

# Quantifying resilience in ATM

- contrasting the impacts of four mechanisms during disturbance

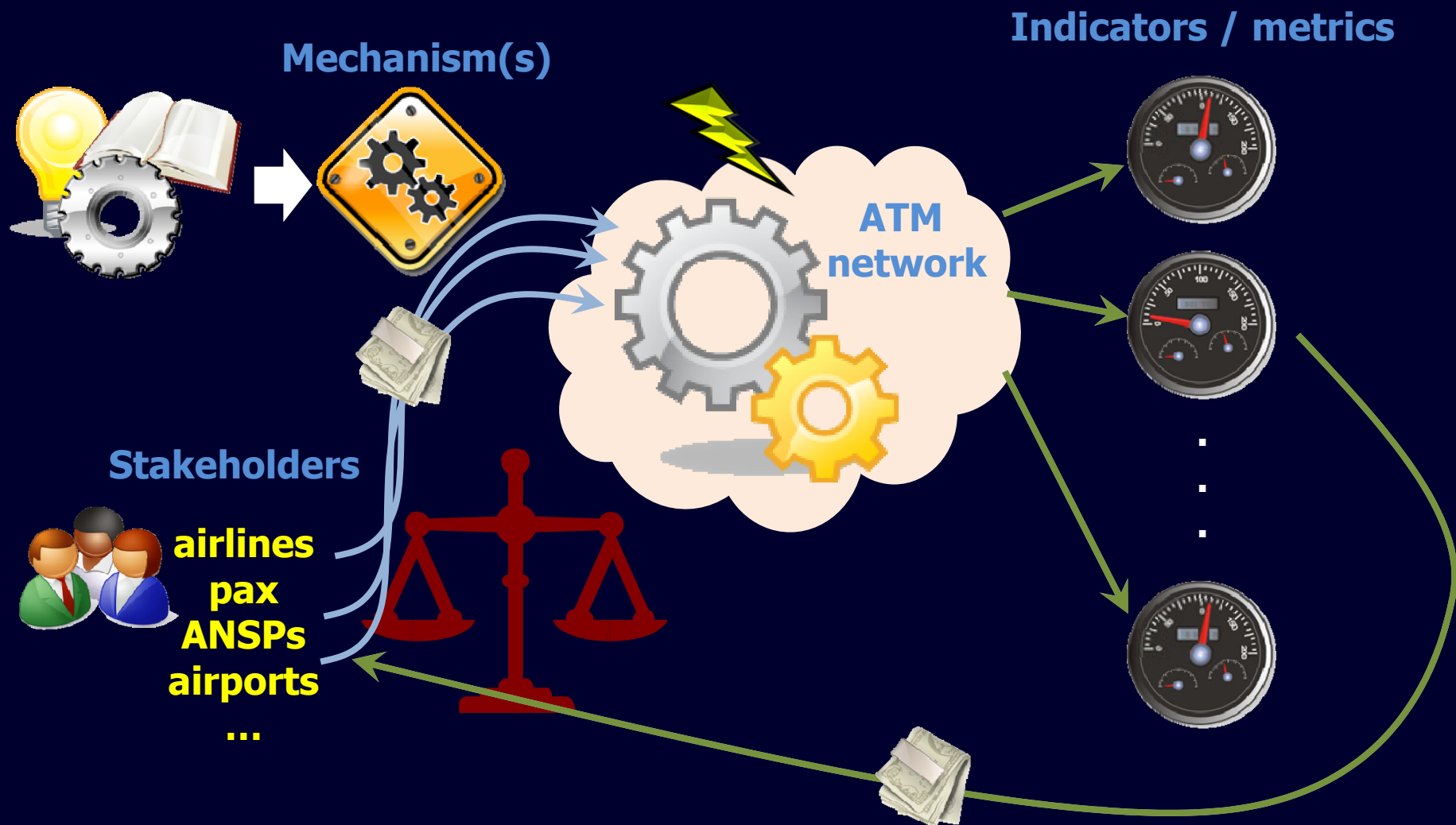
L. Delgado, A. Cook, G. Tanner and S. Cristóbal

Dr Luis Delgado

Senior Research Fellow

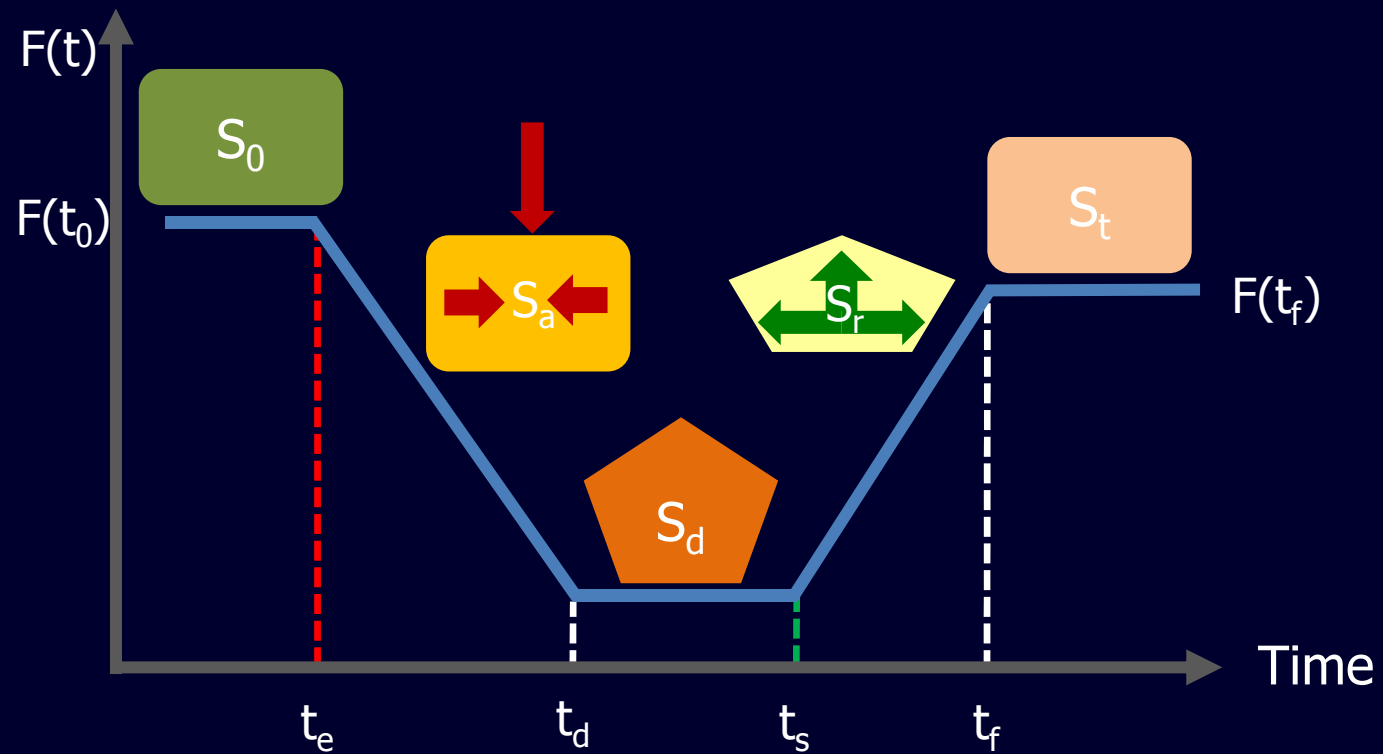
University of Westminster

Innaxis Foundation & Research Institute



# Resilience

Stability  
(absence of disruption)



Disruptive  
event

Resilience  
action

# Cost resilience metric

$$R_C = \frac{\sum_u^d C_u(t) - \sum_u^d \sum_m C_u^m(t) - \sum_m C_m(t)}{\sum_u^d C_u(t)}$$

cost of disruption with mechanism

investment running cost

disruption cost

$$\sum_u^d C_u(t) > 0 \quad \sum_u^d \sum_m C_u^m(t), \sum_m C_m(t) \geq 0$$

$$R_C \leq 1$$

A. Cook, L. Delgado, G. Tanner and S. Cristóbal, Measuring the cost of resilience, Journal of Air Transport Management, Vol. 56, Part A, pp. 38-47, Sept. 2016

# Metrics

- Complementary performance metrics
  - flight-centric
  - passenger-centric
  - cost-centric
- Impacts of disturbance measured on
  - airlines
  - passengers
  - environment

# Stakeholder uptake



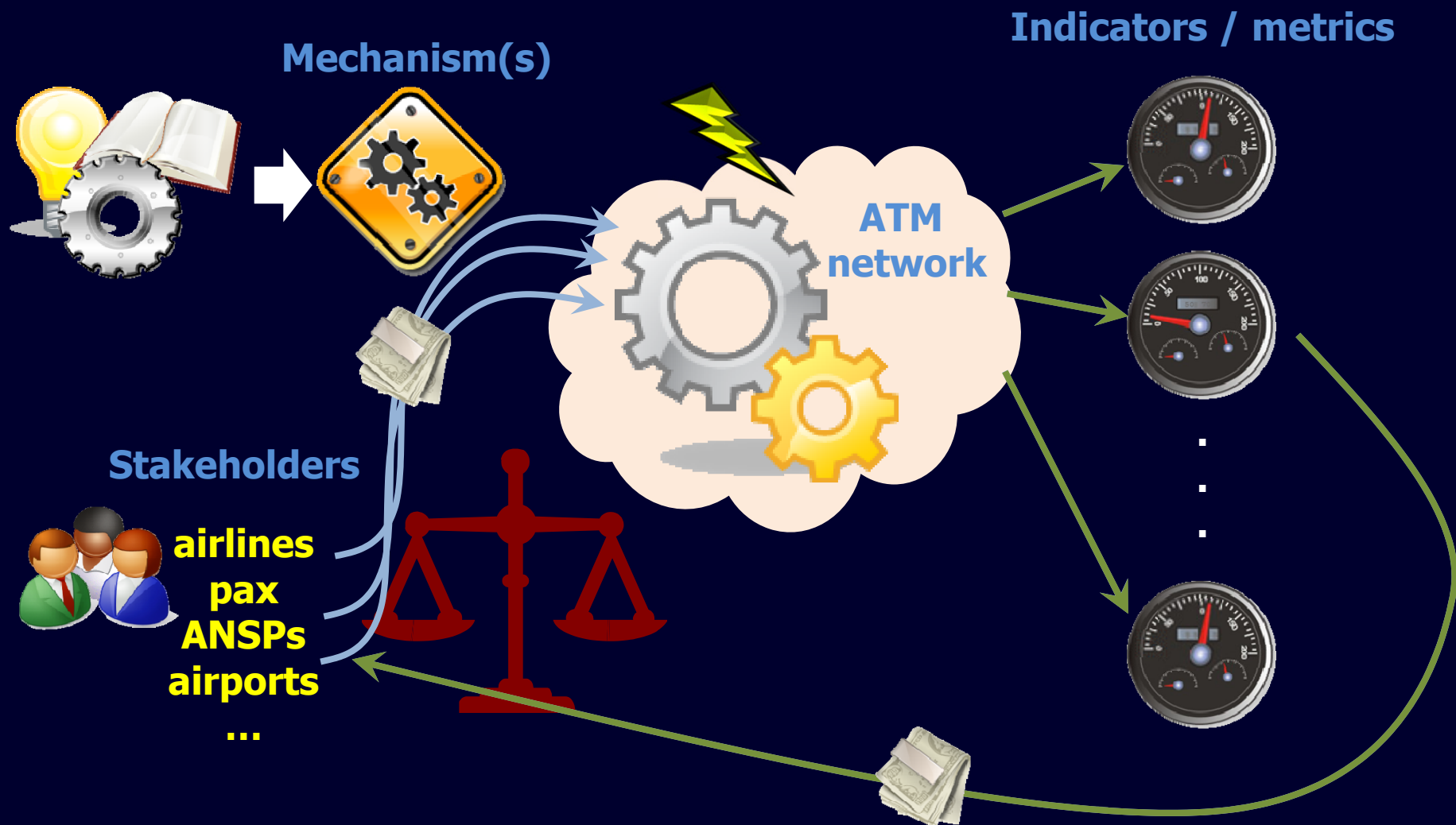
- Differentiated degree of adoption of mechanisms
- Based on stakeholder and mechanism characteristics
  - ANSPs: size, traffic density
  - airlines: business model, size
  - airports: mechanism implementation level, size
- Three levels of uptake considered per mechanism
  - baseline (current ops)
  - early adopters
  - followers



| Institution                                                                  | Support                                                      |
|------------------------------------------------------------------------------|--------------------------------------------------------------|
| DLR – Deutsches Zentrum für Luft- und Raumfahrt                              | Partner in the project                                       |
| ACI Europe (Brussels)                                                        | Passenger throughput data at European airports               |
| Adeline de Montlaur (UPC, Barcelona)                                         | Passenger assignment models (as Visiting Researcher at UoW)  |
| Airlines (numerous, anonymous)                                               | Passenger delay costs, reaccommodation policies & fare rules |
| Bott & Co Solicitors (Wilmslow, UK)                                          | Passenger compensation claims, application of Regulation 261 |
| CODA (EUROCONTROL, Brussels)                                                 | European performance data, especially re. strike actions     |
| DFS Deutsche Flugsicherung GmbH (Langen, German)                             | A-CDM implementation and operation costs                     |
| Dirk Schaefer                                                                | Project Officer                                              |
| GDS (major, anonymous)                                                       | Passenger itinerary data                                     |
| PACE Aerospace Engineering and Information Technology GmbH (Berlin, Germany) | Assessment of DCI mechanism costs                            |
| Performance Review Unit (EUROCONTROL, Brussels)                              | European performance data, especially re. delays             |
| Sabre Airline Solutions (Sabre Corporation, Delaware, US)                    | Assessment of passenger reaccommodation mechanism costs      |

# Overview

- Modell
  - Overview
  - Mechanisms
  - Disturbance
  - Cost allocation
  - Fuel model
  - Passenger itineraries
  - Model calibration
  - Scenarios
- Results and conclusions
- Future research



# Overview



- Modelling
  - Stochastic, layered network
  - Stochastic elements include systemic disturbance and specific modelled disturbance
  - Cost allocation for passengers and airlines
- Data
  - Traffic from busy (unexceptional) September 2014 traffic day as baseline
  - 200 airports in the ECAC area + 50 beyond
  - DDR2 for flight, capacity and airspace data
  - Passenger allocation algorithms based on previous work with IATA and GDS data
  - Historical disruption and delay data sources analysed

# Mechanisms



| Mechanism                                 | Location | Type     | Focus      | Delay driver | Primary investment |
|-------------------------------------------|----------|----------|------------|--------------|--------------------|
| Improving sector capacity with ATCO hours | En-route | Basic    | Mitigation | Magnitude    | ANSP               |
| Dynamic Cost Indexing                     | En-route | Basic    | Mitigation | Cost         | AO                 |
| A-CDM                                     | Airport  | Advanced | Nominal    | Magnitude    | Airport            |
| Improved passenger reaccomodation         | Airport  | Basic    | Nominal    | Cost         | AO                 |

# Improving sector capacity with ATCO hours

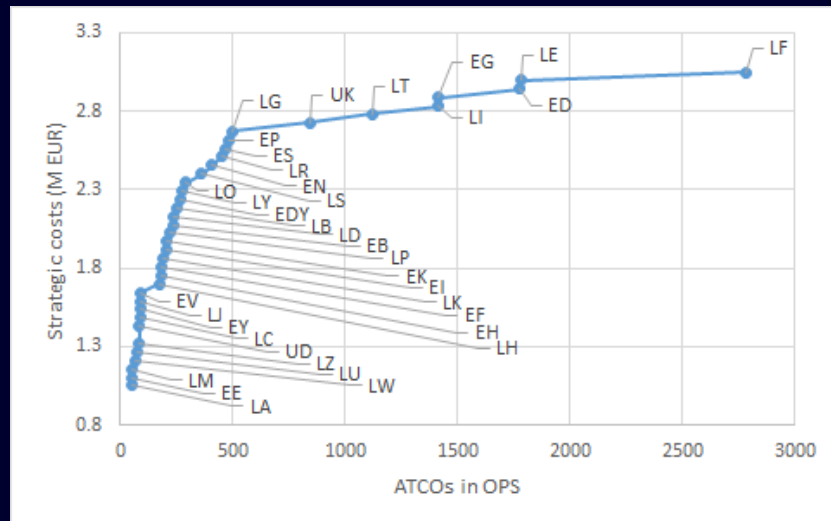


| Uptake         | Cost                                                                                                      |                                                                                                                       | Implementation                                                                                                                                                |
|----------------|-----------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                | Strategic                                                                                                 | Tactical                                                                                                              |                                                                                                                                                               |
| Baseline       | Not applicable                                                                                            |                                                                                                                       | No mitigation                                                                                                                                                 |
| Early adopters | Not applicable                                                                                            | <ul style="list-style-type: none"> <li>• Seven-hour shifts</li> <li>• Based on average extra ATCO capacity</li> </ul> | <ul style="list-style-type: none"> <li>• Extra ATCO hours added</li> <li>• Some ATFM delays may be reduced</li> </ul>                                         |
| Followers      | <ul style="list-style-type: none"> <li>• ANSPs</li> <li>• €1–3M per ANSP (scaled by ANSP size)</li> </ul> | <ul style="list-style-type: none"> <li>• ATCO hourly costs</li> </ul>                                                 | <ul style="list-style-type: none"> <li>• Reduction of ATFM regulation in airspaces that experience increase in demand due to disruption re-routing</li> </ul> |

# Improving sector capacity with ATCO hours



## Strategic costs



## Tactical costs

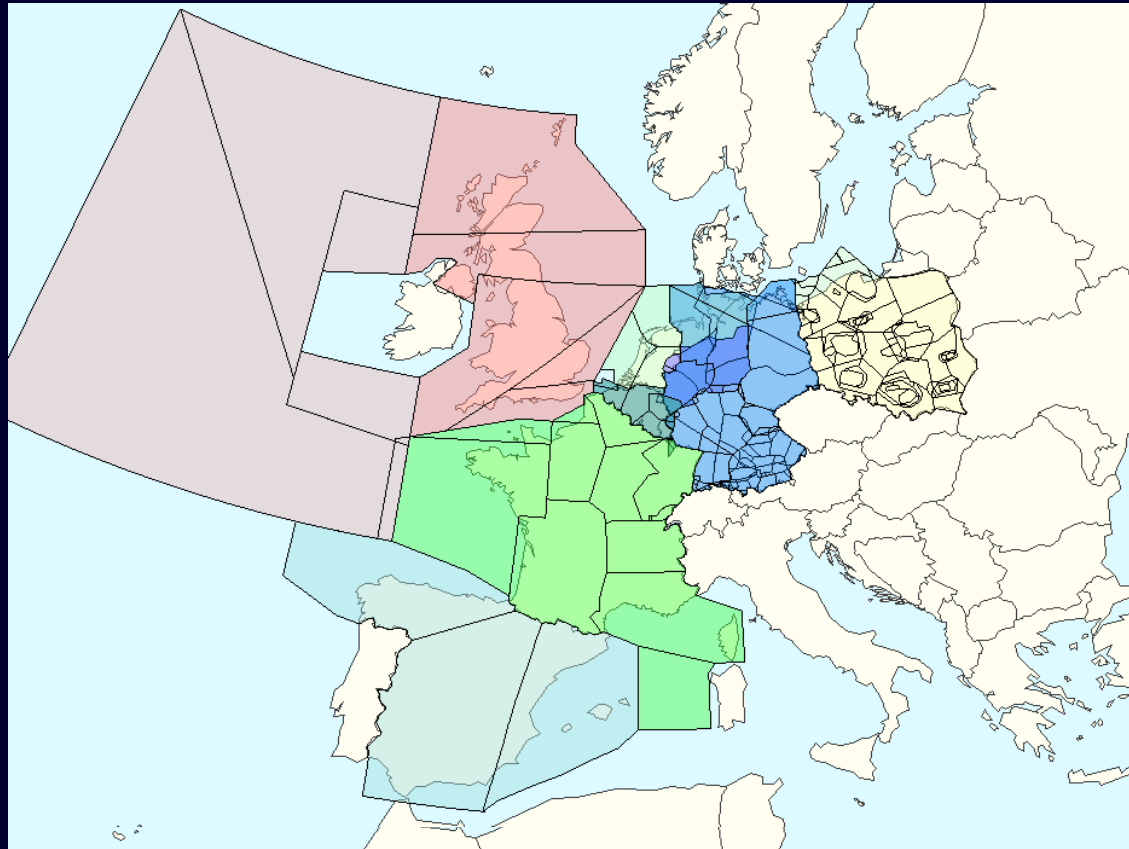
| ANSP | Cost per hour (EUR) | Average difference between controllers available and maximum |
|------|---------------------|--------------------------------------------------------------|
| EDY  | 215                 | 7.0                                                          |
| LF   | 99                  | 9.6                                                          |
| ED   | 197                 | 5.5                                                          |
| EG   | 133                 | 2.7                                                          |
| LE   | 173                 | 6.0                                                          |
| EP   | 96                  | 7.7                                                          |

EUROCONTROL, 2016a. May. ATM Cost-Effectiveness (ACE) 2014 Benchmarking Report with 2015-2019 outlook. Prepared by the Performance Review Unit (PRU) with the ACE Working Group

# Improving sector capacity with ATCO hours



Baseline  
Early adopters  
Followers



# Dynamic cost indexing



| Uptake | Cost      |          | Implementation |
|--------|-----------|----------|----------------|
|        | Strategic | Tactical |                |

|          |                |  |                                                                                                                                                                                                             |
|----------|----------------|--|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Baseline | Not applicable |  | <ul style="list-style-type: none"> <li>• Basic 'rule of thumb'</li> <li>• 10% of flights</li> <li>• Recover as much delay as possible when delay &gt; 15 mins</li> <li>• Maximum extra fuel burn</li> </ul> |
|----------|----------------|--|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

|                |                                                                                                                               |                                                                               |                                                                                                                                                         |
|----------------|-------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------|
| Early adopters | <ul style="list-style-type: none"> <li>• Crew training</li> <li>• Upgrading to Class2 EFB for 50% of aircraft [C2]</li> </ul> | <ul style="list-style-type: none"> <li>• [C1]% of total net saving</li> </ul> | <ul style="list-style-type: none"> <li>• Full DCI</li> <li>• Cost of recovery assessed at TOC</li> <li>• Recovery by discrete blocks of mins</li> </ul> |
| Followers      |                                                                                                                               |                                                                               | <ul style="list-style-type: none"> <li>• Extension of cruise</li> </ul>                                                                                 |

# Dynamic cost indexing



| Uptake         | Actors implementing mechanism                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|----------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Baseline       | <ul style="list-style-type: none"><li>• All flights greater than 60 minutes</li></ul>                                                                                                                                                                                                                                                                                                                                                                              |
| Early adopters | <ul style="list-style-type: none"><li>• Hub carriers of top three ECAC airports: British Airways at EGLL, Lufthansa at EDDF and Air France at LFPG</li></ul>                                                                                                                                                                                                                                                                                                       |
| Followers      | <ul style="list-style-type: none"><li>• Early adopters expand operations at whole network</li><li>• Other hub operators DCI at their major airports. Aircraft operators at five of the Group 1 ECAC airports, i.e.: Turkish Airlines at LTBA (IST), KLM at EHAM (AMS), Alitalia at LIRF (FCO), SAS at EKCH (CPH), SWISS at LSZH (ZRH).</li><li>• Judgement selection other carriers: easyJet at EGKK (LGW), Vueling at LEBL (BCN), Iberia at LEMD (MAD).</li></ul> |

# A-CDM

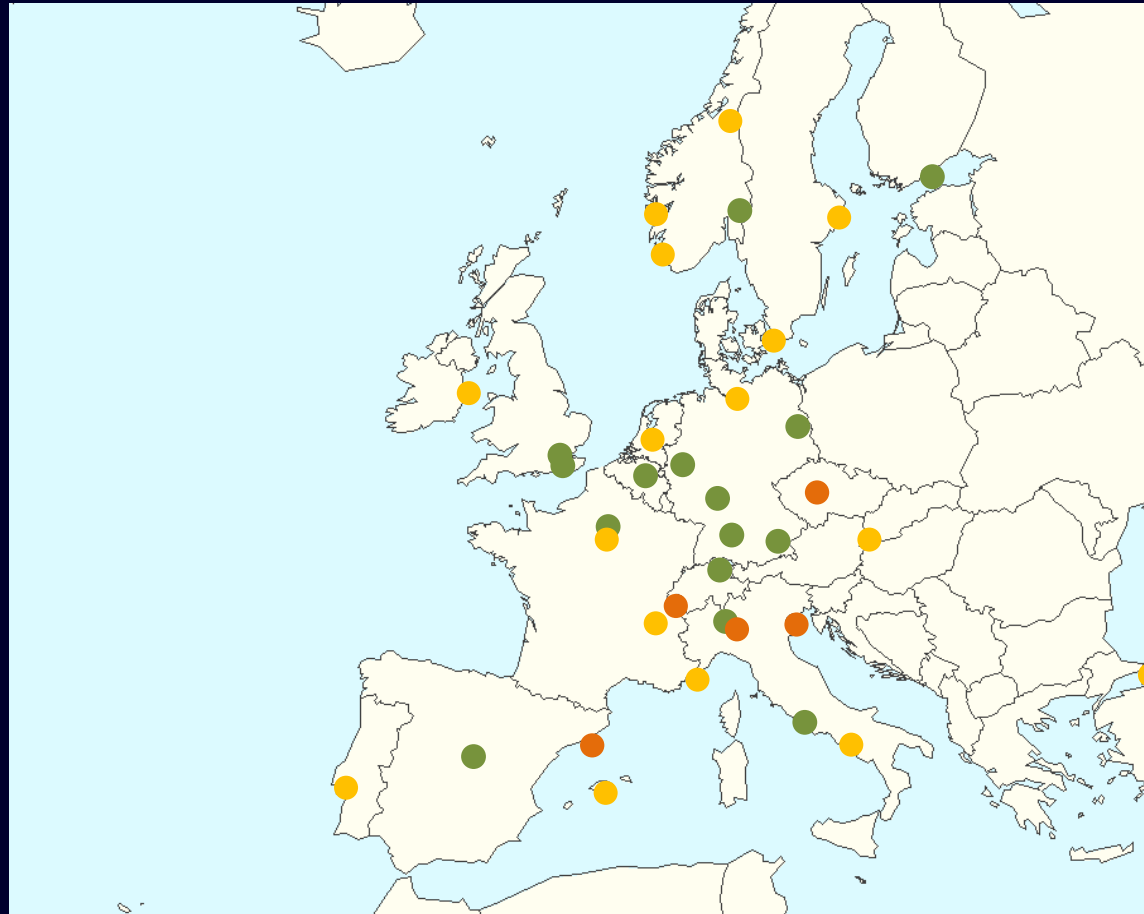


| Uptake         | Cost                                                                                                                                                                                  |                                                                                                                                                                                                  | Implementation                                                                                                               |
|----------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------|
|                | Strategic                                                                                                                                                                             | Tactical                                                                                                                                                                                         |                                                                                                                              |
| Baseline       | Not applicable                                                                                                                                                                        |                                                                                                                                                                                                  | <ul style="list-style-type: none"> <li>Reduction delay propagated: distribution centred on 3%</li> </ul>                     |
| Early adopters | <ul style="list-style-type: none"> <li>Implementation costs €550k – €4800k</li> <li>Airline costs €150k for major/'home' carrier, and €50k in total for the other carriers</li> </ul> | <ul style="list-style-type: none"> <li>Airport, agents and ANSP: €50k – €450k per year</li> <li>Major/'home' carrier: €50k per year</li> <li>Factor 0.34% of the yearly tactical cost</li> </ul> | <ul style="list-style-type: none"> <li>Baseline airports: 4%</li> <li>Airports newly implementing A-CDM: 3%</li> </ul>       |
| Followers      |                                                                                                                                                                                       |                                                                                                                                                                                                  | <ul style="list-style-type: none"> <li>Early adopters airports: 4%</li> <li>Airports newly implementing A-CDM: 3%</li> </ul> |

# A-CDM



Baseline  
Early adopters  
Followers



# Improved passenger reaccommodation



| Uptake         | Cost                                                                 |                                                  | Implementation                                                                                                                                                                                                                                                     |
|----------------|----------------------------------------------------------------------|--------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                | Strategic                                                            | Tactical                                         |                                                                                                                                                                                                                                                                    |
| Baseline       | Not applicable                                                       |                                                  | <ul style="list-style-type: none"> <li>• Local, airport-by-airport solution</li> <li>• Passengers reaccommodated on subsequent flights</li> <li>• Minimisation reaccommodating costs</li> <li>• Passenger compensation cost (Regulation 261) considered</li> </ul> |
| Early adopters | Upgrade of existing software                                         | Fixed cost based on passenger boarded, i.e. [C3] | <ul style="list-style-type: none"> <li>• Network-wide solutions</li> <li>• Assessment passengers missing connection for each outbound flight</li> <li>• Total network costs calculated for 15-minute increments of wait times</li> </ul>                           |
| Followers      | Implementation cost based on volume of passengers boarded, i.e. [C4] |                                                  |                                                                                                                                                                                                                                                                    |

# Improved passenger reaccommodation



| Uptake         | Actors implementing mechanism                                            |
|----------------|--------------------------------------------------------------------------|
| Baseline       | <ul style="list-style-type: none"><li>• Same as early adopters</li></ul> |
| Early adopters | <ul style="list-style-type: none"><li>• Same as DCI mechanism</li></ul>  |
| Followers      | <ul style="list-style-type: none"><li>• Same as DCI mechanism</li></ul>  |

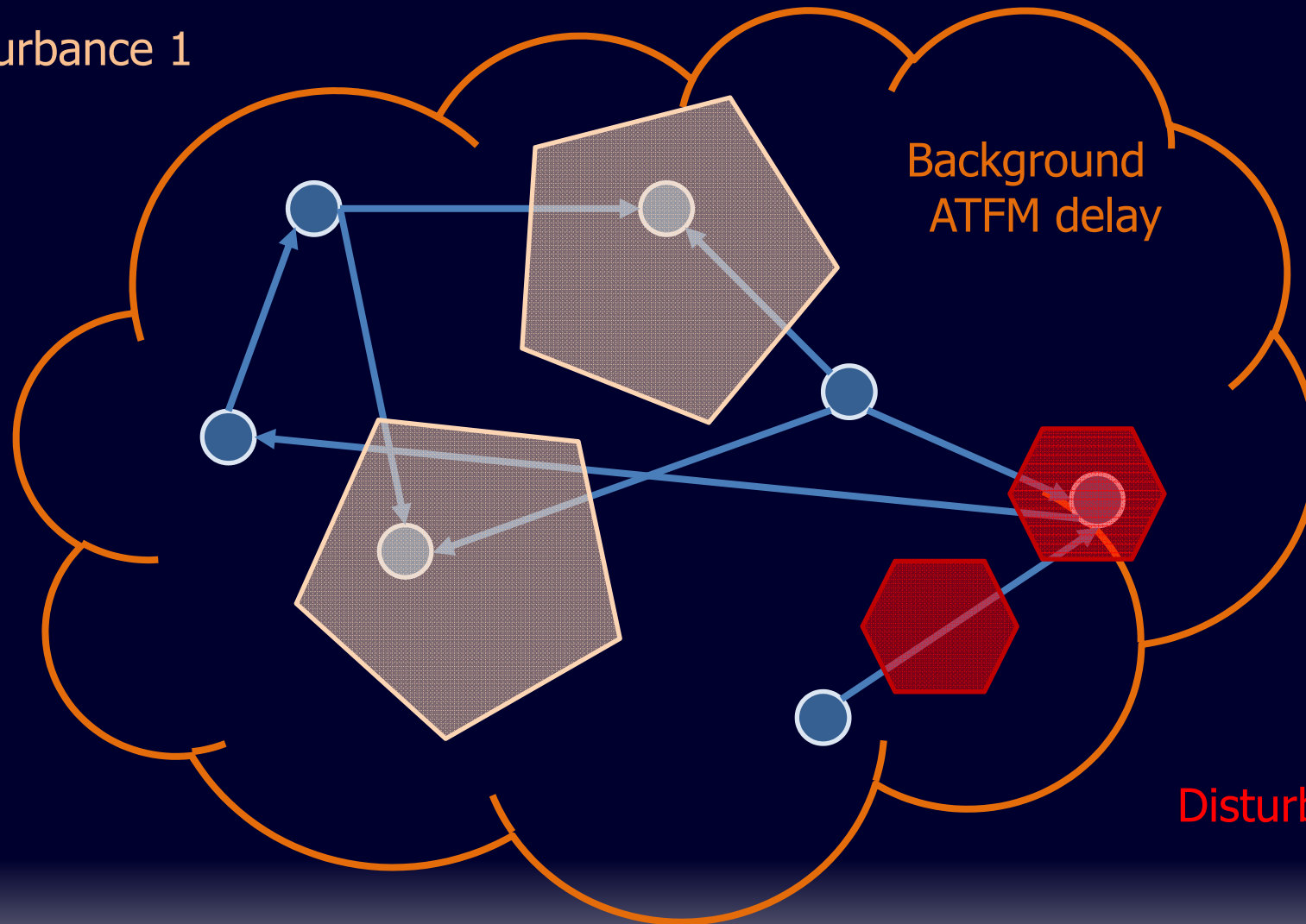
# Mechanisms



| Mechanism                                 | Location | Type     | Focus      | Delay driver | Primary investment |
|-------------------------------------------|----------|----------|------------|--------------|--------------------|
| Improving sector capacity with ATCO hours | En-route | Basic    | Mitigation | Magnitude    | ANSP               |
| Dynamic Cost Indexing                     | En-route | Basic    | Mitigation | Cost         | AO                 |
| A-CDM                                     | Airport  | Advanced | Nominal    | Magnitude    | Airport            |
| Improved passenger reaccomodation         | Airport  | Basic    | Nominal    | Cost         | AO                 |

# Disturbances – ATFM delay

Disturbance 1



Disturbance 2

# Disturbances



- Background ATFM delay
  - Based on delay observed on baseline day (12SEP14)
- Disturbances selected
  - Industrial action
  - Weather
- Scope
  - Local
  - Disperse
- Based on historical disturbances

# Industrial actions



- Data
  - Analysis regulations period ARIAC 1313 – 1413
  - Other data sources (post-operational reports and CODA data)
- Burr fitting for ATFM delay
- Scope
  - Local
    - 24JUN14 (1 ANSP, 124 regulations): French airspace
  - Disperse
    - 30JAN14 (5 ANSPs, 137 regulations): French airspace, Austria, Hungary, Portugal and Slovakia

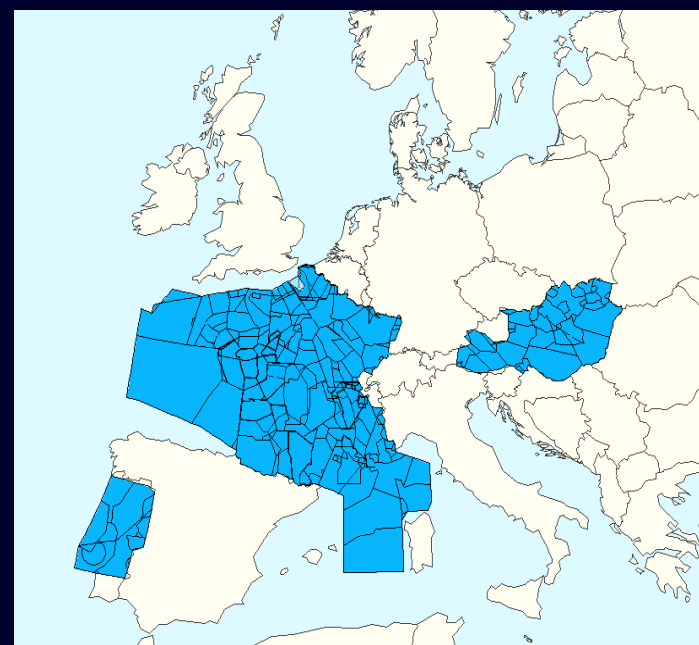
# Industrial actions



24JUN14



30JAN14



# Weather

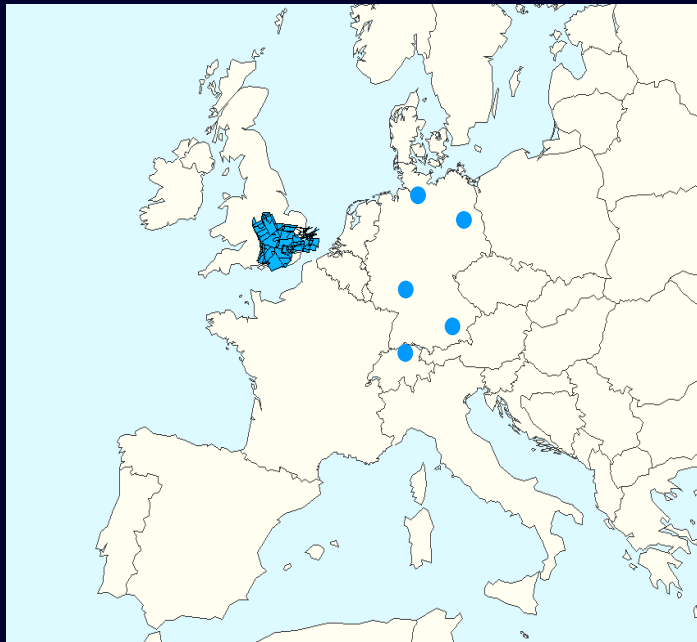


- Data
  - Analysis regulations period ARIAC 1313 – 1413
- Burr fitting for ATFM delay (airport and airspace)
- Scope
  - Local (focus on airports)
    - 18OCT14: Germany, Switzerland and UK
  - Disperse (focus on airspace)
    - 25JUL14: Airports in Poland, Portugal and Switzerland and airspace in France, Germany, MUAC, Portugal, Spain and UK

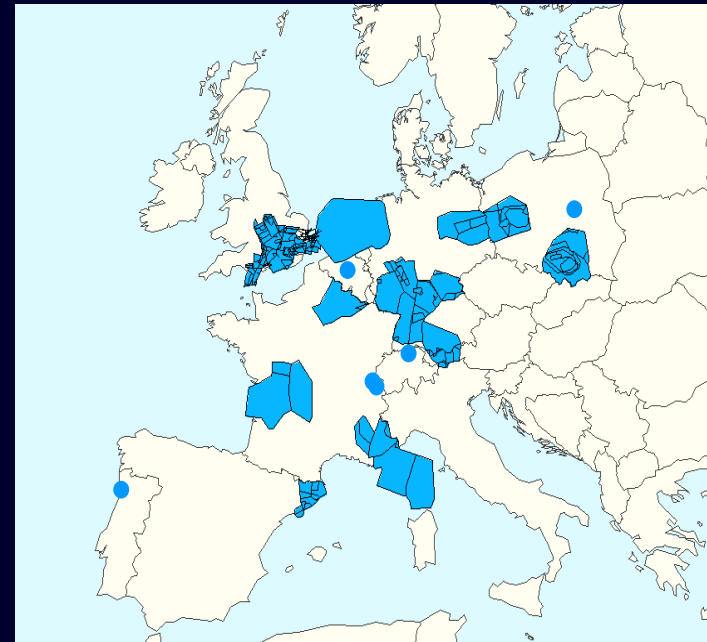
# Weather



18OCT14



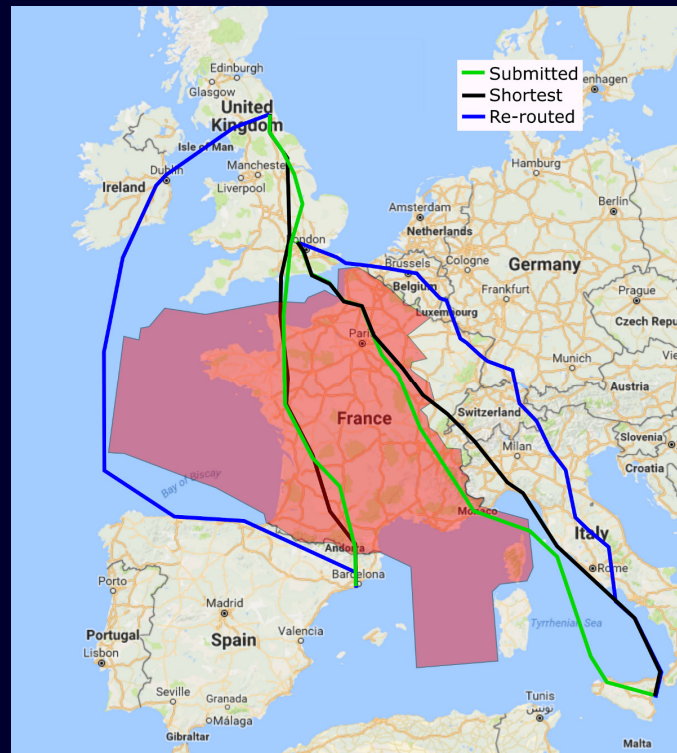
25JUL14



# Re-routing



- Pre-computed shortest route avoiding active regulations



Industrial action  
local

# Re-routing



- Probability being delayed even if re-routed

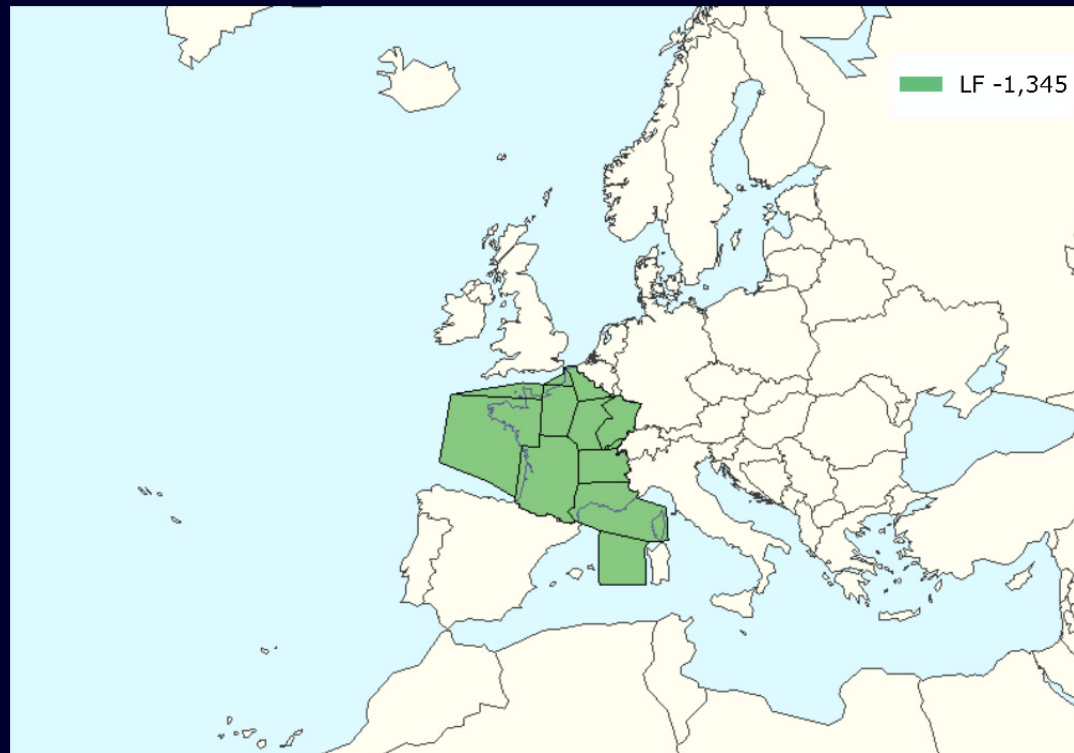


Industrial action  
local

# Re-routing



- Probability being delayed even if re-routed

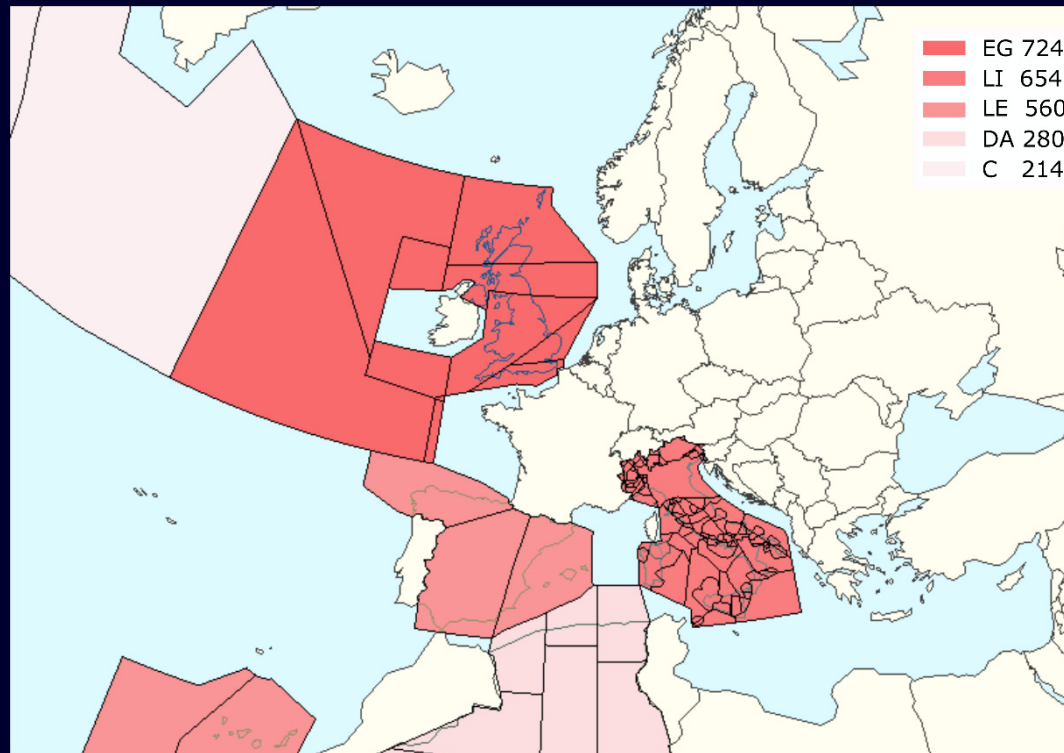


Industrial action  
local

# Re-routing



- Probability being delayed even if re-routed



# Re-routing

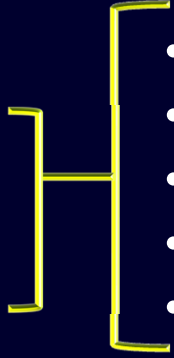


- Probability being delayed even if re-routed

| Disturbance                 | ANSP       | Temporal scope |
|-----------------------------|------------|----------------|
| Industrial action, local    | EG, LI, LE | 0530 - 0900    |
|                             |            | 1800 - 2000    |
| Industrial action, disperse | EG, LI, LE | 0530 – 1000    |
|                             | ED         | 0800 - 1000    |
| Weather, disperse           | LF         | 1600 -1800     |

# Cost allocation



- Airline costs for delay
    - Tactical (day of operations)
    - Reactionary delays will also be assessed
  - Cost updated to 2014 values
- 
- Fleet
  - Fuel (and carbon)
  - Crew
  - Maintenance
  - Passenger costs

# Fuel model



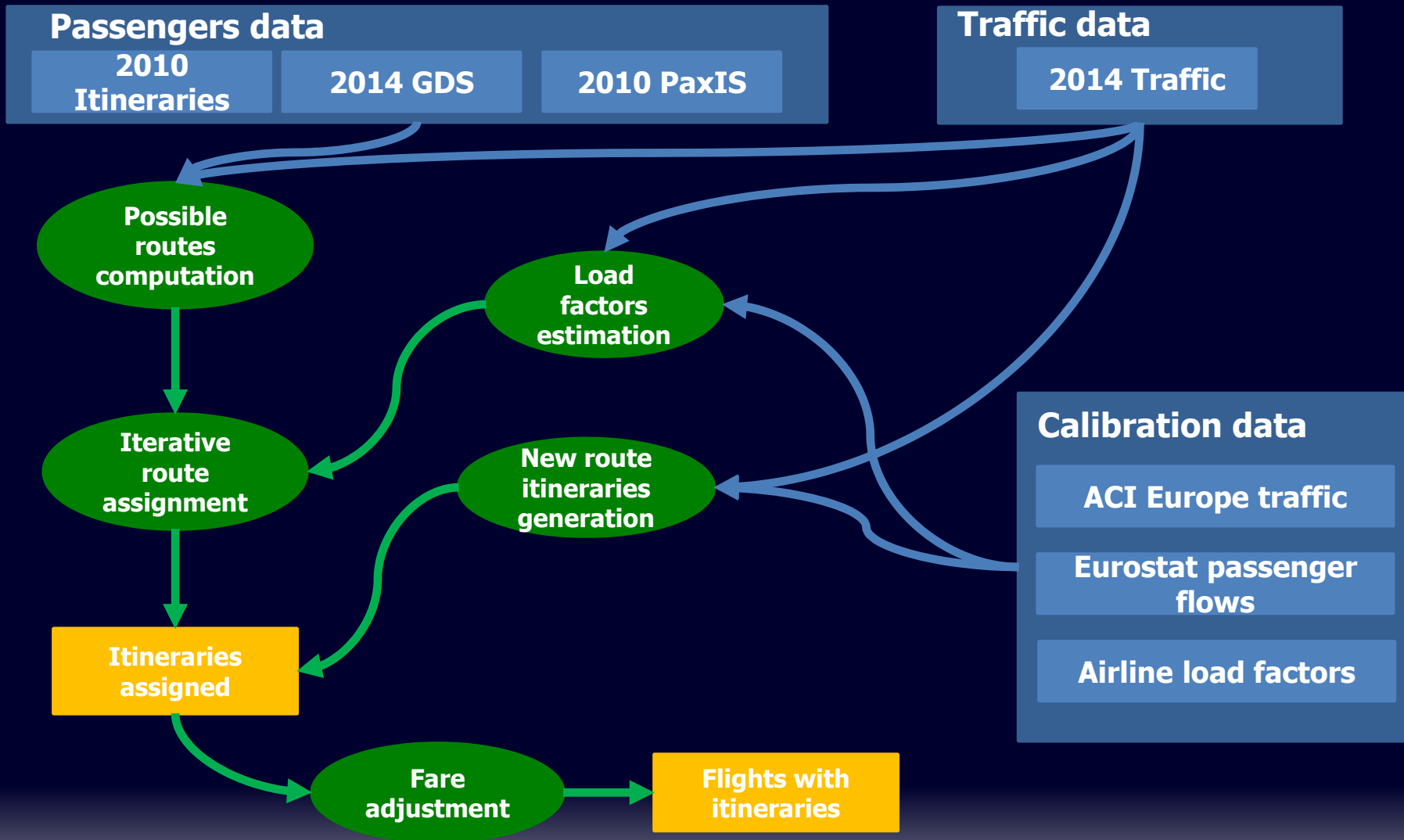
- Estimated considering BADA 4 performance models
- FTFM DDR2 data to estimate flight phases
- Average weight and cruise wind estimated per flight

# Passenger itineraries



- Traffic based on 12SEP14
- To-from 200 ECAC (and 50 non-ECAC) airports selected based on ACI Europe passengers totals
- Flights restored to original schedule

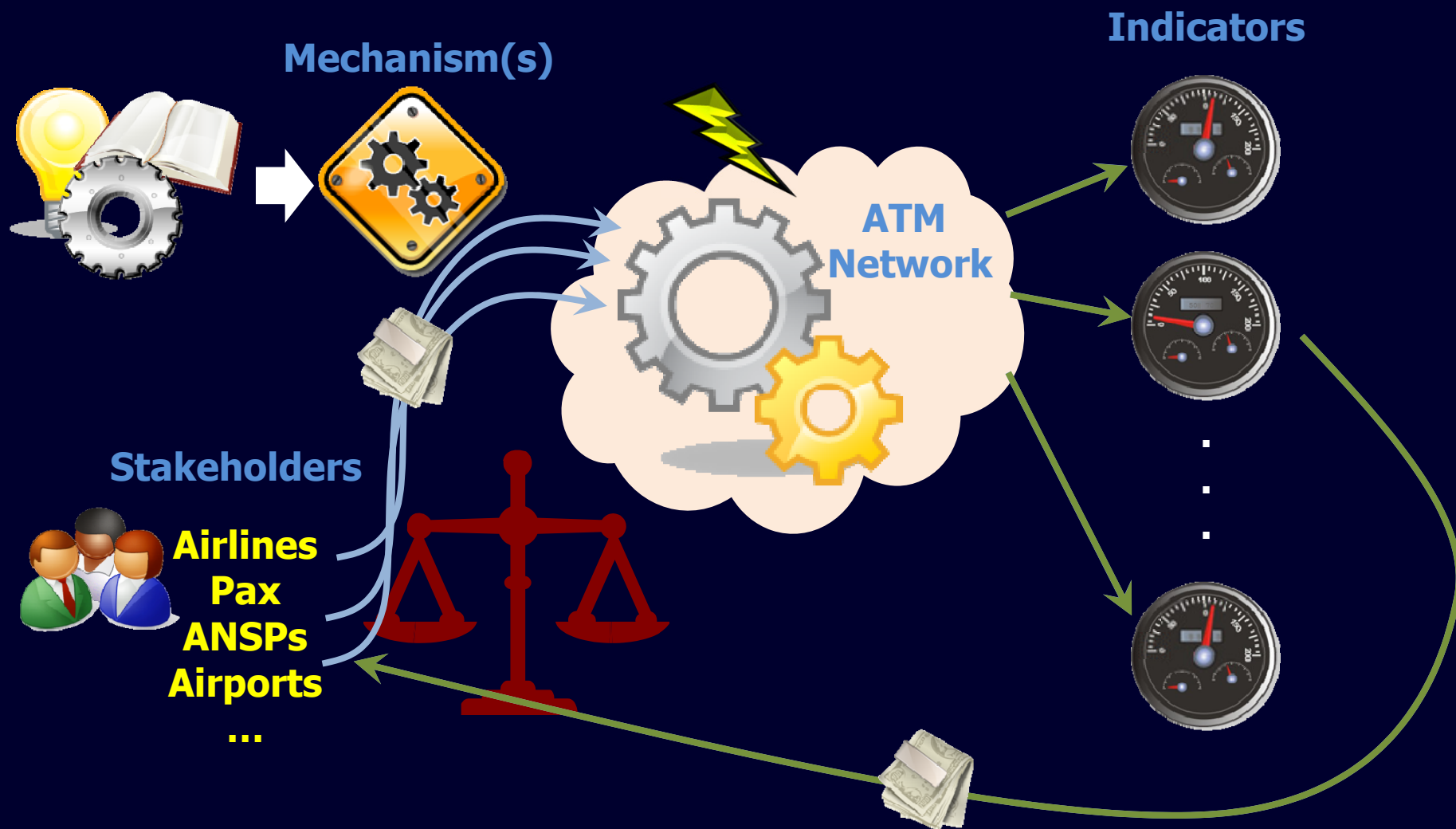
# Passenger itineraries



# Passenger itineraries



| Flights in scope | Seating capacity | Load factors                                                                | Estimated passengers | Overall load factor |
|------------------|------------------|-----------------------------------------------------------------------------|----------------------|---------------------|
| 26k              | 4.5m             | Charter: 91%<br>Full-service: 84%<br>Low-cost carrier: 90%<br>Regional: 75% | 3.8m                 | 84%                 |



# Model calibration

| Metric                                  | Calibration target | Model baseline |
|-----------------------------------------|--------------------|----------------|
| Flight departure delay (mins/flight)    | 10.7               | 10.2           |
| Flight arrival delay (mins/flight)      | 10.0               | 10.2           |
| Reactionary delay (reactionary/total %) | 46.6               | 42.1           |
| Cost of delay (Euros/flight)            | 103                | 104            |

# Model calibration

| Number of flight legs | Passenger itinerary | Passenger proportion targets | Total allocated passengers | Proportion of passengers per number of flight legs |
|-----------------------|---------------------|------------------------------|----------------------------|----------------------------------------------------|
| 1                     | Direct flight       | 80%                          | 3 120 966                  | 83.9%                                              |
| 2                     | One connection      | 18.75%                       | 567 888                    | 15.3%                                              |
| 3                     | Two connections     | 1.25%                        | 30 510                     | 0.8%                                               |
| Totals                |                     | 100%                         | 3 719 364                  | 100%                                               |

| Coverage | Load factor range | Association                  | 12SEP14 overall load factor |
|----------|-------------------|------------------------------|-----------------------------|
| Europe   | 80.3%             | AEA Europe total             | 83.5%                       |
|          | 83.9%             | IATA total market - Europe   |                             |
| Total    | 80.2%             | IATA total market - industry |                             |
|          | 83.6%             | AEA total scheduled          |                             |

# Scenarios

| Mechanism                                    | Location focus | Primary investment | AO delay driver | Disturbance type  |          |         |          |
|----------------------------------------------|----------------|--------------------|-----------------|-------------------|----------|---------|----------|
|                                              |                |                    |                 | Industrial action |          | Weather |          |
|                                              |                |                    |                 | Local             | Disperse | Local   | Disperse |
| 1. Improving sector capacity with ATCO hours | en-route       | ANSP               | magnitude       | ✓                 | ✓        | ✓       | ✓        |
| 2. DCI (+higher fuel cost scenario)          | en-route       | AO                 | cost            | ✓                 | ✓        | ✓       | ✓        |
| 3. A-CDM                                     | airport        | airport            | magnitude       | ✓                 | ✓        | ✓       | ✓        |
| 4. Improved passenger reaccomodation         | airport        | AO                 | cost            | ✓                 | ✓        | ✓       | ✓        |

40 scenarios

# Results and conclusions

# Strategic and tactical costs

| Stakeholder uptake  | Cost      | Improved sectors capacities | DCI, fuel nominal | DCI, fuel high | A-CDM  | Improved passenger reaccomodation |
|---------------------|-----------|-----------------------------|-------------------|----------------|--------|-----------------------------------|
| With early adopters | Strategic | 5 000                       | —                 | —              | 11 300 | 0                                 |
|                     | Tactical  | 2.5*                        | —                 | —              | 3.8    | —                                 |
| With followers      | Strategic | 16 400                      | —                 | —              | 53 100 | —                                 |
|                     | Tactical  | 20.0*                       | —                 | —              | 17.9   | —                                 |

k Euros

\* Costs are assigned per disturbance type; values shown in table are averages over disturbance types

# Resilience Rc – Industrial action disturbance

| Stakeholder uptake  | Scope    | Improved sectors capacities | DCI, fuel nominal | DCI, fuel high | A-CDM | Improved passenger reaccomodation |
|---------------------|----------|-----------------------------|-------------------|----------------|-------|-----------------------------------|
| With early adopters | Local    | 0.038                       | 0.020             | 0.019          | 0.008 | 0.024                             |
|                     | Disperse | 0.049                       | 0.017             | 0.016          | 0.004 | 0.021                             |
| With followers      | Local    | 0.237                       | 0.056             | 0.064          | 0.007 | 0.008                             |
|                     | Disperse | 0.271                       | 0.058             | 0.067          | 0.004 | 0.009                             |

(All values relate to n = 26 860 flights)

# Resilience Rc – Industrial action disturbance

| Stakeholder uptake  | Scope    | Improved sectors capacities | DCI, fuel nominal | DCI, fuel high | A-CDM | Improved passenger reaccomodation |
|---------------------|----------|-----------------------------|-------------------|----------------|-------|-----------------------------------|
| With early adopters | Local    | 0.038                       | 0.020             | 0.019          | 0.008 | 0.024                             |
|                     | Disperse | 0.049                       | 0.017             | 0.016          | 0.004 | 0.021                             |
| With followers      | Local    | 0.237                       | 0.056             | 0.064          | 0.007 | 0.008                             |
|                     | Disperse | 0.271                       | 0.058             | 0.067          | 0.004 | 0.009                             |

(All values relate to n = 26 860 flights)

# Resilience Rc – Industrial action disturbance

| Stakeholder uptake  | Scope    | Improved sectors capacities | DCI, fuel nominal | DCI, fuel high | A-CDM | Improved passenger reaccomodation |
|---------------------|----------|-----------------------------|-------------------|----------------|-------|-----------------------------------|
| With early adopters | Local    | 0.038                       | 0.020             | 0.019          | 0.008 | 0.024                             |
|                     | Disperse | 0.049                       | 0.017             | 0.016          | 0.004 | 0.021                             |
| With followers      | Local    | 0.237                       | 0.056             | 0.064          | 0.007 | 0.008                             |
|                     | Disperse | 0.271                       | 0.058             | 0.067          | 0.004 | 0.009                             |

(All values relate to n = 26 860 flights)

# Resilience Rc – Industrial action disturbance

| Stakeholder uptake  | Scope    | Improved sectors capacities | DCI, fuel nominal | DCI, fuel high | A-CDM | Improved passenger reaccomodation |
|---------------------|----------|-----------------------------|-------------------|----------------|-------|-----------------------------------|
| With early adopters | Local    | 0.038                       | 0.020             | 0.019          | 0.008 | 0.024                             |
|                     | Disperse | 0.049                       | 0.017             | 0.016          | 0.004 | 0.021                             |
| With followers      | Local    | 0.237                       | 0.056             | 0.064          | 0.007 | 0.008                             |
|                     | Disperse | 0.271                       | 0.058             | 0.067          | 0.004 | 0.009                             |

(All values relate to n = 26 860 flights)

# Resilience Rc – Weather disturbance

| Stakeholder uptake  | Scope    | Improved sectors capacities | DCI, fuel nominal | DCI, fuel high | A-CDM   | Improved passenger reaccomodation |
|---------------------|----------|-----------------------------|-------------------|----------------|---------|-----------------------------------|
| With early adopters | Local    | 0.027                       | 0.008             | 0.016          | 0.002   | 0.000                             |
|                     | Disperse | 0.020                       | 0.002             | 0.010          | 0.012   | 0.004                             |
| With followers      | Local    | 0.210                       | 0.053             | 0.064          | 0.002   | -0.000*                           |
|                     | Disperse | 0.211                       | 0.044             | 0.057          | -0.000* | 0.005                             |

\* Adjusted from small negative values statistically equivalent to zero

(All values relate to n = 26 860 flights)

# Resilience Rc

## Industrial actions

| Stakeholder uptake  | Scope    | Improved sectors capacities | DCI, fuel nominal | DCI, fuel high | A-CDM  | Improved passenger reacomodation |
|---------------------|----------|-----------------------------|-------------------|----------------|--------|----------------------------------|
| With early adopters | Local    | 0.038                       | 0.020             | 0.019          | 0.008  | 0.024                            |
|                     | Disperse | 0.049                       | 0.017             | 0.016          | 0.004  | 0.021                            |
| With followers      | Local    | 0.237                       | 0.056             | 0.064          | 0.007  | 0.008                            |
|                     | Disperse | 0.271                       | 0.058             | 0.067          | 0.004  | 0.009                            |
| <b>Weather</b>      |          |                             |                   |                |        |                                  |
| With early adopters | Local    | 0.027                       | 0.008             | 0.016          | 0.002  | 0.000                            |
|                     | Disperse | 0.020                       | 0.002             | 0.010          | 0.012  | 0.004                            |
| With followers      | Local    | 0.210                       | 0.053             | 0.064          | 0.002  | -0.000*                          |
|                     | Disperse | 0.211                       | 0.044             | 0.057          | -0.000 | 0.005                            |

\* Adjusted from small negative values statistically equivalent to zero

# Metric results

| Metric                                       |      | Improved<br>sectors<br>capacities | DCI, fuel<br>nominal | DCI, fuel<br>high | A-CDM | Improved<br>passenger<br>reacomodation |
|----------------------------------------------|------|-----------------------------------|----------------------|-------------------|-------|----------------------------------------|
| Flight dep. delay<br>(mins/flight)           | 10.2 | 14.9                              | 17.6                 | 17.6              | 17.9  | 18.4                                   |
| Flight arrival delay<br>(mins/flight)        |      | 14.9                              | 17.3                 | 17.2              | 17.8  | 18.4                                   |
| Pax arrival delay<br>(mins/pax)              |      | 25.1                              | 27.9                 | 27.8              | 28.3  | 28.4                                   |
| Arr. delay of arr.-delayed<br>pax (mins/pax) |      | 53.4                              | 56.8                 | 56.7              | 56.6  | 56.3                                   |
| Pax / flight delay                           |      | 1.69                              | 1.61                 | 1.61              | 1.59  | 1.55                                   |
| Cost of delay<br>(Euros/flight)              |      | 287                               | 318                  | 316               | 328   | 328                                    |
| Reactionary delay<br>(reactionary/total %)   |      | 44.2                              | 44.9                 | 44.8              | 45.7  | 47.4                                   |

# Metric results

| Metric                                    | Improved sectors capacities | DCI, fuel nominal | DCI, fuel high | A-CDM | Improved passenger reaccommodation |
|-------------------------------------------|-----------------------------|-------------------|----------------|-------|------------------------------------|
| Flight dep. delay (mins/flight)           | 14.9                        | 17.6              | 17.6           | 17.9  | 18.4                               |
| Flight arrival delay (mins/flight)        | 14.9                        | 17.3              | 17.2           | 17.8  | 18.4                               |
| Pax arrival delay (mins/pax)              | 25.1                        | 27.9              | 27.8           | 28.3  | 28.4                               |
| Arr. delay of arr.-delayed pax (mins/pax) | 53.4                        | 56.8              | 56.7           | 56.6  | 56.3                               |
| Pax / flight delay                        | 1.69                        | 1.61              | 1.61           | 1.59  | 1.55                               |
| Cost of delay (Euros/flight)              | 287                         | 318               | 316            | 328   | 328                                |
| Reactionary delay (reactionary/total %)   | 44.2                        | 44.9              | 44.8           | 45.7  | 47.4                               |

# Metric results

| Metric                             | Improved sectors capacities | DCI, fuel nominal | DCI, fuel high | A-CDM | Improved passenger reaccomodation |
|------------------------------------|-----------------------------|-------------------|----------------|-------|-----------------------------------|
| Airborne fuel burn (tonnes/flight) | 8.94                        | 8.45              | 8.45           | 8.93  | 8.93                              |
| Airborne CO2 (tonnes/flight)       | 28.3                        | 26.7              | 26.7           | 28.2  | 28.2                              |
| At-gate CO2 (tonnes/flight)        | 0.215                       | 0.223             | 0.223          | 0.223 | 0.226                             |

# Strategic cost recovery periods

| Stakeholder uptake  | Improved sectors capacities | DCI, fuel nominal | DCI, fuel high | A-CDM   | Improved passenger reaccomodation |
|---------------------|-----------------------------|-------------------|----------------|---------|-----------------------------------|
| With early adopters | 1                           | 6                 | 5              | 10 (1*) | ≈ 0                               |
| With followers      | < 1                         | 4                 | 3              | (5*)    | 2                                 |

months

\* Based on airline implementation costs

# Conclusions

- Cost resilience assessed
  - four mechanisms
  - phased stakeholder uptake
  - explicit local and disperse disturbances
- Flight-, passenger- and cost-centric metrics
- Fully costed results based on extensive industry consultation
- Need for dedicated passenger-centric metrics corroborated
- Cost-resilience metric developed and tested
  - Metric behaves logically and sensitively
  - High-level performance indicator

# Future research

- Model implementation
- Input data and cost assignments
- Disturbances
- Mechanisms
- Analyses

# Thank you