

Multi-stakeholder Optimized Arrival Management with the Target Time Management System (TTMS)

Operational Evidence from a Live Trial at Zurich Airport

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04.12.2025

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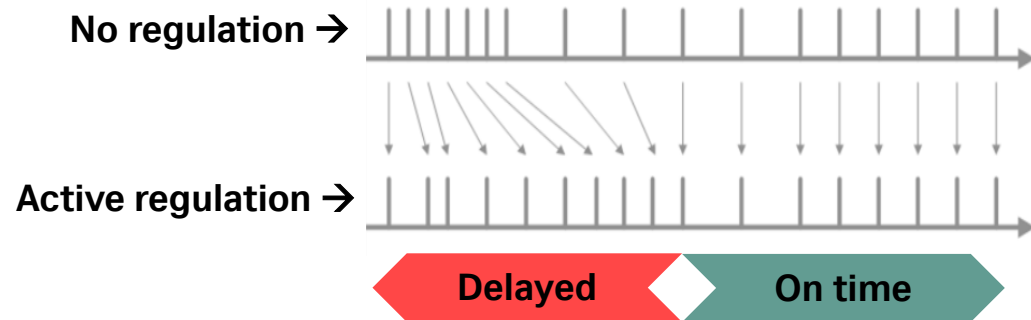
As part of SESAR, HARMONIC aims to create a harmonized arrival network by leveraging smart technology and collaboration across all partners

Motivation

 **Peak-hour congestion** and **daily arrival regulations** lead to frequent delays

 **"First planned, first served"** slot allocation ignores airline-specific priorities

 SWISS can only swap its own slots → **no coordination across stakeholders**



Goal



Implement a **multi-constraint Target Time of Arrival (TTA) system** to optimize arrival flow at Zurich Airport



Consider all stakeholders' priorities and constraints to find the **global optimum**



Position ZRH as the **first Target Time Steered Airport** (mainly focusing on short-haul flights)

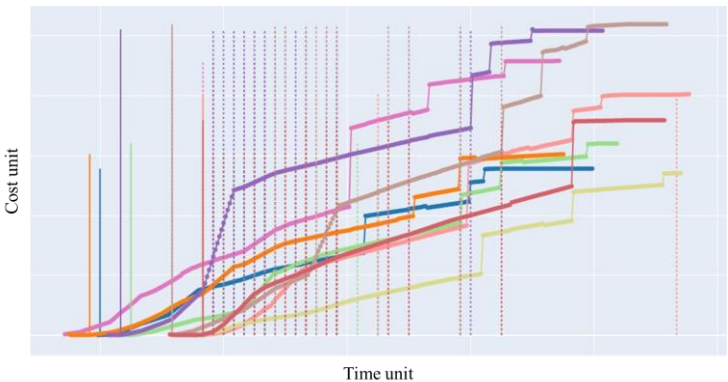


TTMS operationalizes smart coordination by merging airline and airport preferences with ANSP rules into a single optimized TTA sequence



Airlines send weight maps to airport

Cost function over arrival delay calculated per flight with many variables considered (weights = inverted costs)



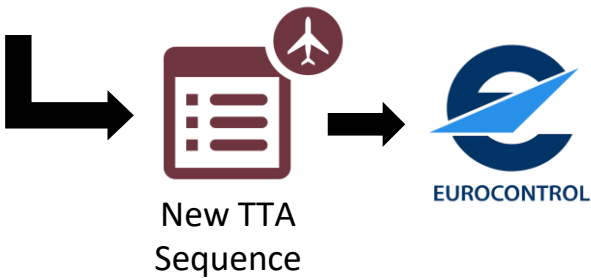
Airport generates default weight maps for non actively participating carriers and adds its own preferences

Flight	18:00	18:01	18:03	18:05	18:07
Flight 1	100000	100000	99403	98719	98034
Flight 2	90000	89998	89985	89960	89922
Flight 3	-1	-1	1000000	-1	-1
Flight 4	-1	-1	38968	38934	38865
Flight 5	-1	-1	39731	39388	39149
Flight 6	-1	-1	89998	89985	89974
Flight 7	-1	-1	-1	33384	33384
Flight 8	-1	-1	-1	-1	21594
Flight 9	-1	-1	-1	-1	90000

→ Optimizer finds **global maximum**

Additional check on TTA sequence

(to make sure ANSP constraints are met)



By combining key cost factors into flight-specific functions, SWISS enables a transparent transformation into weights reflecting each flight's priority



Passenger & Baggage Misconnections



Churn Risk



Additional Fuel Consumption



Passenger Compensation



Landing & Noise Charges



Crew Duty Limit Violations



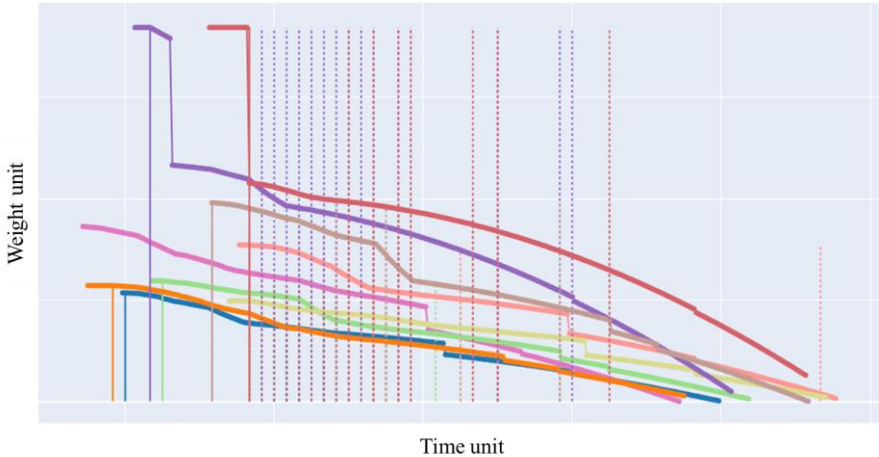
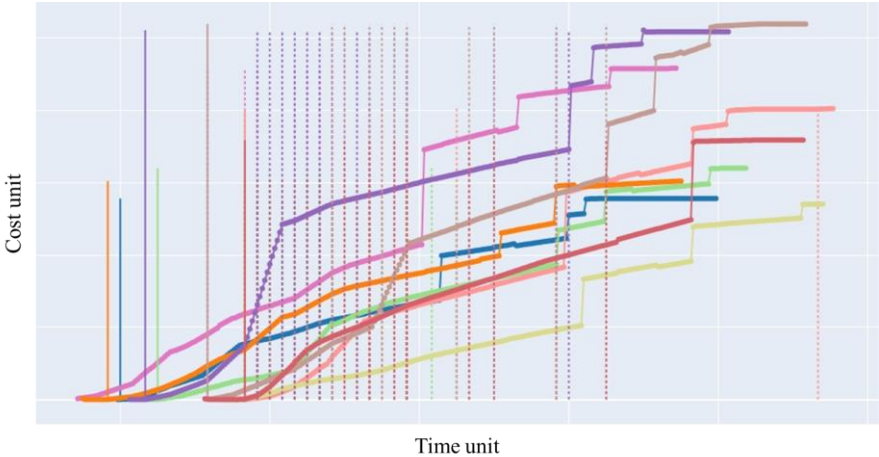
Food & Beverage Vouchers



Curfew Limits



Aircraft & Crew Rotations



Default AU maps complement SWISS inputs for non-participating airlines, while airport weight maps ensure fair stakeholder integration

Default Weight Maps

- Quadratic decay over a **4-hour horizon**:

$$w^{default}(h) = W_{\max}^{default} (1 - (h/240)^2)$$

- Maximum weight** determined via airport-derived priority $p \in [0,1]$:

$$W_{\max}^{default} = 80,000 + 20,000p$$

- SWISS weights are **normalized** so that

$$W_{\max}^{SWISS} = 100,000$$

Airport Preferences

- Capture **airport-level operational sensitivity** to arrival timing and complement airline/default maps to ensure **balanced multi-stakeholder representation**
- Current Inputs (Trial Phase):**



Scheduled Time of Arrival (STA)



Available turnaround time



Aircraft size (seat proxy via ICAO type)

All default and SWISS weights are merged into one airspace-user (AU) weight matrix, and each flight's final weight per slot is computed as $0.5 w^{AU} + 0.5 w^{airport}$

TTMS combines continuously updated weight maps with event-driven optimization to determine accurate, real-time and optimal arrival sequencing

Flight	ETOA	Priority Factor	Scale Factor	18:00	18:01	18:03	18:05	18:07	18:09	18:11	18:13	18:15
Swiss 1	18:00	0.05	4.89	100000	100000	99403	98719	98034	97350	96665	95980	56645
Other Airline 1	18:00	0.50	1.00	90000	89998	89985	89960	89922	89873	89810	89735	89648
Swiss 2	18:02	0.30	4.89	-1	-1	38968	38934	38865	38797	38733	38665	38631
Other Airline 2	18:02	0.50	1.00	-1	-1	89998	89985	89974	89943	89899	89843	89775
Other Airline 3	18:03	0.50	1.00	-1	-1	1000000	-1	-1	-1	-1	-1	-1
Swiss 3	18:03	0.12	4.89	-1	-1	39731	39388	39149	38880	38699	38508	38308
Swiss 4	18:05	0.24	4.89	-1	-1	-1	33384	33384	33344	33271	33198	33124
Swiss 5	18:06	0.10	4.89	-1	-1	-1	-1	21594	21560	21501	21437	21408
Other Airline 3	18:07	0.50	1.00	-1	-1	-1	-1	90000	89993	89974	89943	89899

Continuous Weight Generation

Airline and airport weight maps are recomputed every 10 minutes in the background, ensuring the optimizer always works with up-to-date operational priorities.

Event-Driven Optimization

Optimization only begins once a regulation is published with at least ~120 minutes lead time, after which TTMS re-optimizes the arrival sequence every 10 minutes.

EOBT-Based Blocking Rule

Flights approaching departure are frozen based on an EOBT-based cutoff, with the next trial restoring an EOBT-10 min rule to avoid premature locking of short-haul flights.

An eight-week live trial (May & June 2025) with 51 regulations and 3,372 flights provided the basis to assess TTMS performance under real-world conditions

Operational Improvements



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- +20.2% punctuality (within 15 min)
- 23.5% heavy delays (≥ 30 min)
- 19.8% critical connections (25 – 40 min)
- 33.3% missed connections (< 25 min)
- 11% total delay minutes
- 14% missed connections
- 9% knock-on delays

Applied Constraints during Live Trial



TTMS was only activated when a **Network Cherry Picking (NCP) regulation** was applied by Skyguide



TTMS was only activated for **regulations with rates greater than 22/h**



ATFM delay with TTMS **should not deviated more than 10%** from the baseline ATFM delay



All project partners could **always decide to stop or deactivate TTMS** due to increased operational complexity (e.g., weather situation, unacceptable delays for important flights or technical issues)

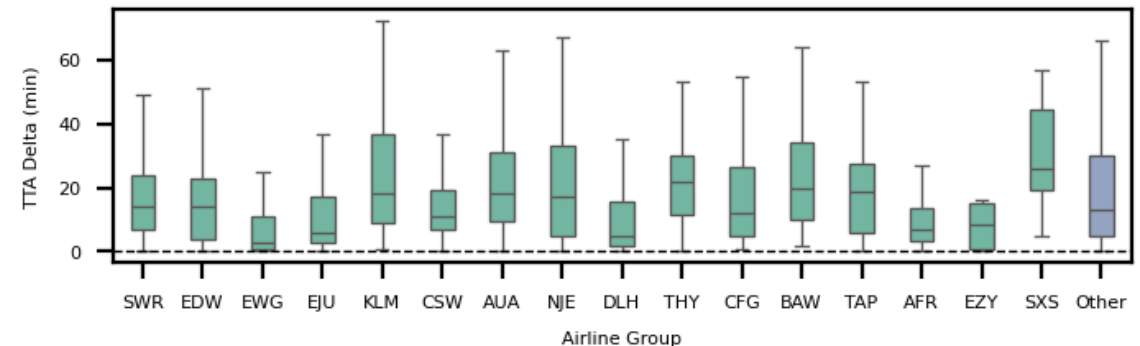
Theil index analysis and group-level comparisons indicate a fair and balanced delay allocation under TTMS

Theil Index

- Measures **between-group divergence** in mean delay assignments
- Formula:** $T = \sum_g \frac{n_g}{N} \left(\frac{\mu_g}{\bar{\mu}} \right) \ln \left(\frac{\mu_g}{\bar{\mu}} \right)$
- Interpretation:** $T = 0 \rightarrow$ perfect fairness (internal equity threshold used: $T = 0.4$)
- Properties:** scale-invariant (robust across airlines with different numbers of flights)
- Application in TTMS:**
 - Flights were grouped by airline
 - Delay measure: $\Delta_{TTA} = TTA - ETA$

Results

- Theil Index = 0.03072 $\rightarrow$ **no evidence of systematic penalization** across all airlines
- No complaints or concerns raised** by non-participating airlines during the trial
- Within SWISS, lower-priority received more delay, reflecting **utility-based optimization**



The identified limitations guide targeted improvements, with upcoming trials focusing on increasing robustness and scalability

Limitations

- **Safeguard logic issue:** Switching to EOBT – 40 min froze short-haul flights too early
- **Low declared rates:** Weight maps lose discriminatory power → priority factor must dominate
- **Short lead-times:** Regulations <120 min lead time left some flights already taxiing/airborne → no TTAs assigned
- **Airport factor limits:** Currently based mainly on booking data
- **MPR constraint:** CASA only applies the Most Penalizing Regulation → TTMS benefits lost when the local regulation is not the MPR

Future Work & Outlook

- **Extended live trial** (Oct–Dec 2025)
- **Full-year trial** (2026): Transition toward continuous operational deployment
- **More airline participation:** Integrate Edelweiss (EDW) as a second airline with flight-specific weight maps
- **Enhanced cost modeling** and **refined cost-to-weight transformation**
- **Improve airport factor** by adding more granular data
- **Include MPR handling** to ensure reliable peak-period operation and large-scale European rollout

Thank you
Danke
Merci
Grazie
Grazia



Back-up Slides

Top-level overview

Cost functions (1/2)

Costs	Short Description
 Passenger and Baggage Misconnection Costs	Costs incurred when passengers miss their outbound flight at ZRH due to an inbound delay, including rebooking, HOTAC, and mishandled baggage costs ¹ .
 Passenger Compensation Costs	Costs coming from compensating passengers because of the delay as required by the claim costs (EU261).
 Food and Beverage Voucher Costs	Costs of handing out food and beverage vouchers (with a take rate) to passengers.
 Churn Costs	Costs of lost revenue due to potential customer churn (switching to competitors).
 SCRAM Costs	SCRAM costs at ZRH by incorporating landing charges and noise charges .

¹Mishandled baggage refers to luggage that misses the flight while the passenger does not, with costs applied per bag.

Top-level overview

Cost functions (2/2)

Costs	Short Description
 Curfew Costs	Costs of cancelling a flight due to the curfew at ZRH or possibly the curfew at the outstation. The curfew costs are calculated by adding the HOTAC , passenger compensation , and rebooking costs together.
 Speed Costs	Way to define the minimum physically possible TTA by incorporating the costs per reduced minute of the EET .
 Crew Duty Limit Violation Costs	Costs of cancelling a flight (and possibly its next rotation) if the assigned crew's duty time limit is exceeded.
 Aircraft Rotation Costs	Costs for outbound flights with delayed aircraft rotations due to the delay of the current aircraft . The rotation costs include all the costs listed above for the flights in question.
 Crew Rotation Costs	Costs for delayed outbound flights when cockpit crew rotations are disrupted due to a delay in the preceding flight . These rotation costs include the same costs as aircraft rotation costs.

¹Mishandled baggage refers to luggage that misses the flight while the passenger does not, with costs applied per bag.

Passenger and baggage misconnections costs

Calculation Logic

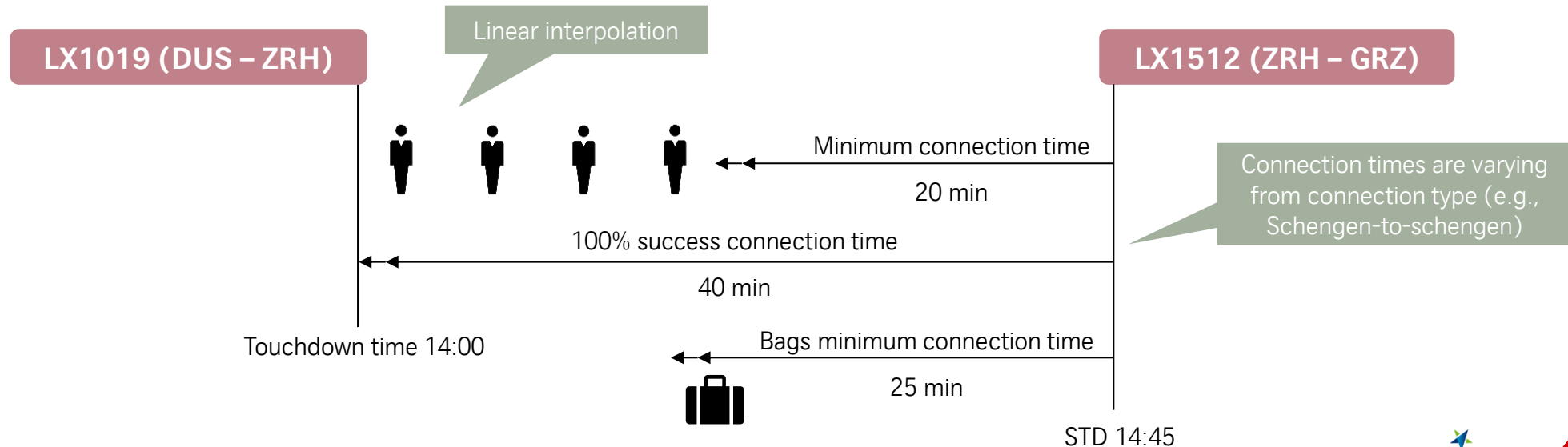


Passenger and baggage misconnection costs
= Rebooking costs + HOTAC costs + Mishandled baggage costs

Based on historical route-level rebooking costs for each class

Only added after rebooking limit in ZRH (21:30 LT) is reached

Compensation for bags that miss their connection



Passenger compensation costs

Calculation Logic

$$\text{Passenger compensation costs} = (\text{EU261 rate} + \text{Claim handling costs}) * \text{Total Passenger} * \text{Take Rate}$$



Passenger compensation according to EU261:

Distance from (km)	Distance to (km)	Time Threshold (minutes)	Currency	Amount
0	1499	180	EUR	250
1500	3499	180	EUR	400
3500	99999	180	EUR	600

Food and Beverage Voucher

Calculation Logic and Exemplary Cost Function



Food and beverage voucher costs

= Case specific food and beverage voucher costs * Total Passenger * Take Rate

Depending on compartment, travel distance (GDC) and for how long the passenger is waiting

Churn costs

Calculation Logic and Exemplary Cost Function



For churns on SWISS, we are calculating with a CLV reduction (either from status to base or from base to deal seeker)

For churns on the itinerary, we are calculating with a 15% reduction of the average yield per PAX on the itinerary

Churn costs

**= Status passenger churn on SWISS costs + Status passenger churn on itinerary costs
+ Base passenger churn on SWISS costs + Base passenger churn on itinerary costs**

SCRAM costs

Calculation Logic



(Additional) SCRAM Costs = SCRAM Costs – Initial SCRAM costs



SCRAM Costs = Landing Charges + Noise Charges

According to Airport Charges Regulation for Zurich Airport (depending on noise and MTOM class and arrival/departing time window)

Speed costs

Calculation Logic and Exemplary Cost Function



Speed costs = Extra fuel required * Fuel price per kg



(1 / Relative Fuel Change * Flight Duration in min) * Time Gained in min

**Aircraft-specific efficiency
factor from static data**

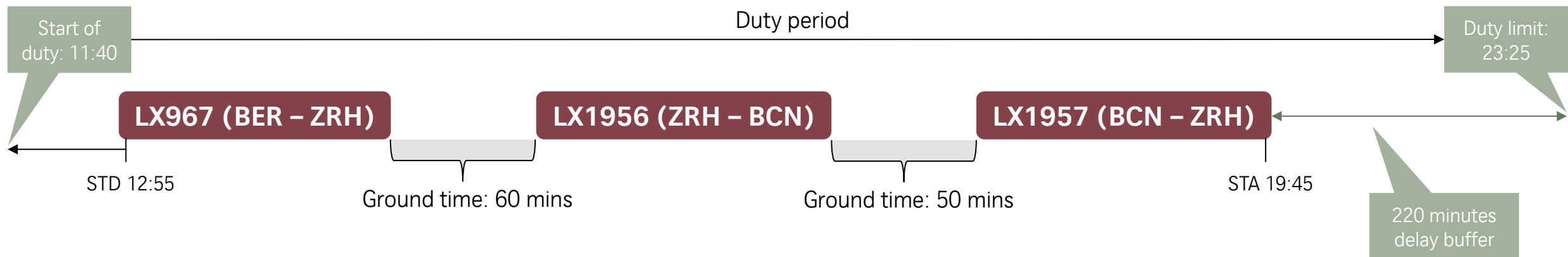
Crew duty limit violation costs

Calculation logic



**Crew duty limit violation costs = Cancellation Cost of Current Flight
+ Cancellation Cost of Next Flight (if applicable)**

Rebooking costs + HOTAC costs + Passenger compensation costs

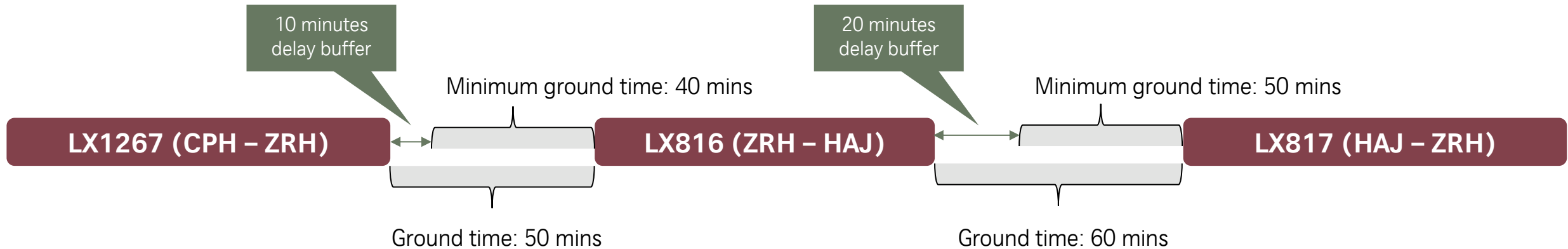


Aircraft rotation costs

Calculation logic



Aircraft rotation costs = Sum of all other costs for the next rotation



Crew rotation costs

Calculation logic and Exemplary Cost Function



Only if the crew member is changing the aircraft (otherwise delay costs are already incorporated in aircraft rotation costs)

Crew rotation costs = Sum of all other costs for the next rotation