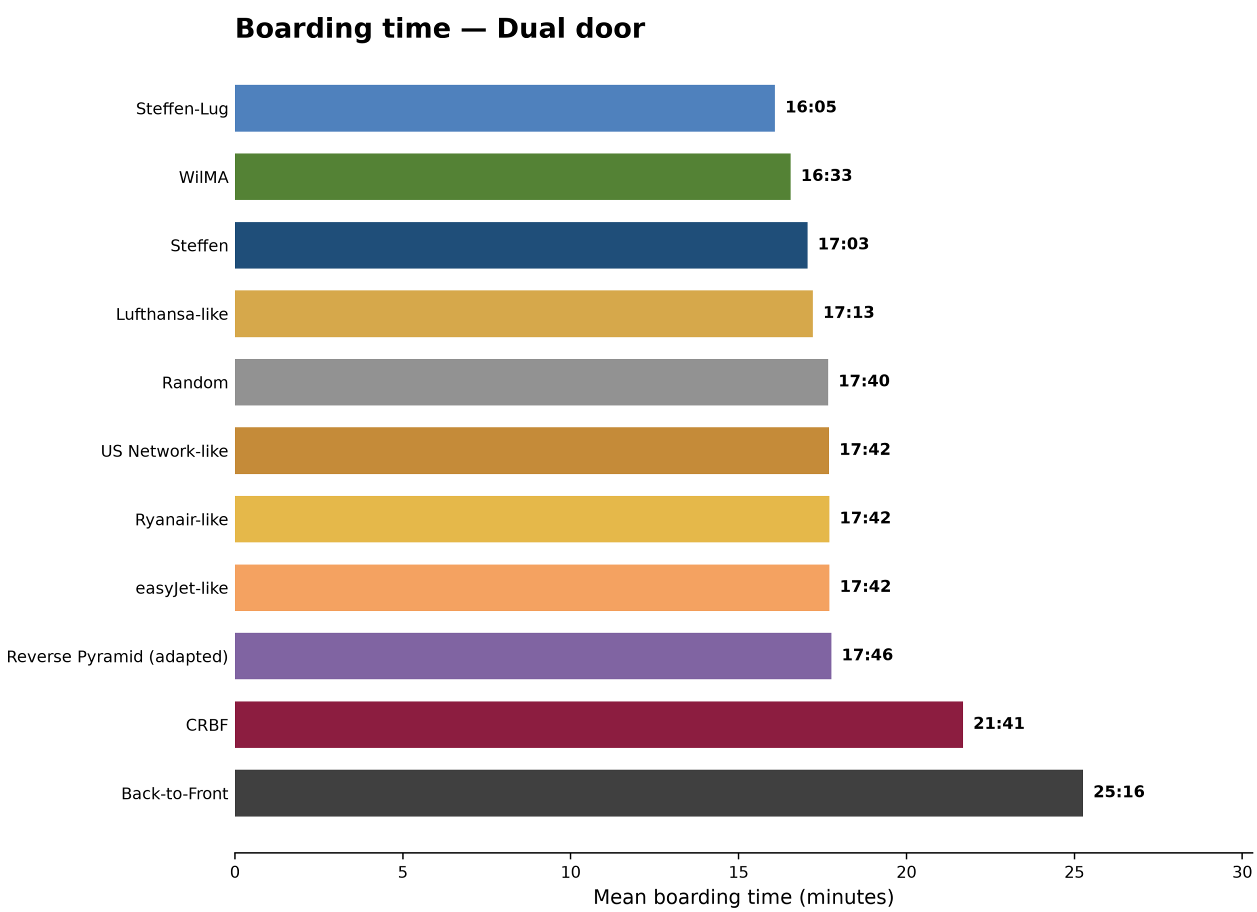

| Rank | Strategy | Mean | P95 | SD |
|---|---|---|---|---|
| 1 | CRBF | 13 min 55 sec | 14 min 52 sec | 0.54 min |
| 2 | Steffen | 17 min 49 sec | 19 min 04 sec | 0.74 min |
| 3 | Steffen-Lug | 22 min 19 sec | 24 min 26 sec | 1.24 min |

| Rank | Strategy | Mean | P95 | SD |
|---|---|---|---|---|
| 4 | Reverse Pyramid (adapted) | 24 min 28 sec | 26 min 58 sec | 1.39 min |
| 5 | WilMA | 25 min 33 sec | 28 min 02 sec | 1.45 min |
| 6 | Lufthansa-like | 26 min 31 sec | 29 min 17 sec | 1.59 min |
| 7 | easyJet-like | 27 min 13 sec | 29 min 57 sec | 1.55 min |
| 8 | Random | 27 min 13 sec | 30 min 00 sec | 1.60 min |
| 9 | Ryanair-like | 27 min 14 sec | 29 min 58 sec | 1.60 min |
| 10 | US Network-like | 27 min 14 sec | 29 min 51 sec | 1.61 min |
| 11 | Back-to-Front | 39 min 23 sec | 42 min 42 sec | 1.96 min |

CRBF was the fastest strategy in the clean single-front-door scenario, averaging **13 min 55 sec**.

Its performance was associated with extremely low aisle blocking and high parallel luggage-stowage activity.

## 9.2 7.2 Dual-door scenario




| Rank | Strategy | Mean | P95 | SD |
|---|---|---|---|---|
| 1 | Steffen-Lug | 16 min 05 sec | 17 min 44 sec | 0.95 min |
| 2 | WilMA | 16 min 33 sec | 18 min 26 sec | 1.07 min |
| 3 | Steffen | 17 min 03 sec | 18 min 52 sec | 1.13 min |

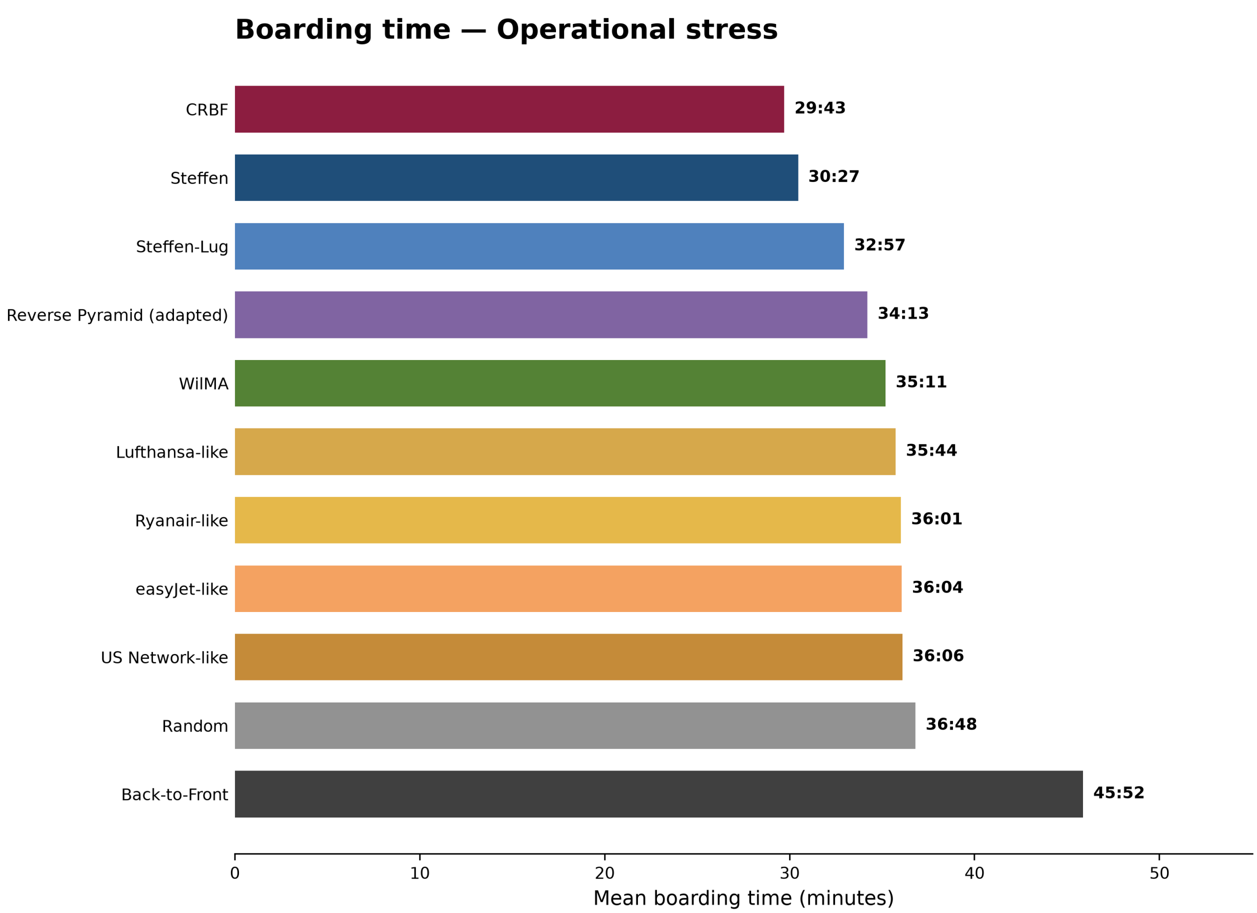
| Rank | Strategy | Mean | P95 | SD |
|---|---|---|---|---|
| 4 | Lufthansa-like | 17 min 13 sec | 19 min 08 sec | 1.12 min |
| 5 | Random | 17 min 40 sec | 19 min 40 sec | 1.16 min |
| 6 | US Network-like | 17 min 42 sec | 19 min 52 sec | 1.19 min |
| 7 | Ryanair-like | 17 min 42 sec | 19 min 47 sec | 1.15 min |
| 8 | easyJet-like | 17 min 42 sec | 19 min 43 sec | 1.17 min |
| 9 | Reverse Pyramid (adapted) | 17 min 46 sec | 19 min 42 sec | 1.10 min |
| 10 | CRBF | 21 min 41 sec | 23 min 57 sec | 1.36 min |
| 11 | Back-to-Front | 25 min 16 sec | 27 min 57 sec | 1.57 min |

Opening both the front and rear doors changed the ranking.

Steffen-Lug became the fastest method at **16 min 05 sec**.

This demonstrates that the fastest strategy cannot be identified independently of aircraft infrastructure.

## 9.3 7.3 Operational stress




| Rank | Strategy | Mean | P95 | SD |
|---|---|---|---|---|
| 1 | CRBF | 29 min 43 sec | 33 min 00 sec | 1.93 min |
| 2 | Steffen | 30 min 27 sec | 33 min 51 sec | 1.93 min |

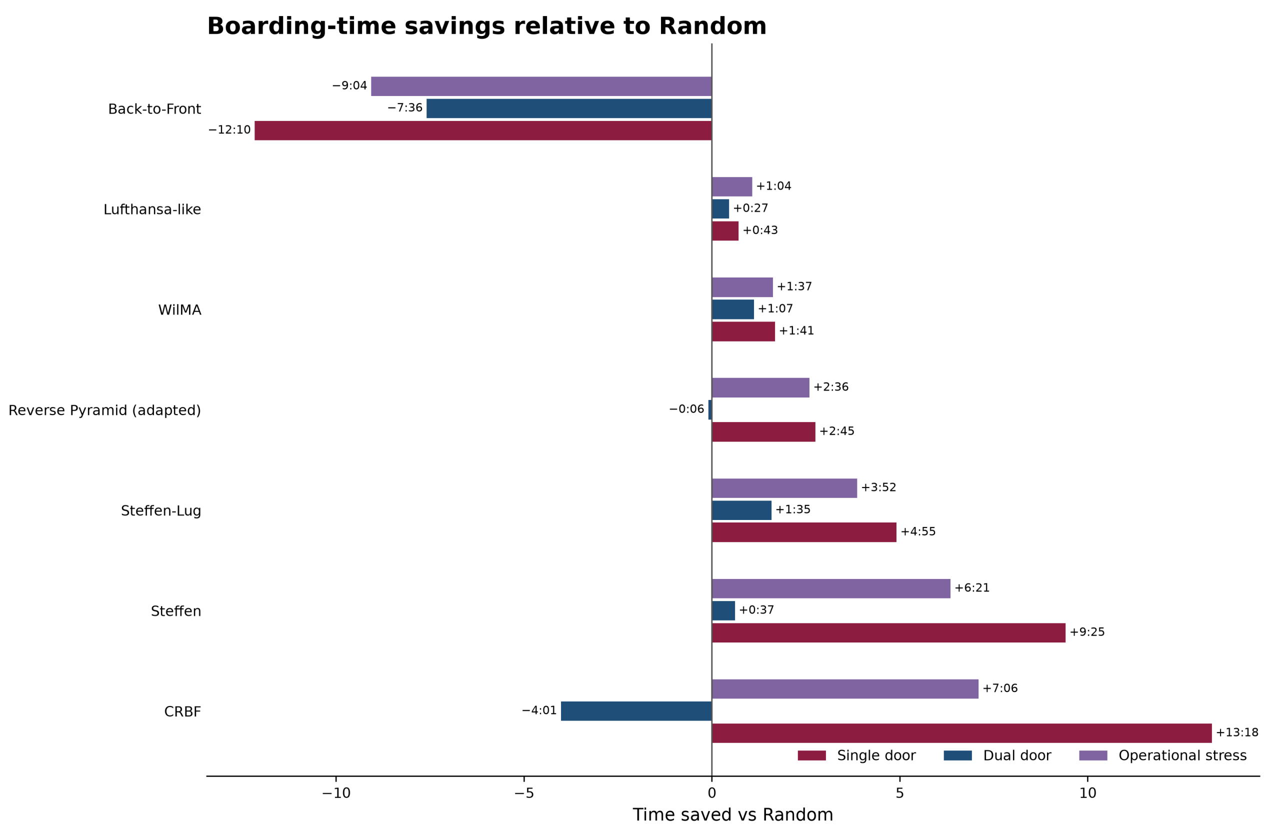
| Rank | Strategy | Mean | P95 | SD |
|---|---|---|---|---|
| 3 | Steffen-Lug | 32 min 57 sec | 36 min 13 sec | 1.98 min |
| 4 | Reverse Pyramid (adapted) | 34 min 13 sec | 37 min 43 sec | 2.09 min |
| 5 | WilMA | 35 min 11 sec | 38 min 47 sec | 2.14 min |
| 6 | Lufthansa-like | 35 min 44 sec | 39 min 40 sec | 2.26 min |
| 7 | Ryanair-like | 36 min 01 sec | 39 min 47 sec | 2.26 min |
| 8 | easyJet-like | 36 min 04 sec | 40 min 00 sec | 2.24 min |
| 9 | US Network-like | 36 min 06 sec | 40 min 03 sec | 2.28 min |
| 10 | Random | 36 min 48 sec | 40 min 44 sec | 2.31 min |
| 11 | Back-to-Front | 45 min 52 sec | 50 min 32 sec | 2.76 min |

Under high luggage volume, 75% compliance and travel-group disruption, CRBF again produced the lowest mean boarding time: **29 min 43 sec**.

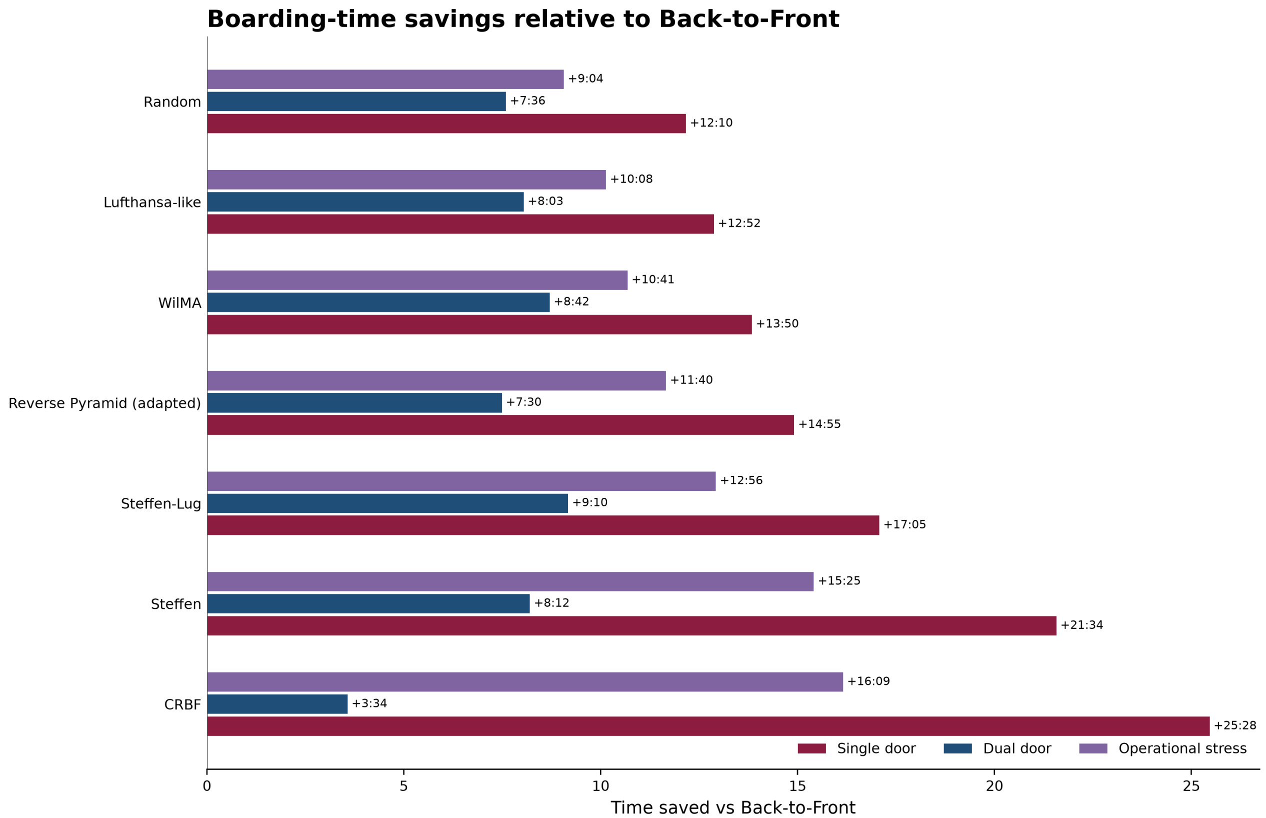
However, the difference between the best strategies became much smaller than under the clean single-door condition.

# 10 8. Time Savings

## 10.1 8.1 Relative to Random boarding



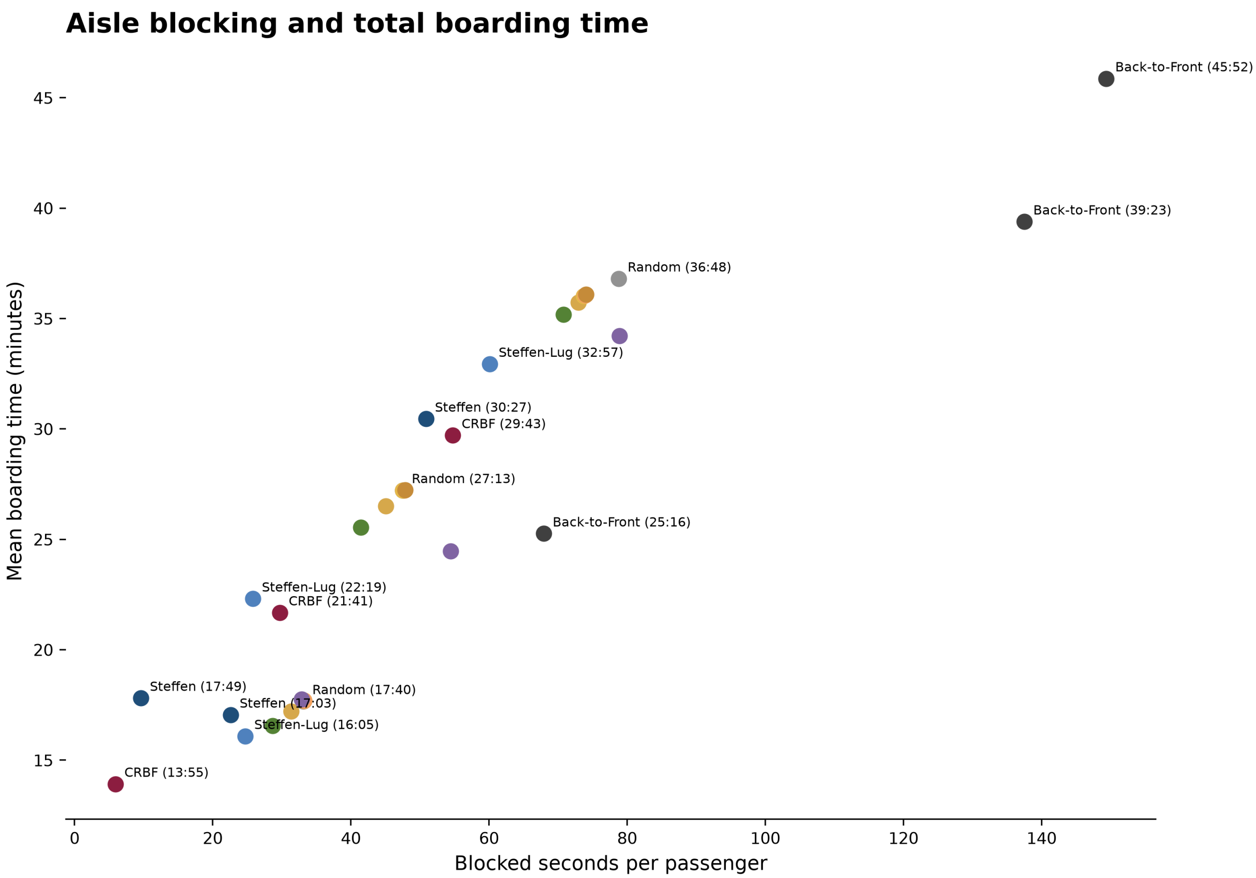
## 10.2 8.2 Relative to Back-to-Front




The largest improvements appeared when highly structured methods were compared with Back-to-Front boarding.

This is consistent with the model mechanism: Back-to-Front concentrates passengers in similar cabin regions and therefore creates substantial local aisle congestion.

# 11 9. Why the Strategies Behave Differently

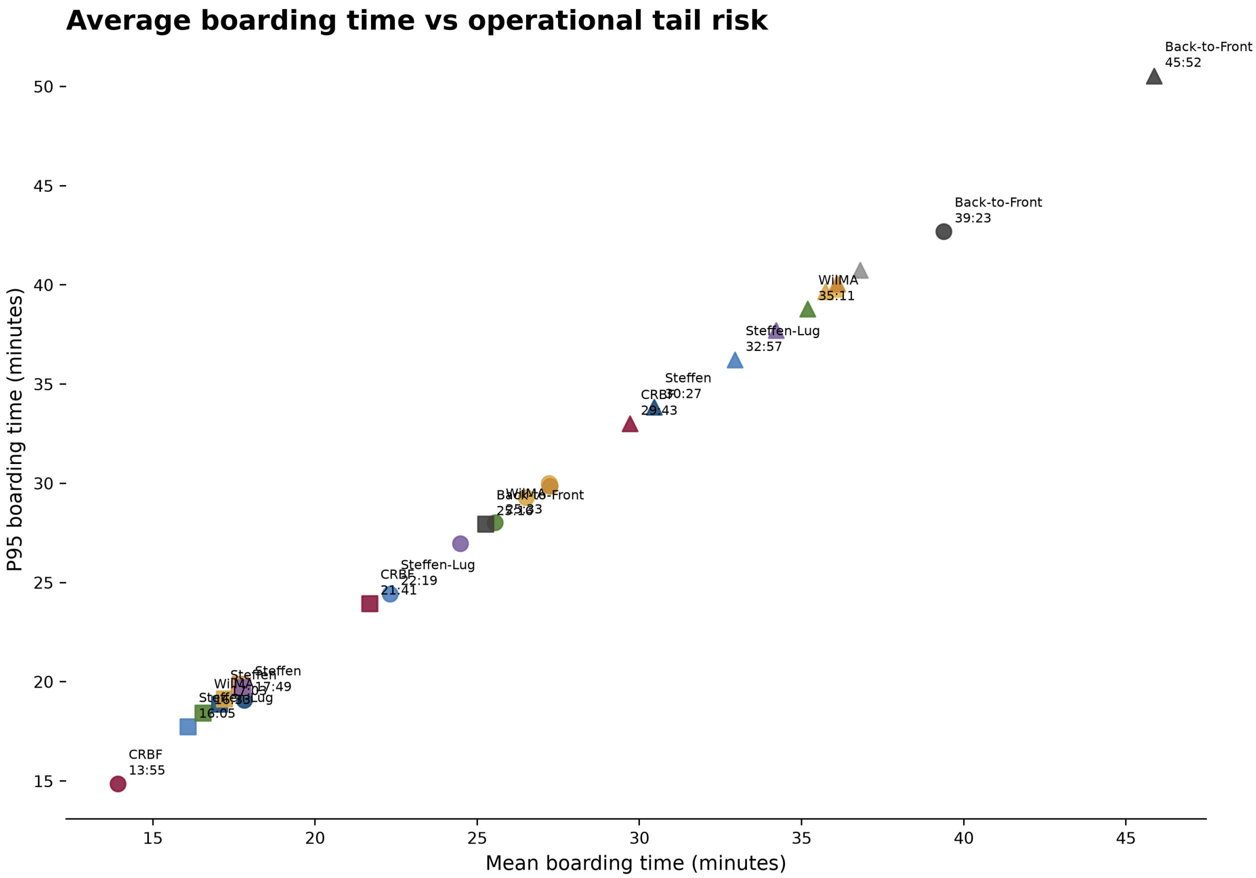



Aisle blocking provides an important explanation for the differences between policies.

Methods such as CRBF and Steffen create spatial separation and allow multiple passengers to perform useful work simultaneously.

Methods that concentrate passengers into adjacent rows create moving bottlenecks.

# 12 10. Reliability

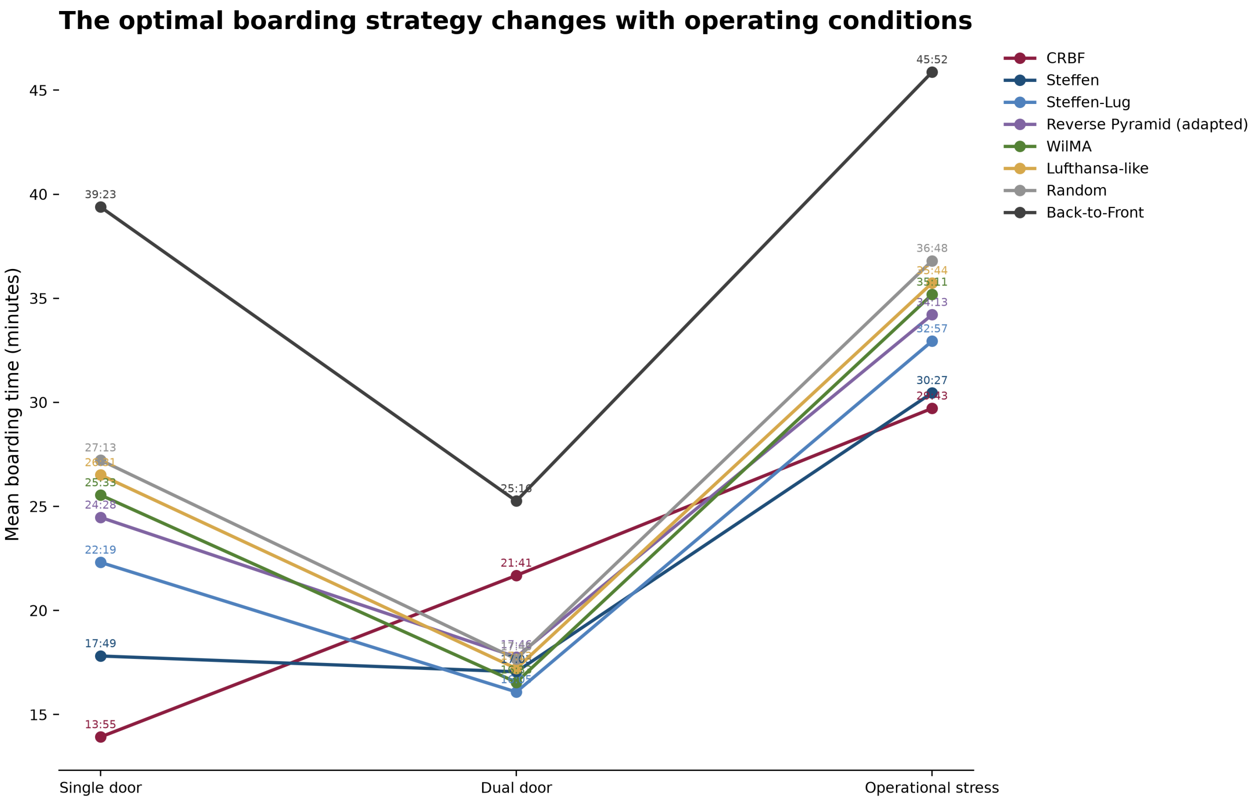



Mean boarding time describes average performance.

P95 provides a more operational interpretation: a boarding time exceeded by only approximately 5% of simulated runs.

For schedule planning, a strategy with slightly slower average performance may still be attractive if it provides lower tail risk.

# 13 11. Scenario Sensitivity

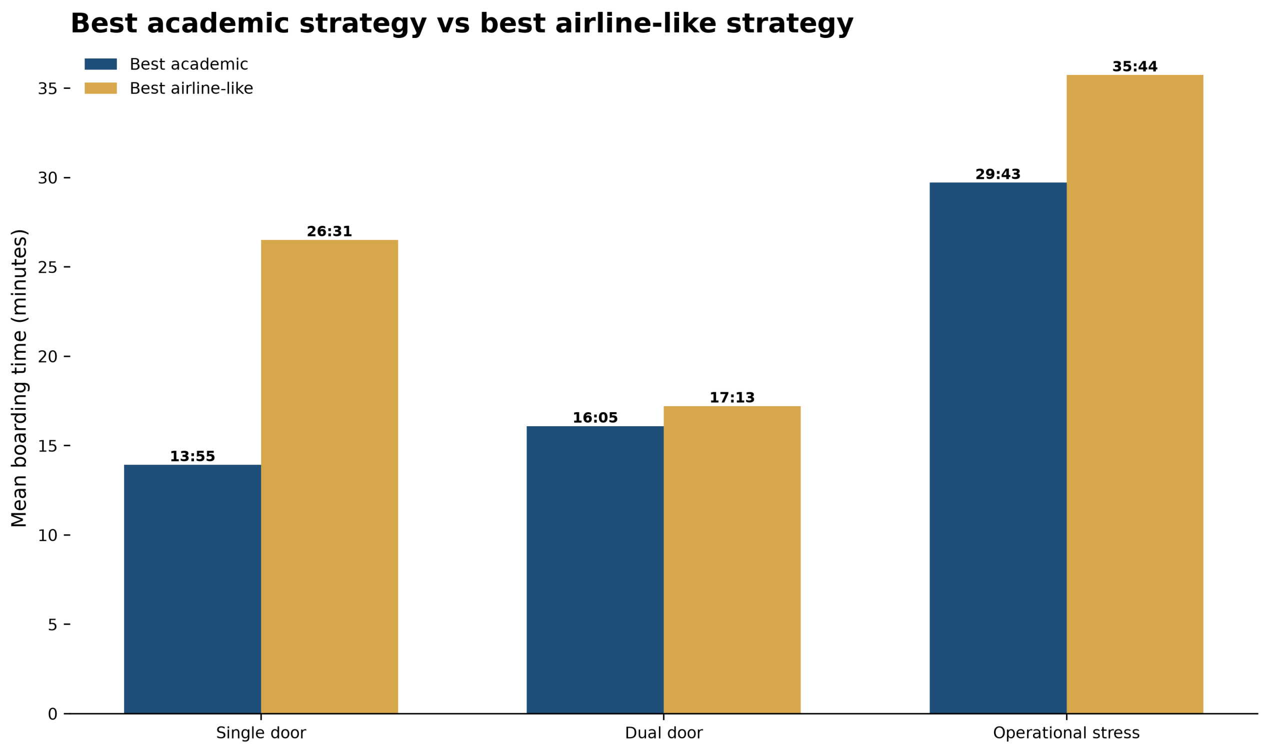



The ranking changes substantially between operating scenarios.

CRBF was exceptionally strong with a single front door but lost much of its advantage under the fixed dual-door split.

Steffen-Lug moved in the opposite direction and became the fastest dual-door strategy.

# 14 12. Academic vs Airline-Like Boarding




Strongly spatial academic strategies generally outperformed the simplified airline-like structures in pure boarding-flow efficiency.

This does not imply that airlines are necessarily using inferior commercial policies.

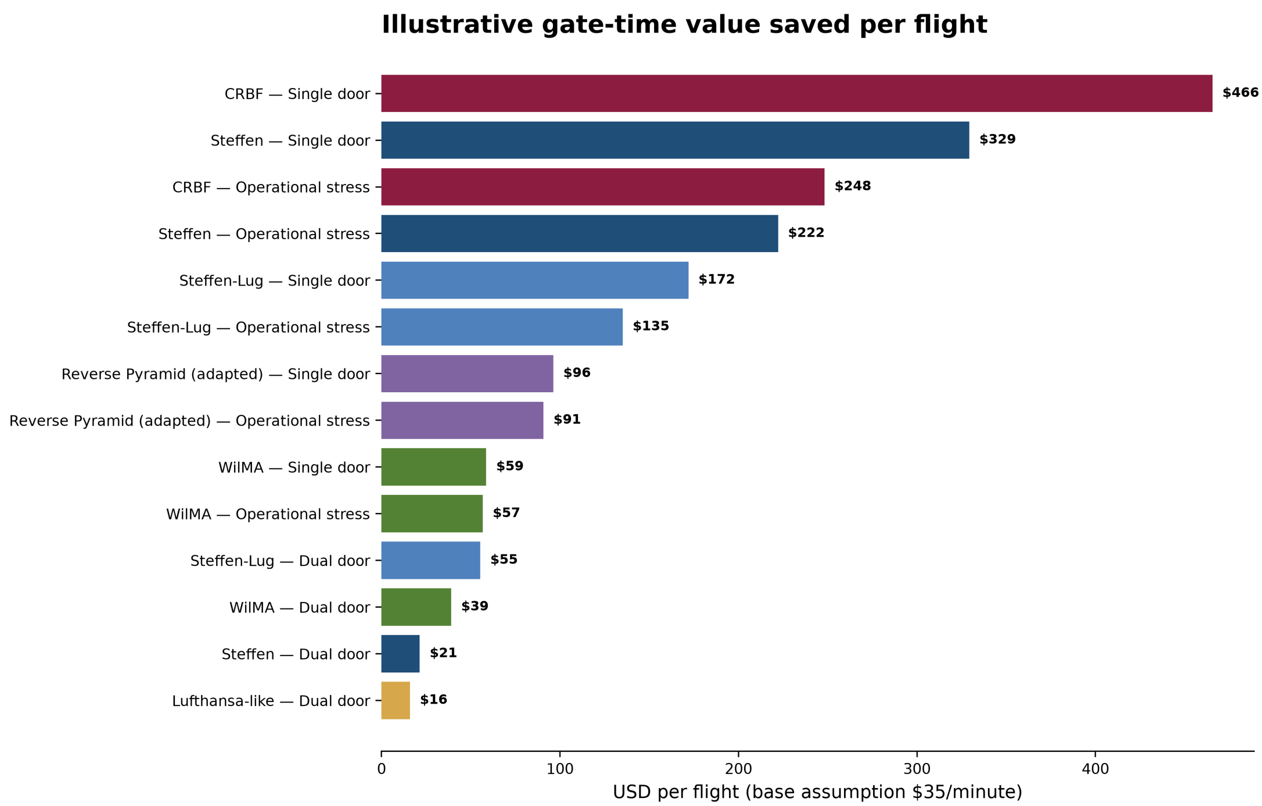
Real airline boarding must balance additional objectives such as:

- premium products,
- accessibility,
- families,
- loyalty status,
- passenger comprehension,
- enforcement complexity,
- gate configuration,
- and revenue.

# 15 13. Economic Interpretation

The economic dataset is now a directed **all-vs-all comparison of all 11 strategies**. It contains 363 rows: 11 $\times$ 11 choices $\times$ 3 scenarios. This includes A = B comparisons (zero difference) and both directions of every pair. Excluding self-comparisons and reverse duplicates, there are 55 unique pairs per scenario and 165 across the study.

The chart below retains Random as one readable cross-section of the larger all-vs-all dataset; Random is not treated as the only benchmark.




The economic layer applies an illustrative gate-time value of:

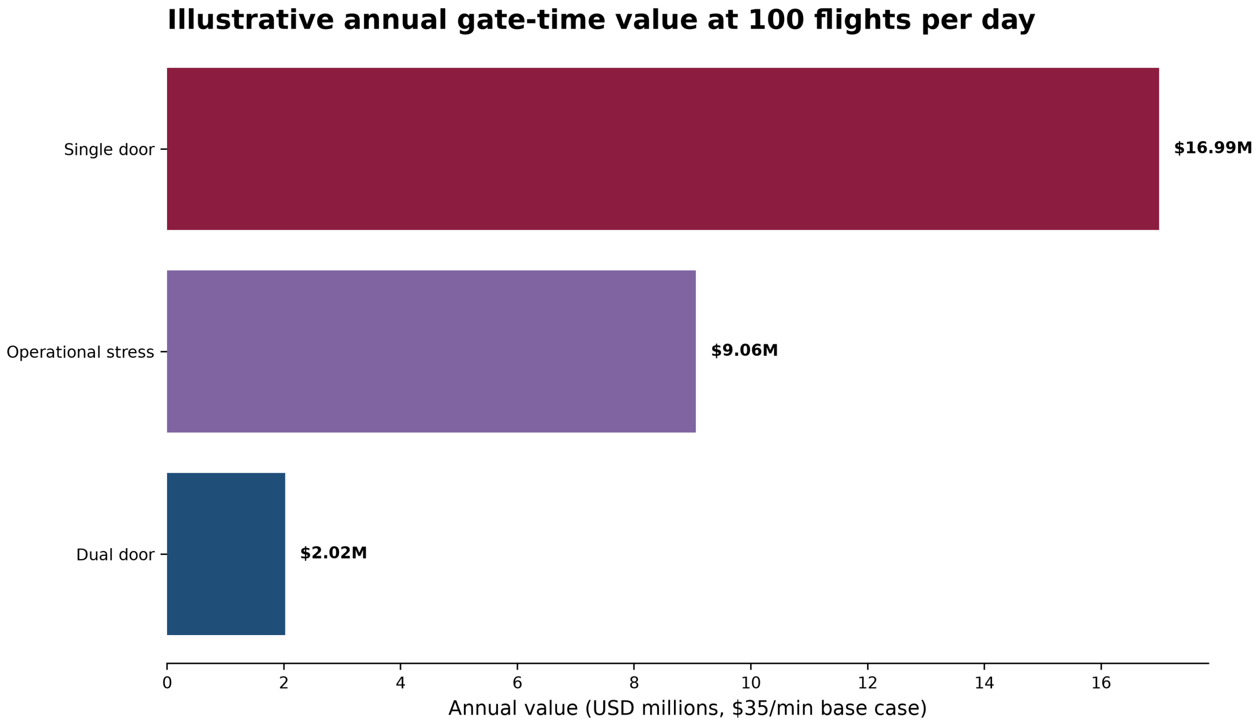
- **\$30/minute — low**
- **\$35/minute — base**
- **\$40/minute — high**

The calculation is:

$$\text{Value per flight} = \text{boarding minutes saved} \times \text{assumed cost per minute}$$

**Illustrative operating value, not profit.**

## 15.1 13.1 Annualized operating scale




The time-saving effect can also be extrapolated across repeated daily operations.

The calculation is:

$$\text{Annual value} = \text{minutes saved per flight} \times \text{cost per minute} \times \text{flights per day} \times 365$$

For a compact operational table, every strategy is shown against Back-to-Front at 10 flights per day. The interactive calculator and exported economic workbook allow any of the full 11 × 11 choices.

| Scenario | Strategy A | Reference B | Time difference/flight | Base value/flight | Annual base value at 10 flights/day |
|---|---|---|---:|---:|---:|
| Single door | CRBF | Back-to-Front | +25 min 28 sec | $891 | $3,253,056 |
| Single door | Steffen | Back-to-Front | +21 min 34 sec | $755 | $2,755,964 |
| Single door | Steffen-Lug | Back-to-Front | +17 min 05 sec | $598 | $2,181,423 |
| Single door | Reverse Pyramid (adapted) | Back-to-Front | +14 min 55 sec | $522 | $1,905,168 |
| Single door | WilMA | Back-to-Front | +13 min 50 sec | $484 | $1,767,974 |
| Single door | Lufthansa-like | Back-to-Front | +12 min 52 sec | $451 | $1,644,649 |
| Single door | Ryanair-like | Back-to-Front | +12 min 10 sec | $426 | $1,553,646 |
| Single door | easyJet-like | Back-to-Front | +12 min 10 sec | $426 | $1,555,205 |
| Single door | US Network-like | Back-to-Front | +12 min 09 sec | $425 | $1,551,957 |
| Single door | Random | Back-to-Front | +12 min 10 sec | $426 | $1,553,861 |
| Single door | Back-to-Front | Back-to-Front | 0 min 00 sec | $0 | $0 |
| Dual door | CRBF | Back-to-Front | +3 min 34 sec | $125 | $456,597 |
| Dual door | Steffen | Back-to-Front | +8 min 12 sec | $287 | $1,048,041 |
| Dual door | Steffen-Lug | Back-to-Front | +9 min 10 sec | $321 | $1,171,900 |

| Scenario | Strategy A | Reference B | Time difference/flight | Base value/flight | Annual base value at 10 flights/day |
|---|---|---|---|---|---|
| Dual door | Reverse Pyramid (adapted) | Back-to-Front | +7 min 30 sec | $262 | $957,249 |
| Dual door | WilMA | Back-to-Front | +8 min 42 sec | $305 | $1,112,331 |
| Dual door | Lufthansa-like | Back-to-Front | +8 min 03 sec | $282 | $1,028,022 |
| Dual door | Ryanair-like | Back-to-Front | +7 min 33 sec | $264 | $965,175 |
| Dual door | easyJet-like | Back-to-Front | +7 min 33 sec | $264 | $964,709 |
| Dual door | US Network-like | Back-to-Front | +7 min 34 sec | $265 | $966,327 |
| Dual door | Random | Back-to-Front | +7 min 36 sec | $266 | $969,906 |
| Dual door | Back-to-Front | Back-to-Front | 0 min 00 sec | $0 | $0 |
| Operational stress | CRBF | Back-to-Front | +16 min 09 sec | $566 | $2,064,097 |
| Operational stress | Steffen | Back-to-Front | +15 min 25 sec | $539 | $1,968,913 |
| Operational stress | Steffen-Lug | Back-to-Front | +12 min 56 sec | $452 | $1,651,342 |
| Operational stress | Reverse Pyramid (adapted) | Back-to-Front | +11 min 40 sec | $408 | $1,489,354 |
| Operational stress | WilMA | Back-to-Front | +10 min 41 sec | $374 | $1,365,019 |
| Operational stress | Lufthansa-like | Back-to-Front | +10 min 08 sec | $355 | $1,294,612 |
| Operational stress | Ryanair-like | Back-to-Front | +9 min 51 sec | $345 | $1,258,422 |
| Operational stress | easyJet-like | Back-to-Front | +9 min 48 sec | $343 | $1,252,913 |
| Operational stress | US Network-like | Back-to-Front | +9 min 46 sec | $342 | $1,247,968 |
| Operational stress | Random | Back-to-Front | +9 min 04 sec | $317 | $1,158,046 |
| Operational stress | Back-to-Front | Back-to-Front | 0 min 00 sec | $0 | $0 |

The annual values are **scenario extrapolations**.

They do not include:

- aircraft utilization effects,
- network recovery,
- crew costs,
- passenger connections,
- schedule redesign,
- revenue implications,
- or actual airline accounting costs.

# 16 14. Interactive Results Table

# 17 15. Discussion

Three findings dominate the study.

## 17.1 15.1 Spatial organization matters

The fastest policies were not simply priority systems.

They controlled where passengers were located inside the aircraft and therefore how many passengers could walk, stow luggage or sit down simultaneously.

## 17.2 15.2 Infrastructure changes the optimum

The same policy can perform very differently when the boarding infrastructure changes.

The strong decline in CRBF performance under dual-door boarding is one of the clearest examples.

## 17.3 15.3 Statistical significance is not operational significance

With 2,000 paired trials, relatively small differences can become statistically significant.

A difference of several seconds or tens of seconds should therefore be interpreted differently from a saving of several minutes.

# 18 16. Limitations

The results should be interpreted within the model boundary.

Important limitations include:

- simulation rather than direct live-airline observation,
- representative passenger distributions,
- simplified airline-like procedures,
- fixed 26-row narrow-body geometry,
- adapted Reverse Pyramid zoning,
- simplified behavioural assumptions,
- limited gate-area modelling,
- no direct revenue optimization,
- and no airline network simulation.

The economic section represents illustrative operating-value scenarios, not an accounting forecast.

# 19 17. Conclusion

The study does not identify one universally optimal aircraft boarding strategy.

Instead, boarding performance depends on the interaction between:

- passenger sequencing,
- aisle congestion,
- luggage,
- behavioural compliance,
- and aircraft infrastructure.

In the final simulation:

**CRBF was fastest with a single front door.**

**Steffen-Lug was fastest with dual-door boarding.**

**CRBF was fastest under operational stress.**

The practical question for an airline is therefore not simply:

> Which boarding strategy is fastest?

It is:

> Which boarding strategy is fast, robust, understandable and operationally compatible with the environment in which it must actually be used?

# 20 18. References

The bibliography below is limited to sources present in the supplied literature folder and verified from the documents' actual title pages or publisher records. Two differently named supplied PDFs contain the same Coppens et al. article; it is listed once.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# 21 Appendix A — Interactive Strategy Explorer

# 22 Appendix B — Economic Assumptions

| Parameter | Assumption |
|---|---|
| Low | \$30/minute |
| Base | \$35/minute |

| Parameter | Assumption |
| --- | --- |
| High | $40/minute |