Network-wide assessment of 4D trajectory adjustments using an agent-based model

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Luis Delgado, Gerald Gurtner, Andrew Cook

Piero Mazzarisi, Silvia Zaoli , Fabrizio Lillo

Damir Valput

DOMINO

founding members

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Domino project

UNIVERSITY OF WESTMINSTER

EUROCONTROL

UNIVERSITÀ DEGLI STUDI DI TRIESTE

innaxis

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA A.D. 1088

Domino project

Domino aims at studying the degree of 'tightness' under which the air transportation system operates.

➔ Interdependency between components, propagation of disruptions etc.

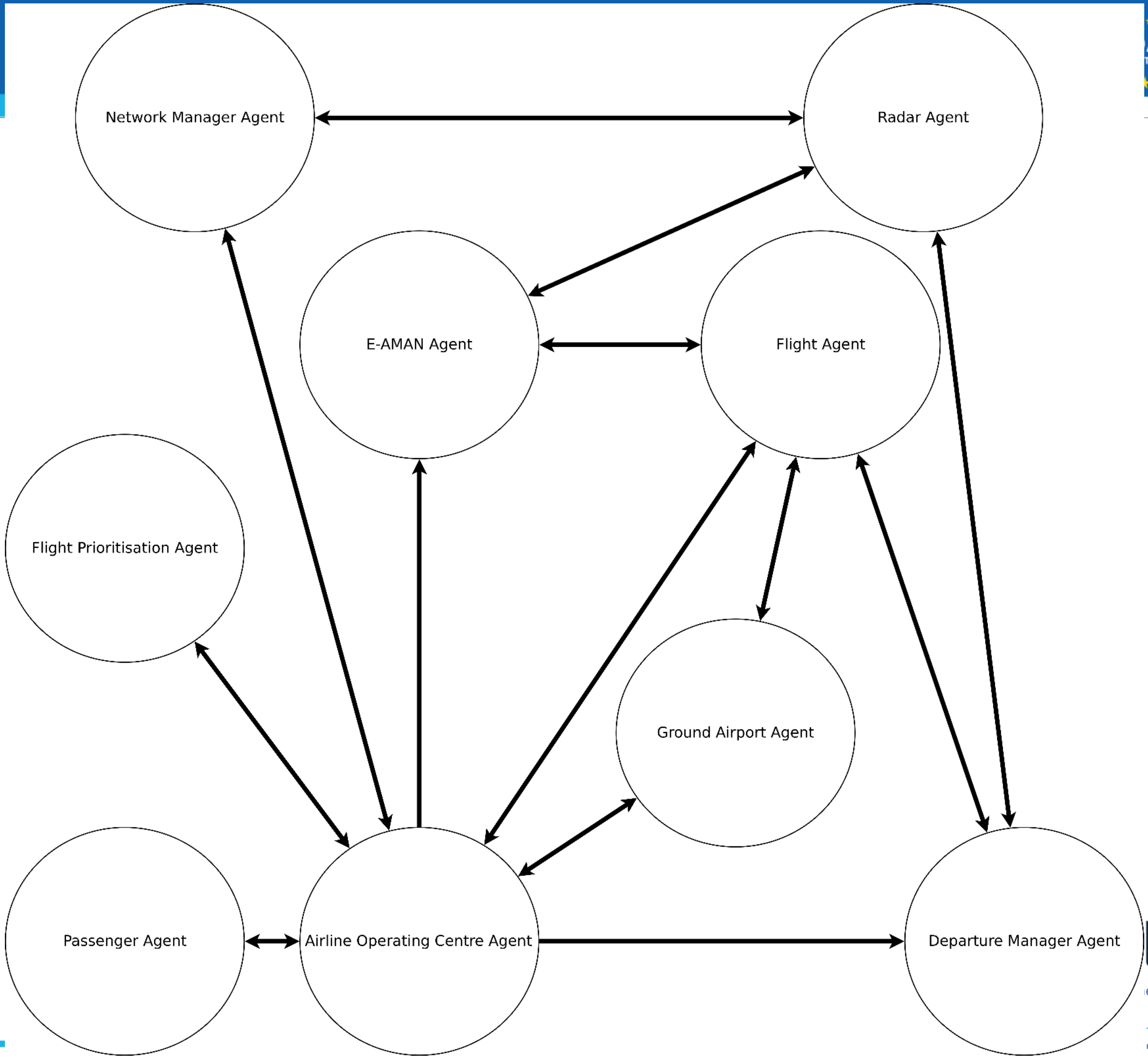
Objectives:

- Build model able to catch complex network effect on a day of operation.
- Review and complement metrics that could be used to measure systemic and network effects.
- Analyse a few case studies, using the model to simulate a typical day operations with various alternative mechanisms and the metrics to assess their impact.

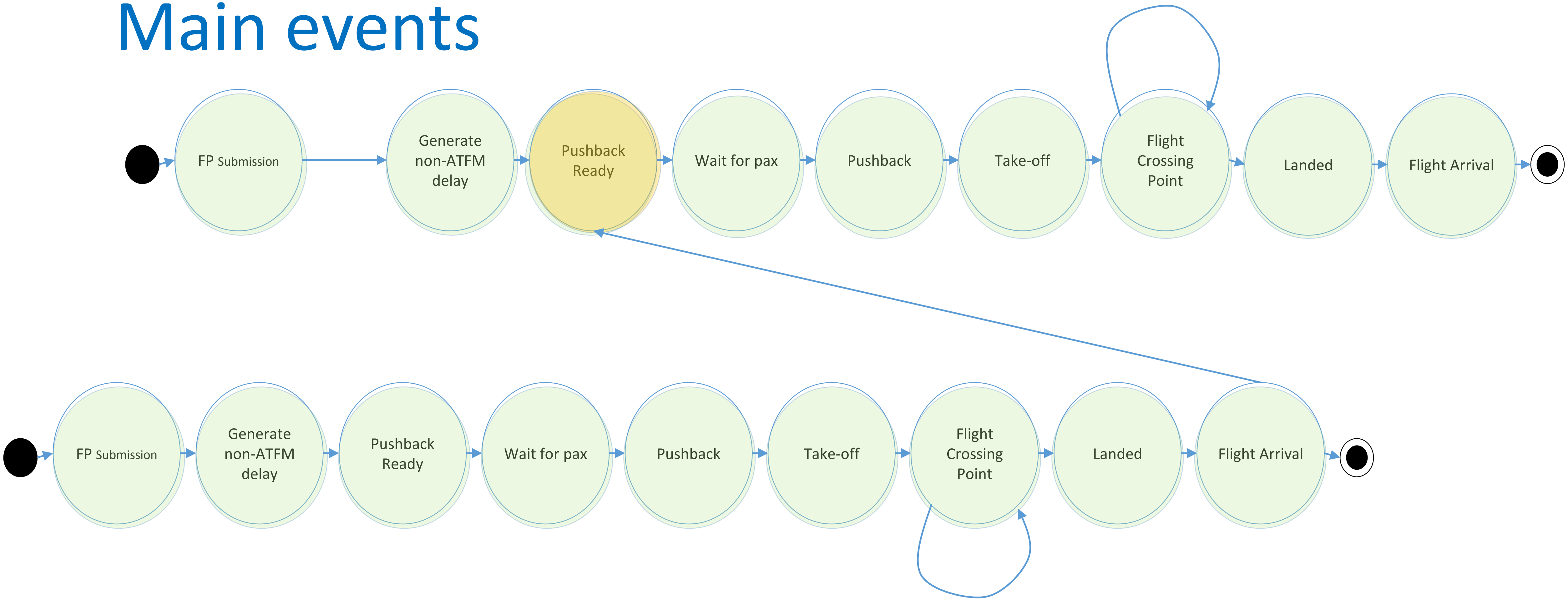
The Mercury ABM

- Mercury is a European-scale simulator developed over nearly a decade.
- Last version has been developed in Domino and features:
  - Detailed description of a day of operation (pre-tactical/tactical).
  - Individual passenger tracking, including connections.
  - European-scale: 800 airports, all flights (30k) and pax (3.4M) arriving, departing, or connecting at a European airport.
  - Monte-Carlo simulation relying on a high number of tailored distributions: various delays, connecting times, cancellations.
  - Agent-based paradigm: ground airports, network manager, airline operating centres, flights, E-AMAN, etc.

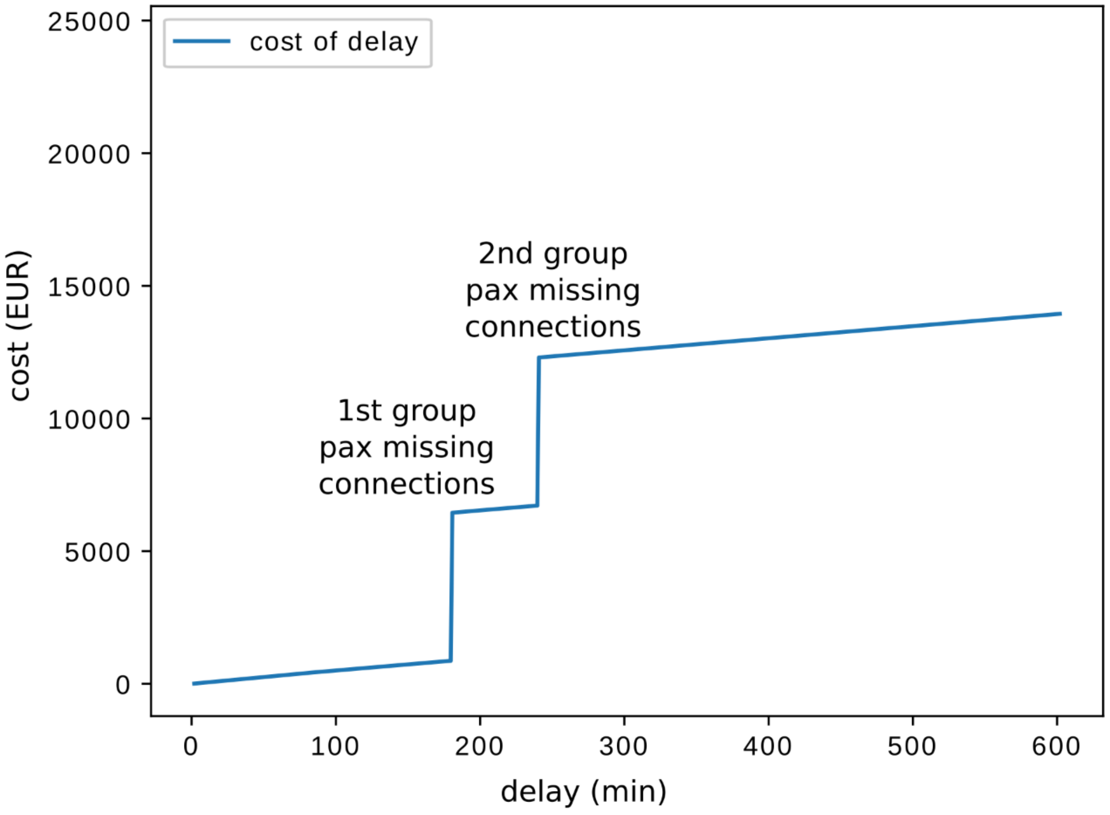
Agents

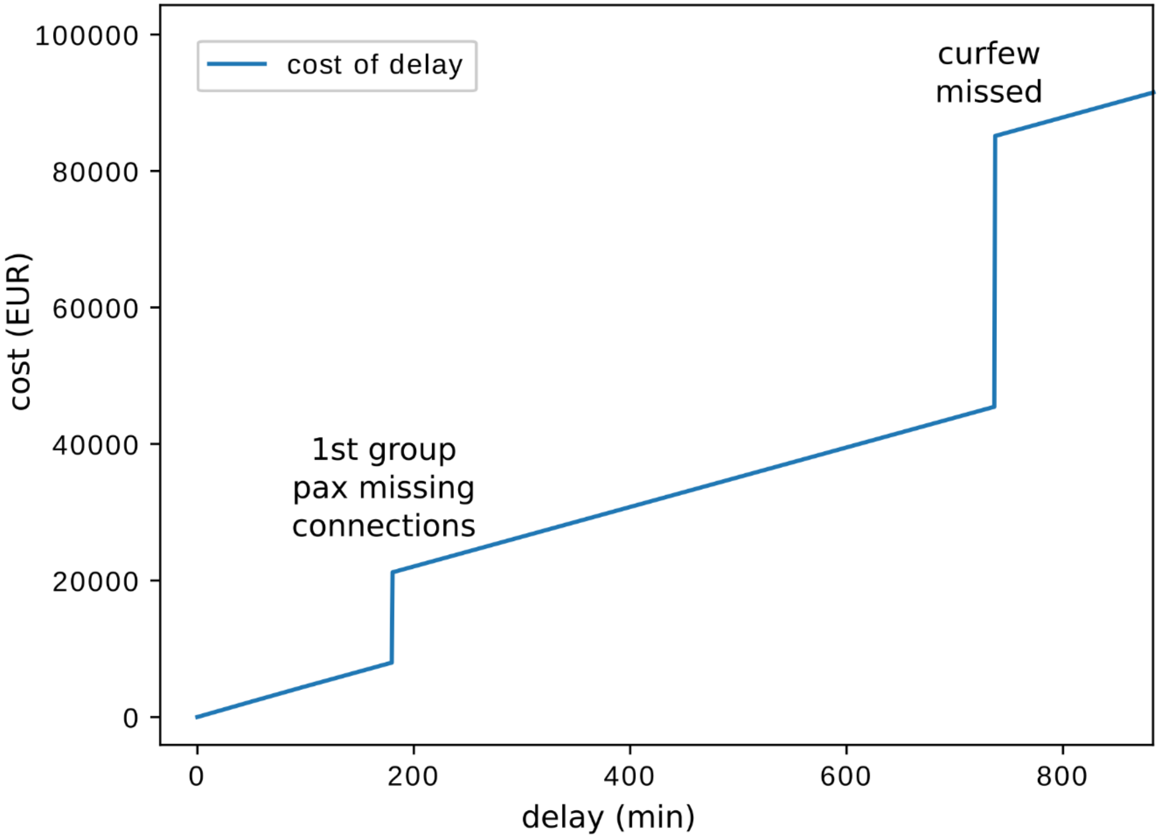

Network Manager Agent
Radar Agent
E-AMAN Agent
Flight Agent
Flight Prioritisation Agent
Ground Airport Agent
Passenger Agent
Airline Operating Centre Agent
Departure Manager Agent

Main events


FP Submission
Generate non-ATFM delay
Pushback Ready
Wait for pax
Pushback
Take-off
Flight Crossing Point
Landed
Flight Arrival
FP Submission
Generate non-ATFM delay
Pushback Ready
Wait for pax
Pushback
Take-off
Flight Crossing Point
Landed
Flight Arrival

Airline cost function





Scenario

- Model is calibrated on real data from the 12th Sept. 2014, a busy but not disrupted day.
- This is the standard baseline for the results.
- Domino defined a stressed baseline is order to test the behaviours of the mechanisms in different environments.
  - 30 minutes of delay in average against 11 for the standard baseline
- A scenario is then:
  - A baseline + the application of different mechanisms allowing the agents to mitigate the effects of delay.

Mechanisms

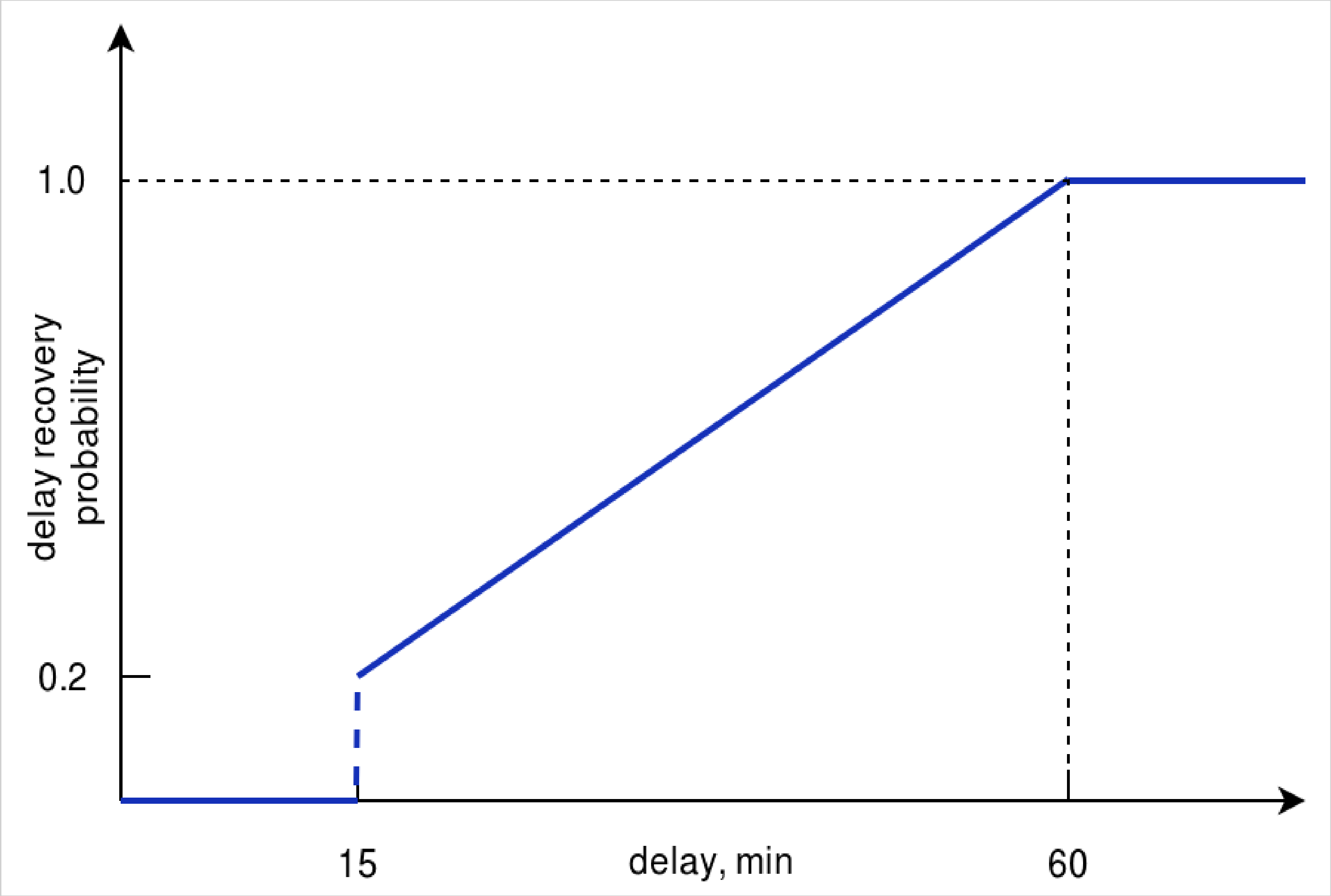
Domino explored three mechanisms:

- 4D trajectory adjustments (4DTA): combination of wait for passengers (WfP) and speed adjustments (DCI).
- Flight prioritisation: possible flight swapping (UDPP) for flights in airport regulation at arrival, among own flights and between companies.
- Flight arrival coordination: Extended arrival manager (E-AMAN) with different rules and different horizons.

4D trajectory adjustments

Level 0 - rule of thumb:

- Wait only for premium passengers up to 15 minutes
- Probability of speeding up based on expected delay.



4D trajectory adjustments (cont.)

Level 1:

- WfP balances two costs:
  - Cost of delaying passengers ready to board (incl. connections).
  - Cost of paying for rebooking or reaccommodation for connecting passengers.
- Cost index is decided at top of climb and balances:
  - Cost of fuel.
  - Cost of delay.

Level 2:

- Same decision but CI is assessed with WfP.
- Optimal CI is assessed twice: before departure and at top of climb.
- Can slow down with respect to the nominal speed.

Classical metrics

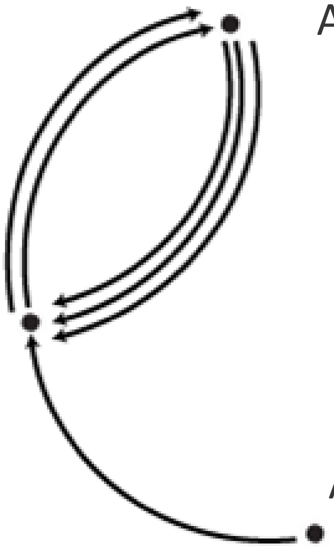
ABM allows to have a high number of observables on the system. Consolidated metrics:

- Flight departure/arrival delay,
- Passenger final arrival delay,
- Cost of fuel, pax compensation, etc.

Results of Mercury are stochastic: one output is a one realisation
➔ statistics are needed on the output.

Centrality

Centrality (Katz, PageRank) of a node on a network (airports as nodes, flights as edges):



$kc_i = \alpha \times$ (#walks of length 1) $+ \alpha^2 \times$ (#walks of length 2) + ...

$\alpha \leq 1$ (longer walks contribute less)

Pax and trip centrality

New metrics, defined by Domino:

- Trip centrality takes into account legit paths, i.e. feasible connection based on flight schedules.
- Can take into account connection times, can be used by layers (intra-alliance for instance).
- ➔ variations of centrality measures the potential connectivity loss (between scheduled and actual itineraries) of a given airport.
- Centralities can weighted by the passengers using these itineraries, which defines passenger centrality.

Note: See 2018 SID presentation for more details about these metrics (Zaoli et al)

(Granger) causality

- Granger causality answers to the question: “Can we predict the state (e.g. congestion) of node A knowing the state of node B?”.
- If so ➔ causal link between A and B (‘B causes A’).
- How? Use an autoregressive model:

$$\begin{cases} x_t & = \phi_0^1 + \Sigma_{j=1}^{p} \phi_j^{11} x_{t-j} + \Sigma_{i=1}^{p} \phi_i^{12} y_{t-i} + \epsilon_t^1 \\ y_t & = \phi_2^1 + \Sigma_{j=1}^{p} \phi_j^{21} x_{t-j} + \Sigma_{i=1}^{p} \phi_i^{22} y_{t-i} + \epsilon_t^2 \end{cases}$$

- Different choice for the ‘state’:
  - Classical (Granger in mean): x and y are departure delays, averaged for instance over 1 hour.
  - New in Domino (Granger in tail): use ‘extreme’ states i.e. x=1 if delay over a threshold, 0 otherwise.

Results

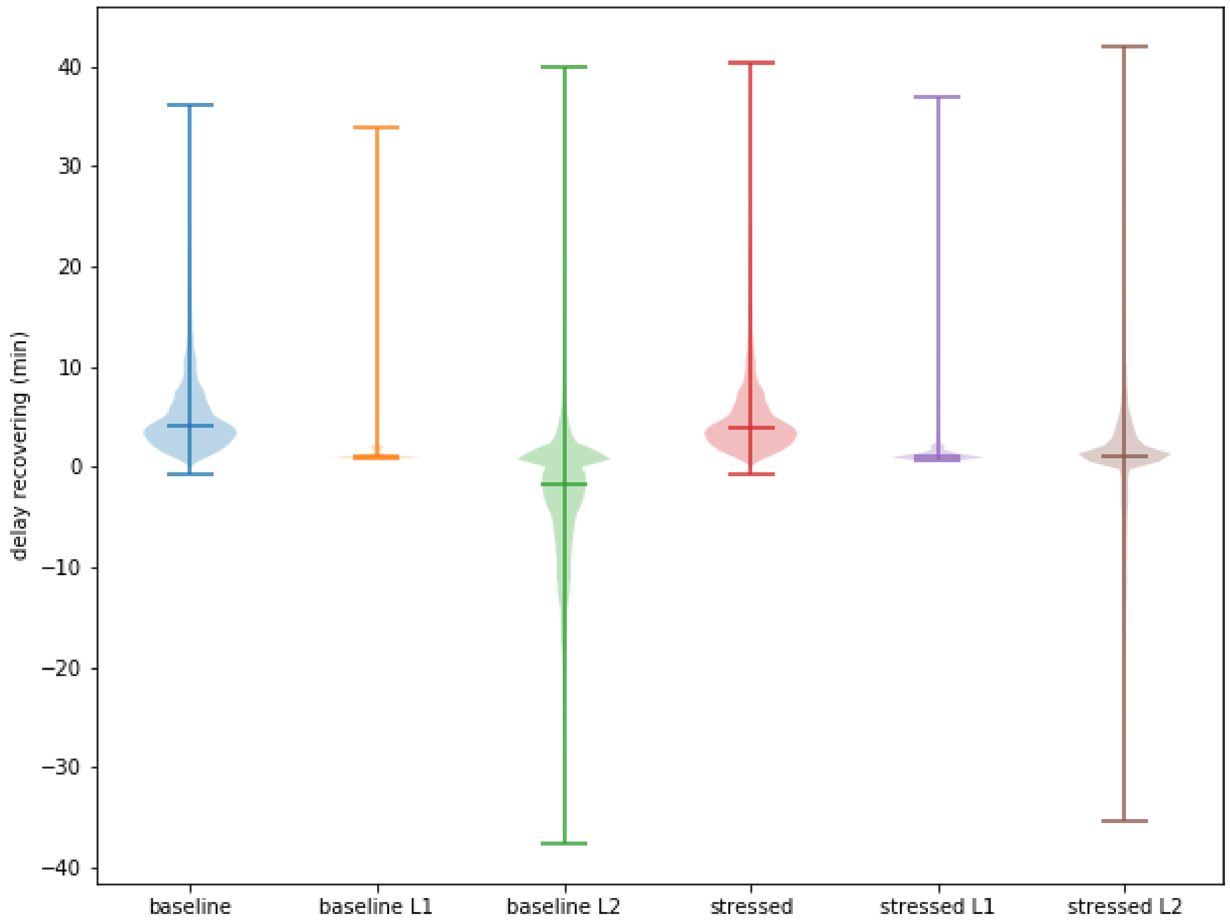
Model results:

- Per baseline type, standard or stressed.
- Per level, L0, L1, or L2.
- L1 and L2 are contrasted with L0, the closest to the current behaviour.

Agent behaviour

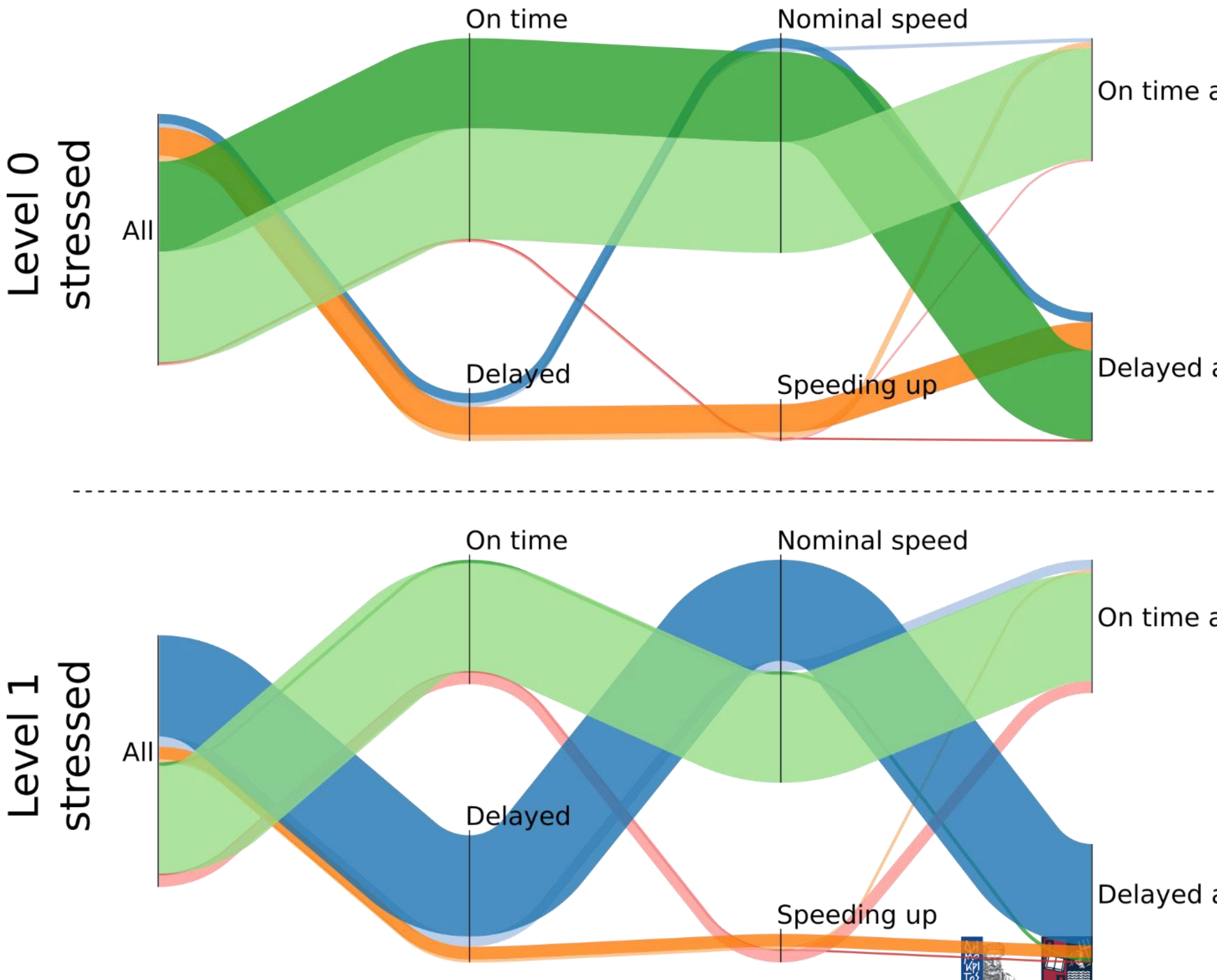
When do flights speed up?

- L0: flights try to speed up to recover delay
- L1: flights don't speed up in general: too costly!
- L2: some flights wait for pax and speed up, others try to save fuel by slowing down. In stressed sc.: no more slowing down!



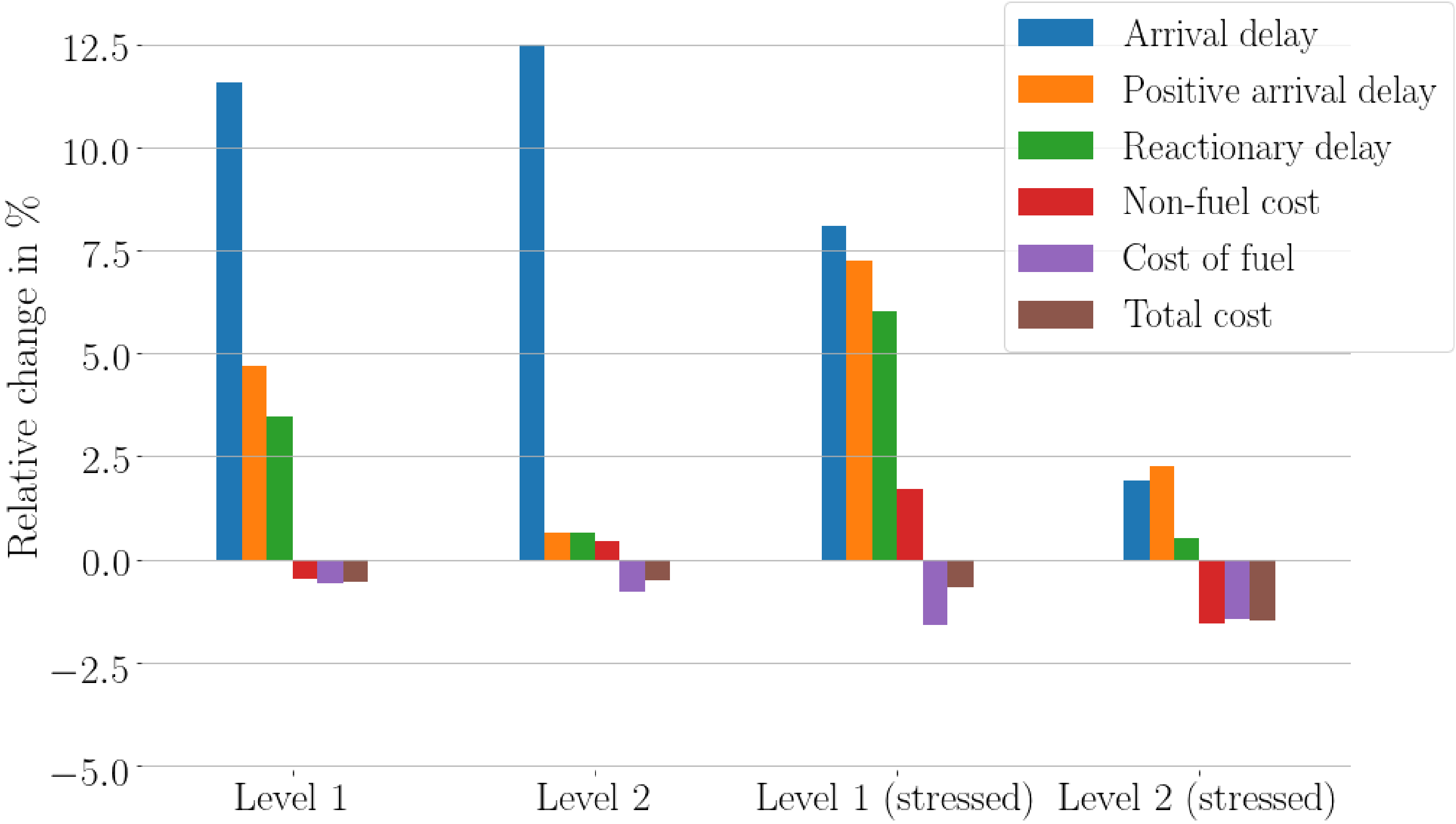
Agent behaviour

- L0: lots of flights do not speed up and end up late.
- L1: flights wait more for passenger and use their buffer instead of speeding up.



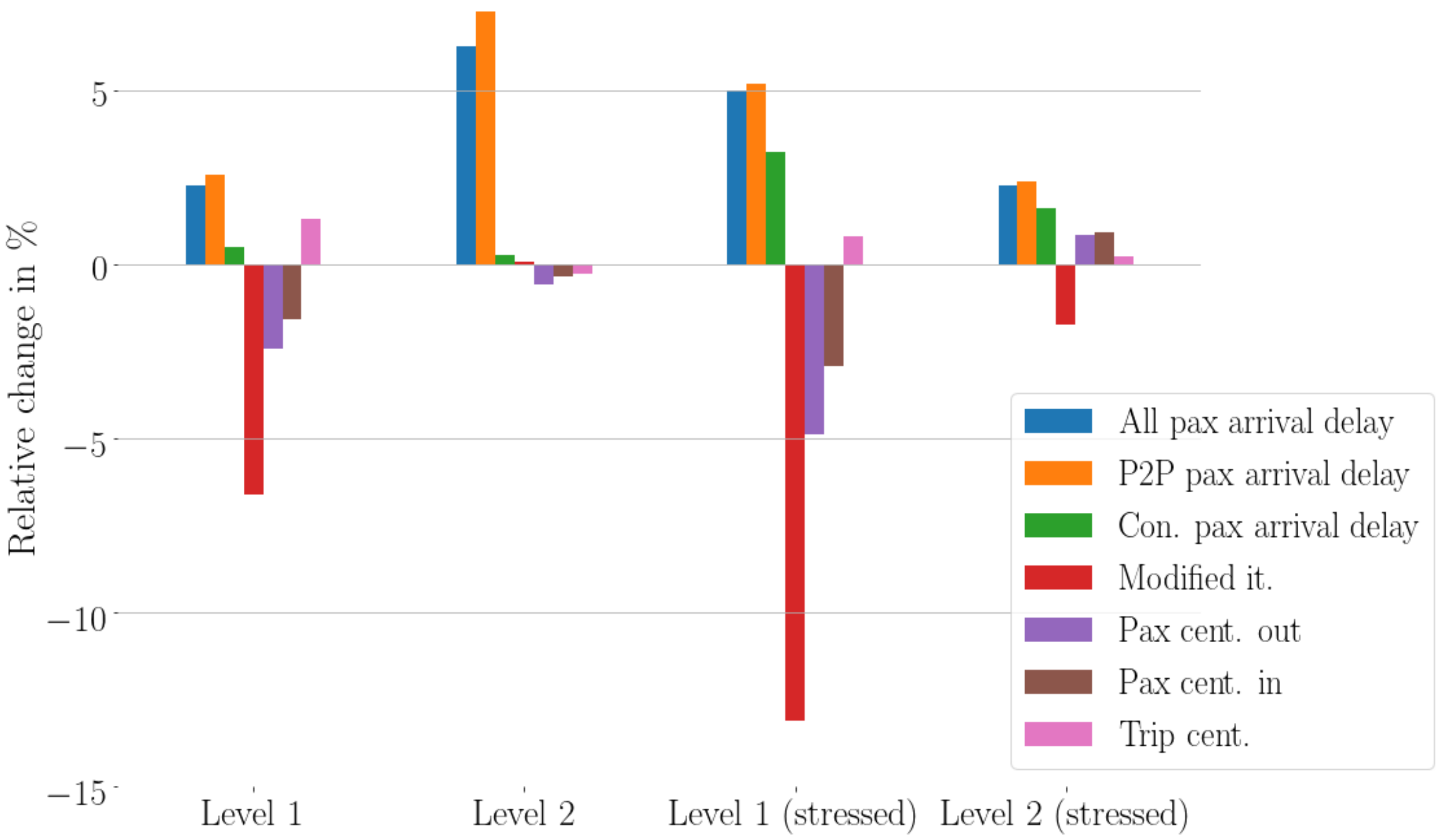
Results on airline indicators

- L1 allows to save pax and fuel costs at the expense of some increased delays. Mostly, early flights are not early anymore.
- L1 in the stressed sc. is focused on saving fuel.
- L2 only impacts early flights in the baseline.
- L2 allows important savings in the stressed situation, with little delay increase



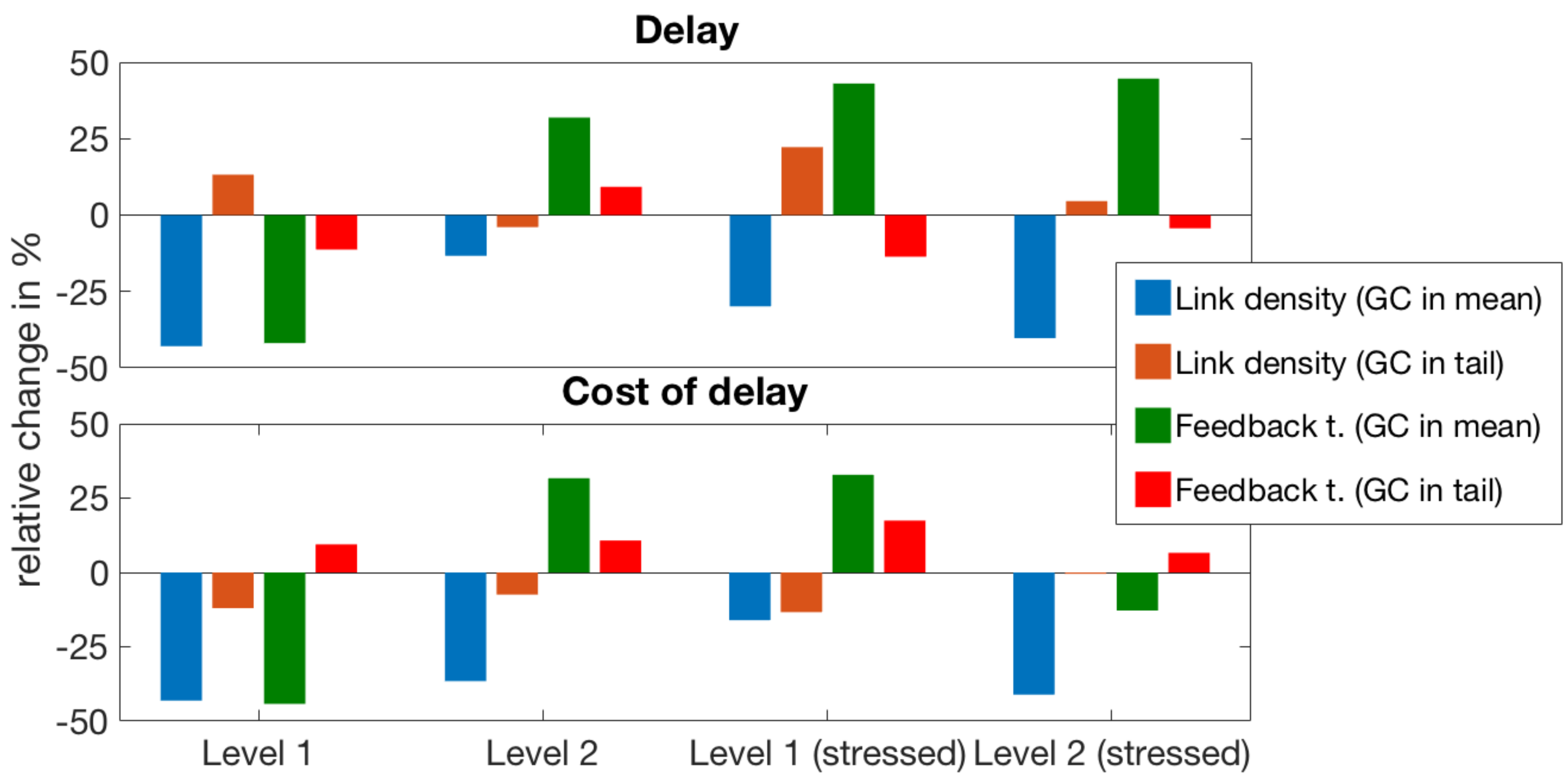
Results on passenger indicators

- Passengers are usually worse off with the mechanisms
- Non-connecting passengers are particularly impacted, since they are very unlikely to beneficiate from any mechanisms.
- Itineraries are less disrupted, and trip centrality increases, showing that connections are conserved.



Results on causality

- Causality in mean decreases: flight act as smart buffer between airport to avoid delay propagation.
- Causality in tail increases or stay constant: large events are more easily propagated among airports



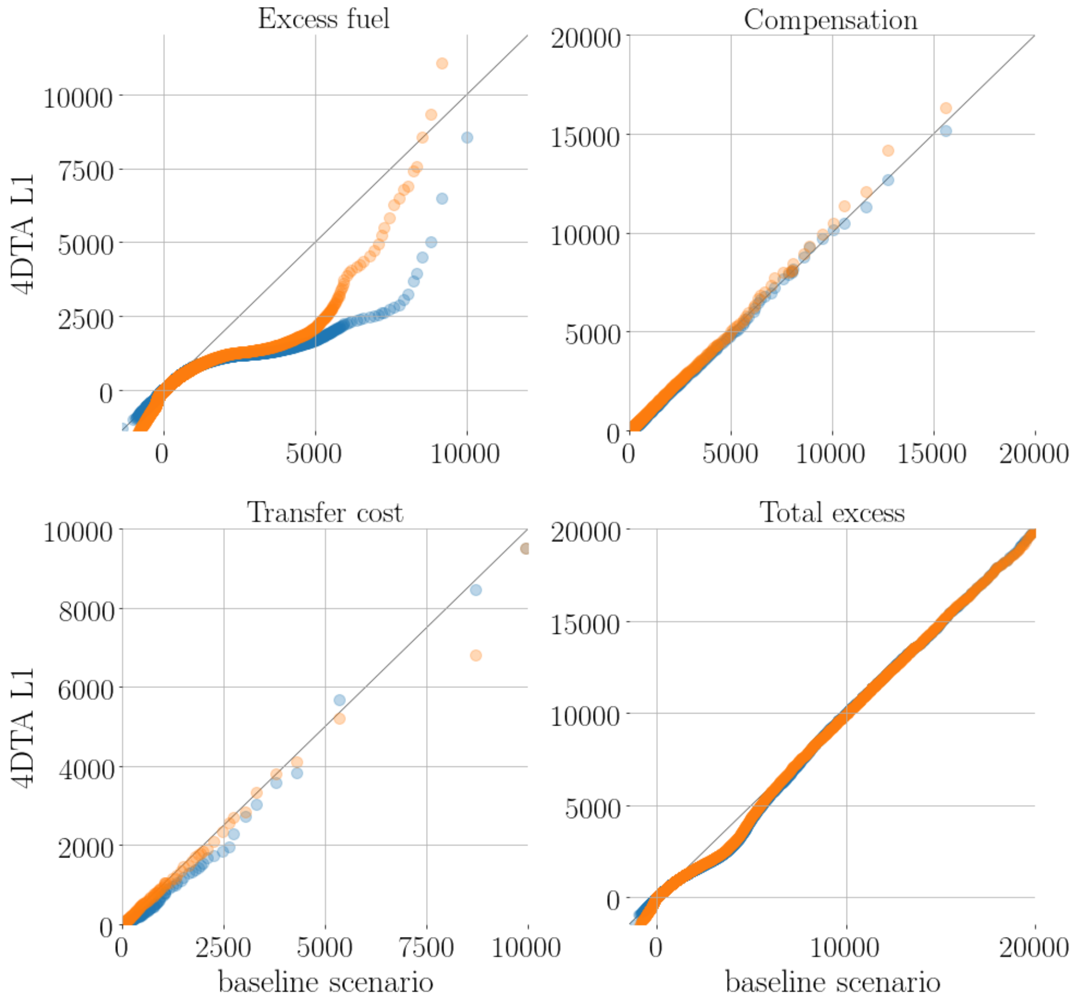
Conclusions

- Domino built an ABM able to model very finely the air transportation system, on a European scale and down to the individual passenger.
- Domino tested different implementation of DCI and WfP rules to test how they would impact systemically the system.
- Domino defined and tested new metrics able to catch network effects: trip & passenger centrality, causality.
- A clear trade-off between most passenger and airlines metrics is visible with 4DTA
- 4DTA gives some slack to the system and decrease airports interdependency. On the other hand, big events may propagate more easily.

Spare

Results on airline indicators

- Averages are not enough to capture all the complexity of the results.
- Mechanisms impact differently different flights.



Agent rules

- Agents are composed of different roles, with:
  - Limited information on their environment,
  - Their own objectives,
  - Their own channel of communication with other roles (of other agents).
- Airlines have detailed cost functions:
  - Cost of crew, maintenance, fuel…
  - Explicit passenger connection knowledge, with associated missing costs, including compensation, duty of care, soft cost etc.
  - Curfew costs