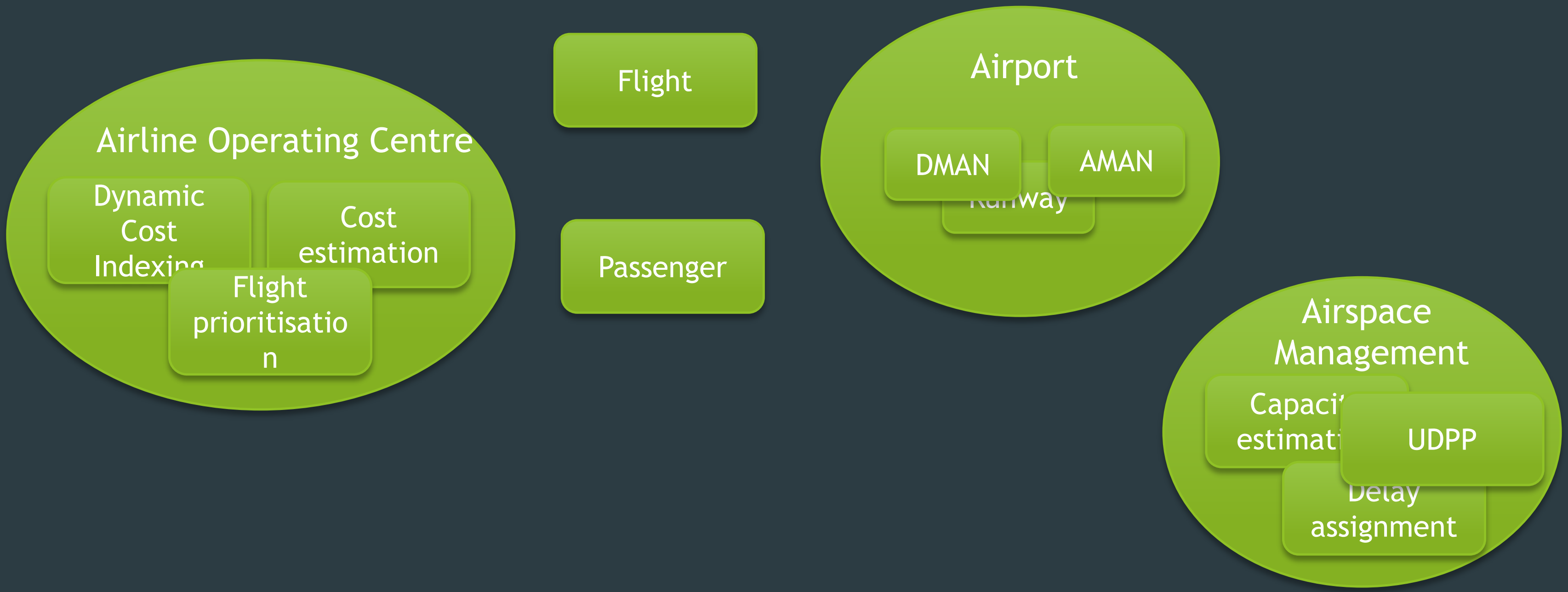
Network-wide and future indicators

Gérald Gurtner

g.gurtner@westminster.ac.uk

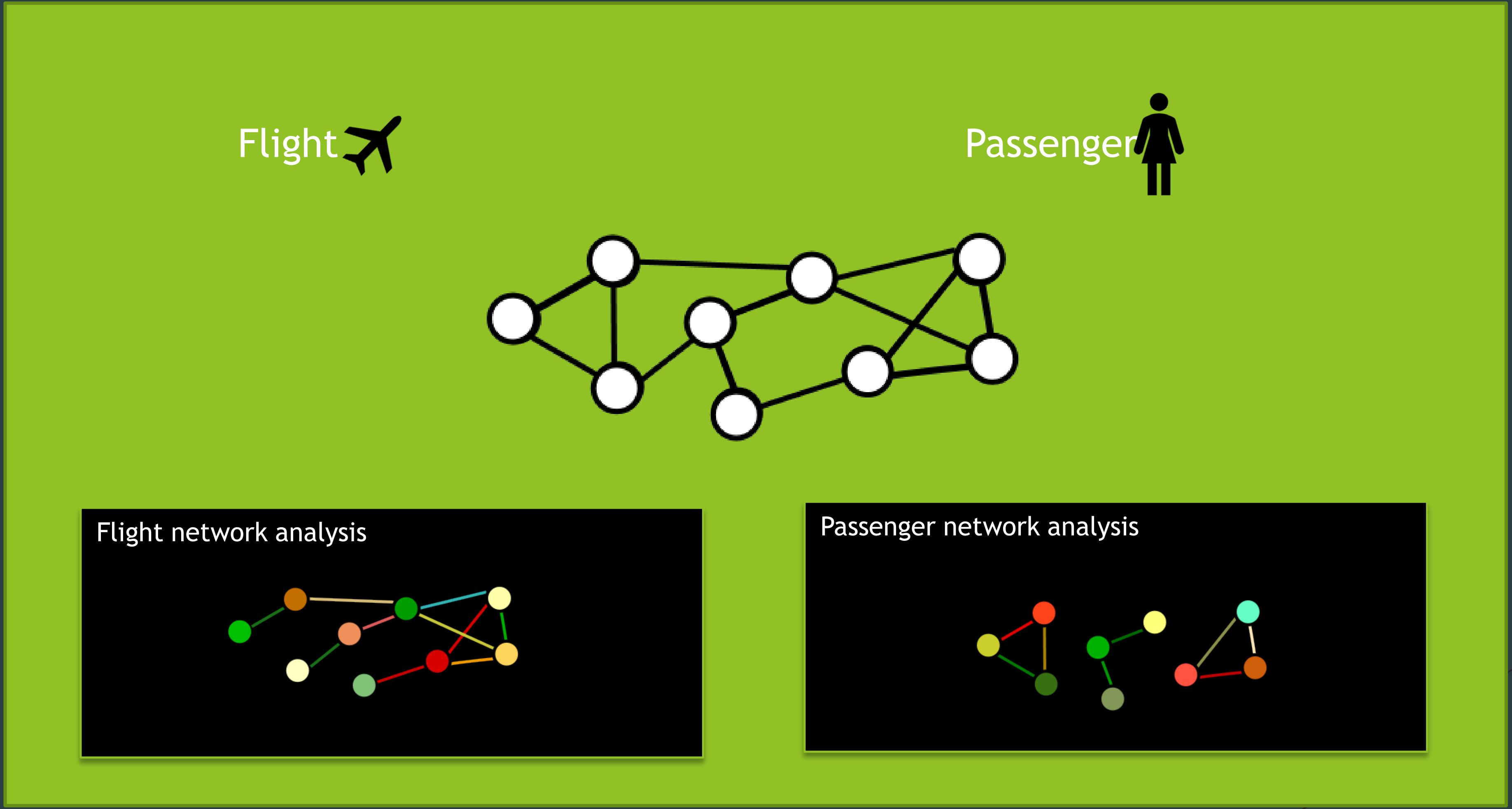
University of Westminster

The entwinement of the air transportation system



The entwinement of the air transportation system

Stakeholder perspective



How to capture network effects

Assessing the network impact of a potential change in the system involves two ingredients:

- A model able to capture network effects:
  - In Domino, we used Mercury, an agent-based model able to simulate passengers and flights tactically Europe-wide.
- Network metrics:
  - Either standard metrics that are assessed network-wide (e.g. pax delay)
  - And/or dedicated metrics, intrinsic to the network itself.

Standard metrics

- Delay:
  - departure, arrival, and gate-to-gate delay
  - delays weighted with the number of passengers per flight
  - percentage of flights with delays larger than a given threshold
  - total delays
  - missed connections
  - departing (arrival) queue delay at airports
  - …
- Cost:
  - excess costs of fuel
  - passenger costs: compensation, duty of care, cost of rebooking, soft costs
  - non-passenger costs: crew and maintenance
  - total excess cost (actual flight plan compared to scheduled one)
  - …

Tail & network

- Standard ATM metrics address `means', but distributions might be important
- Standard ATM metrics ignore the network aspects

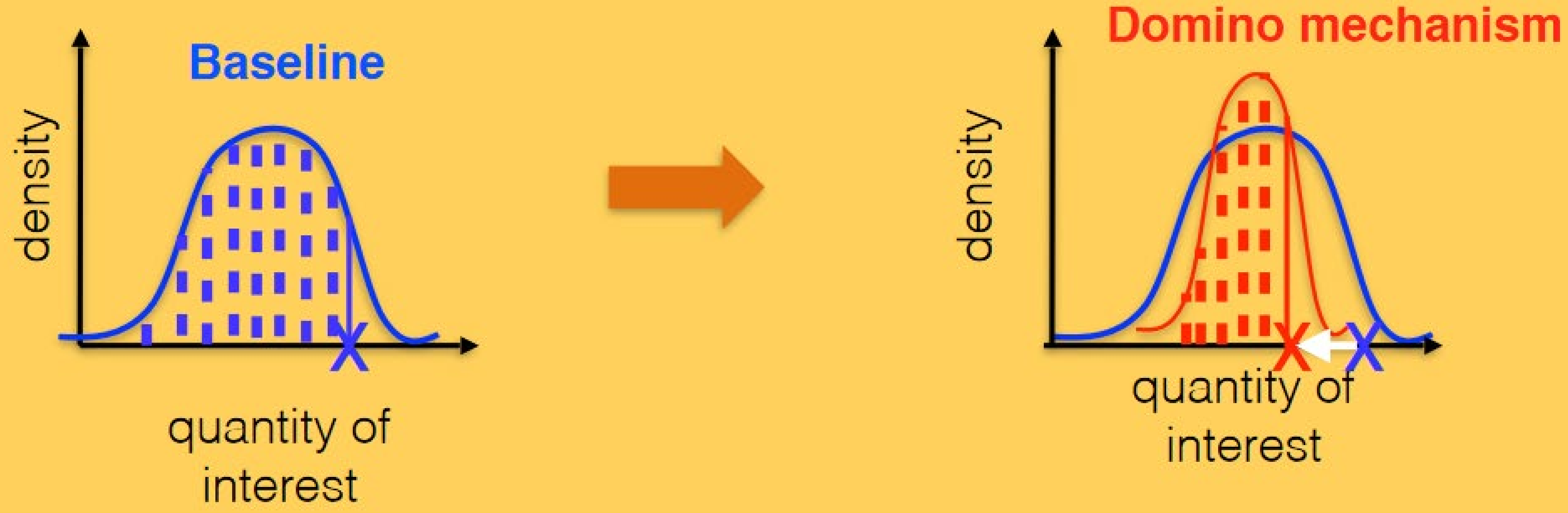
Our approach in Domino

More focus on the extreme (tail) events for standard ATM metrics

New metrics scaled up to the network level

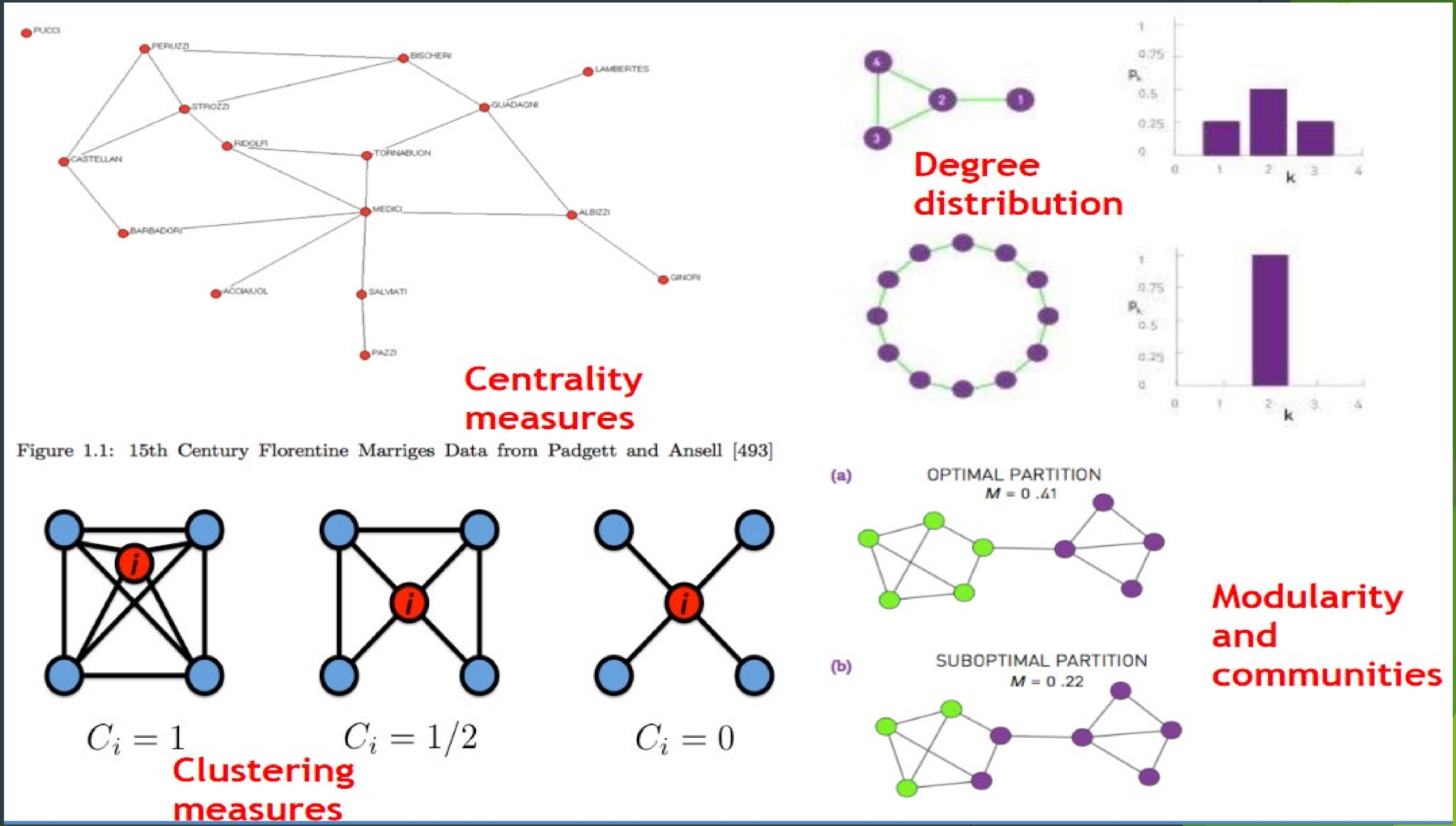
Metrics "in tail"

For instance, when moving from the baseline to a scenario with a modification in the system, a decrease of the 90th percentile for the delay distribution means less occurrence of extreme delays. This may or may not affect the average.

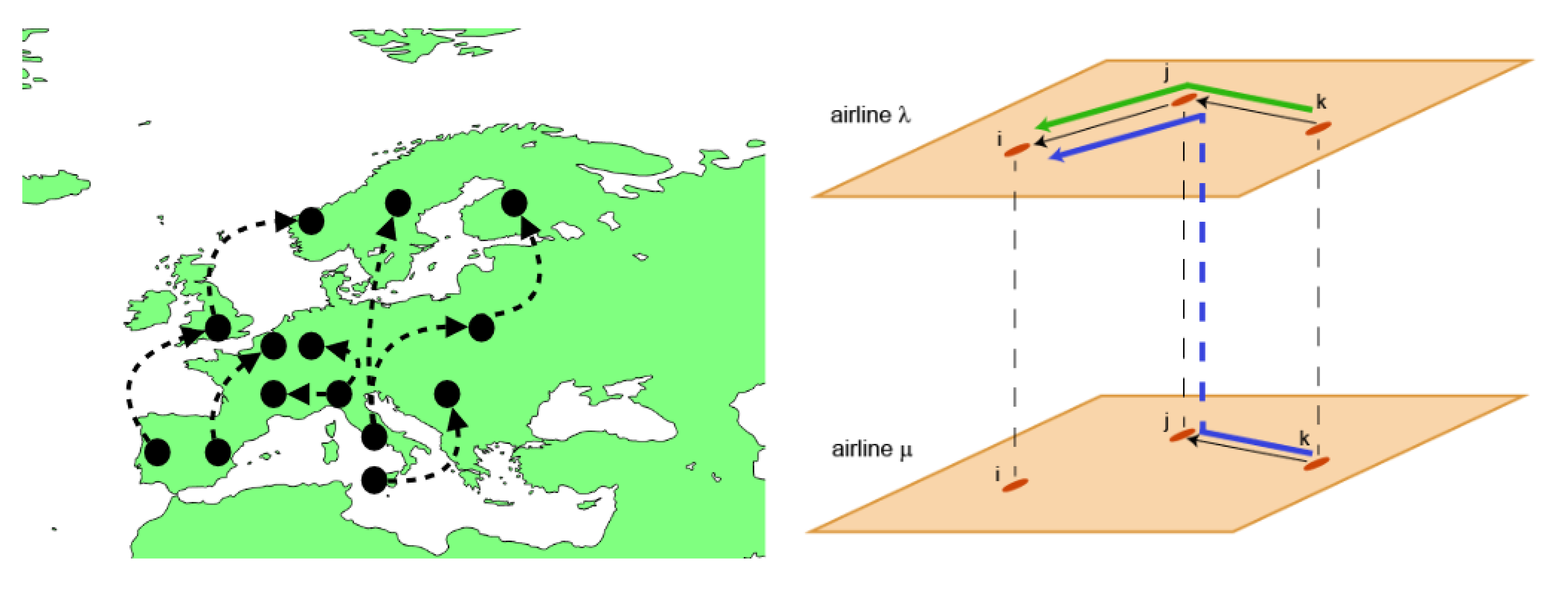


Important because people or even companies may be more sensitive to large events. Moreover, large disruptions may be proportionally more problematic for the system.

Network metrics

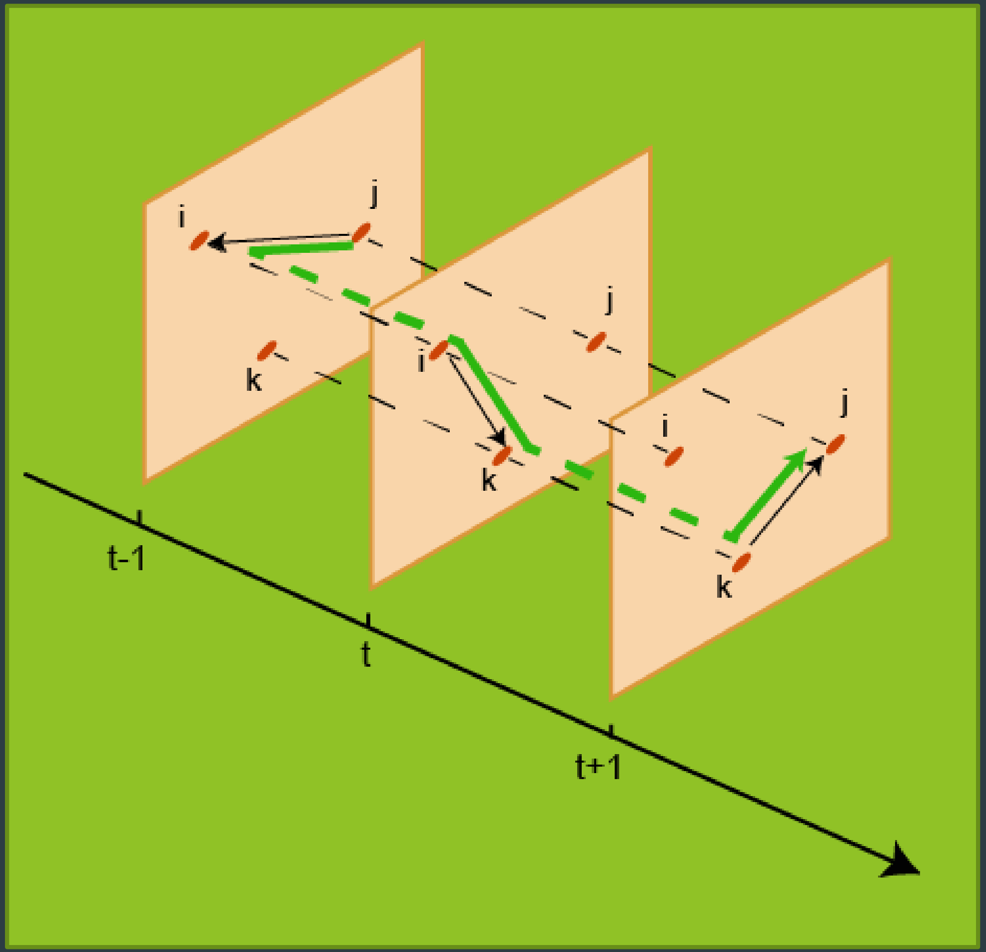


The air transportation system: a multi-layered network (multiplex)



- Layers can be companies, types of passengers etc ➔ each sublayer has an inner consistency and various interactions with other layers (network of networks).

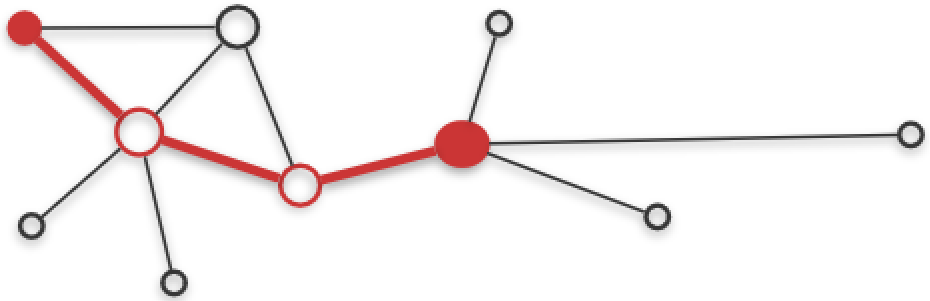
The air transportation system: a temporal network



- The network changes at each time step
- Walks are time-oriented

Importance of nodes: centrality metrics

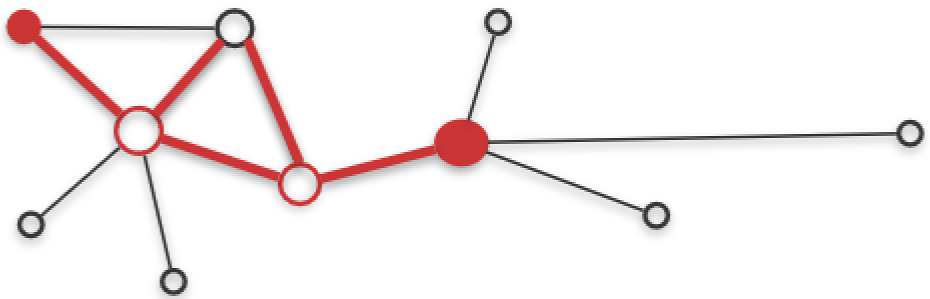
Based on shortest paths and distances



Betweenness centrality

$$b_i = \sum_{j,k \neq i} \frac{\#\ shortest\ paths\ between\ j\ and\ k\ passing\ from\ i}{\#\ shortest\ paths\ between\ j\ and\ k}$$

Based on walks



Katz centrality

PageRank

$kc_i = \alpha \times (\#\text{walks of length 1}) + \alpha^2 \times (\#\text{walks of length 2}) + \ldots$ $\alpha \leq 1$

(longer walks contribute less)

A new centrality metrics

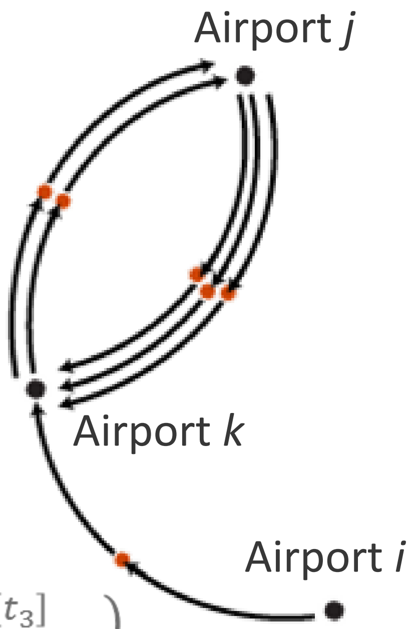
We need to define new centrality metrics for temporal multiplexes, where walks represent itineraries that can actually be traveled

Standard Katz Centrality $kc_i^{out} = \sum_{n=1}^{\infty} \sum_j \alpha^n A_{ij}^n$

A_{ij} adjacency matrix of the network
A_{ij}=1 if there is a link from *i* to *j*

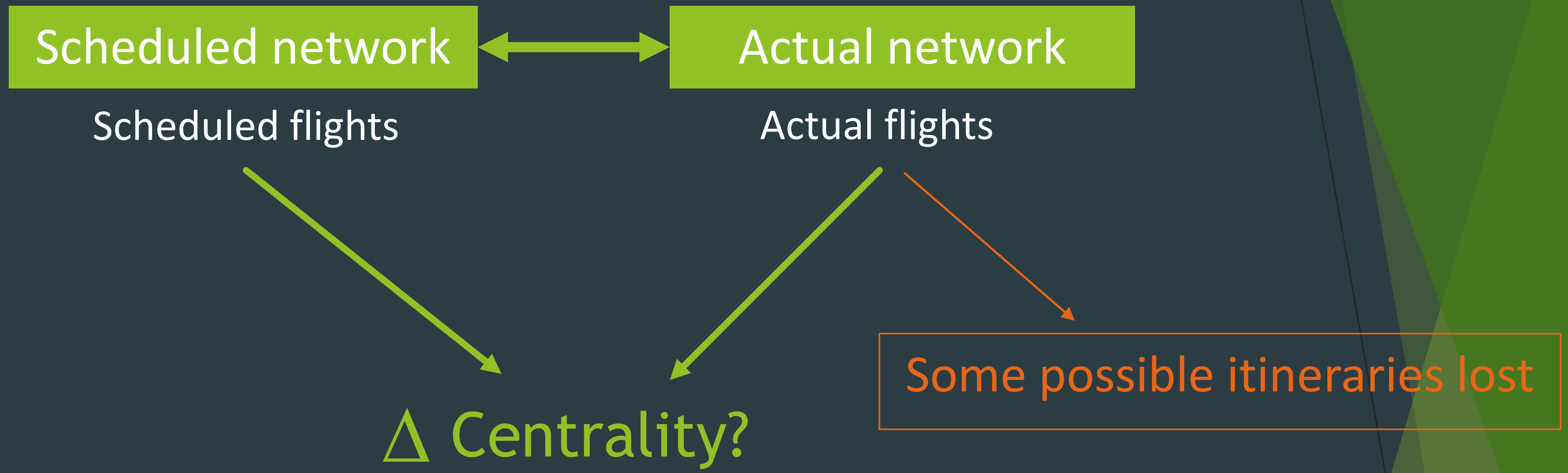
Trip Centrality tc_i^{out}

- Adjacency matrix $A^{[t]}$ depends on time
- Introduction of secondary nodes ensures that walks respect schedules
- A copy of each airport per layer, each inter-layer jump has a cost ε (the walk weights less)



To obtain tc_i^{out} I sum contributions of the form $\left(\alpha A^{[t_1]} K \alpha A^{[t_2]} K \alpha A^{[t_3]} \dots\right)_{ij}$
where $K = K(\varepsilon)$ and $t_1 < t_2 < t_3 \dots$

Centrality loss



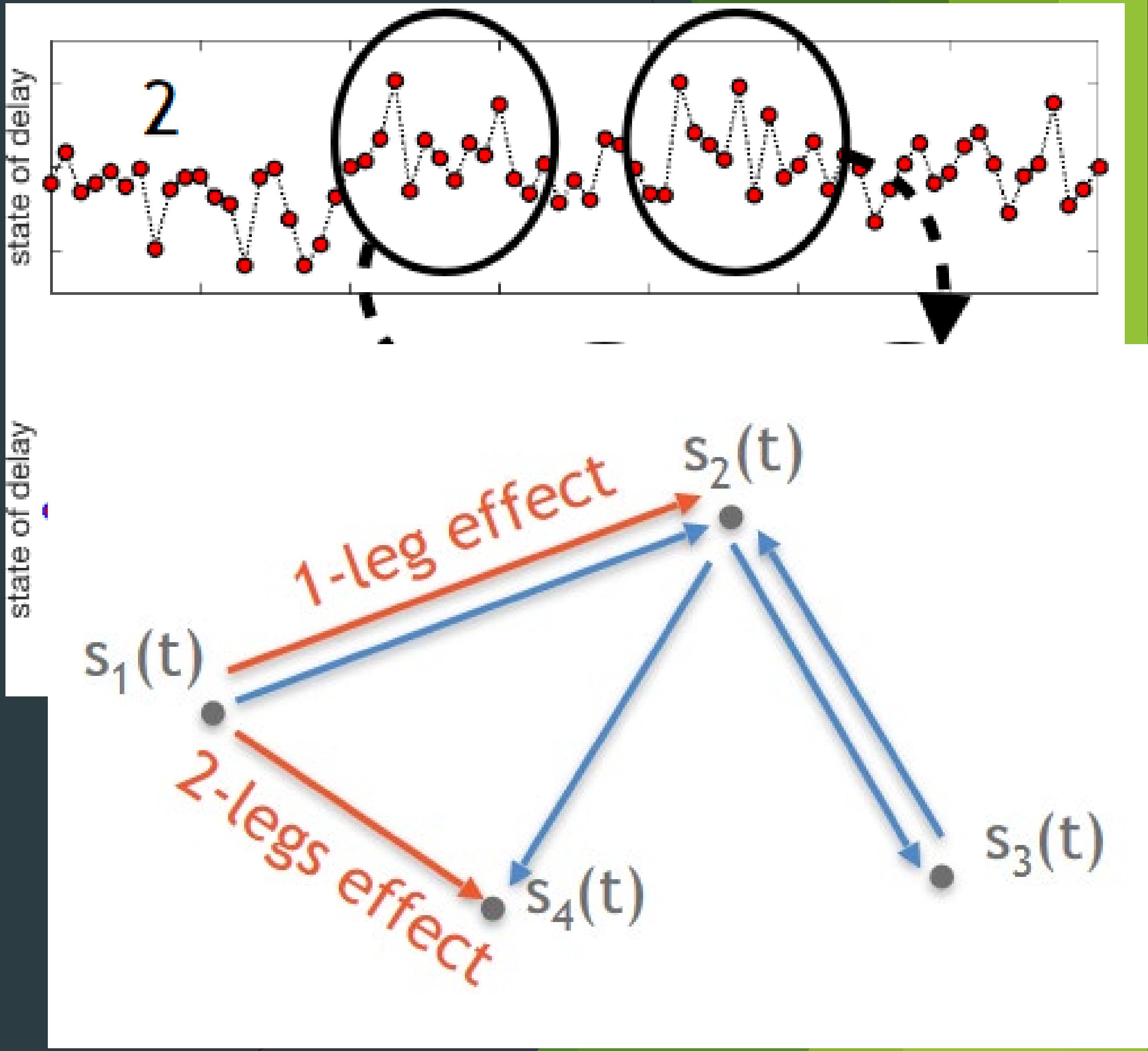
Difference in centrality measures the loss of connectivity due to delays!

→ Innovations (solutions etc) make the systems more robust if they preserve the centrality under stressed conditions

In particular, what about local solutions?

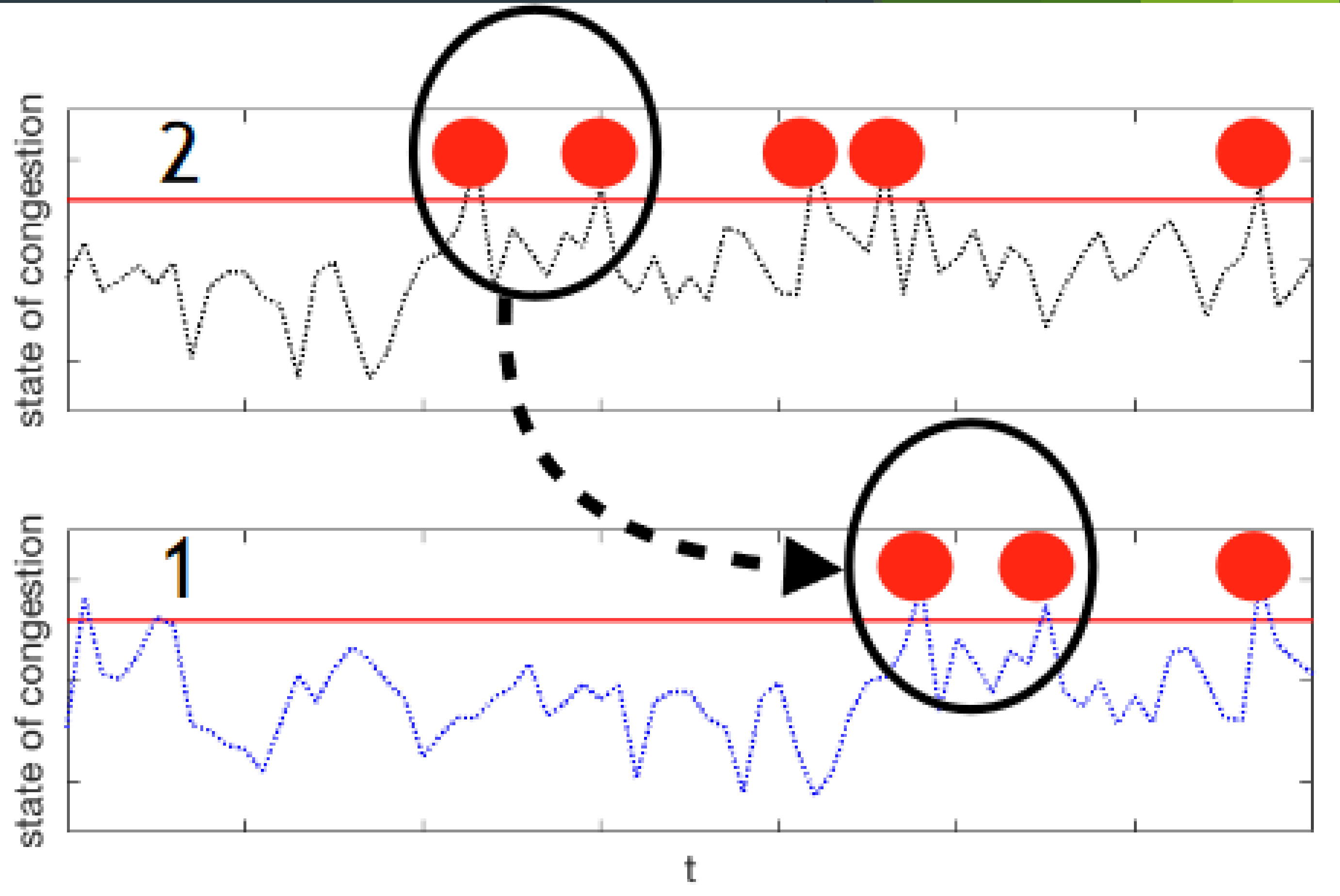
Network 'tightness': causality metrics

- Granger causality is a metrics designed to measure the impact of a node on another node. (note: this is causality).
- It is based on time series localised at nodes: for instance, delays along the day at two given airports.
- Can we predict time series number 1 better if we know time series number 2? If so, 2 "causes" 1, i.e. 2 has an effect on the state of 1.
- Nodes can influence each other even if they are not connected on the network.
- High causality → nodes do not operate independently, network is "tight".



Mixing “in tail” metrics and causality

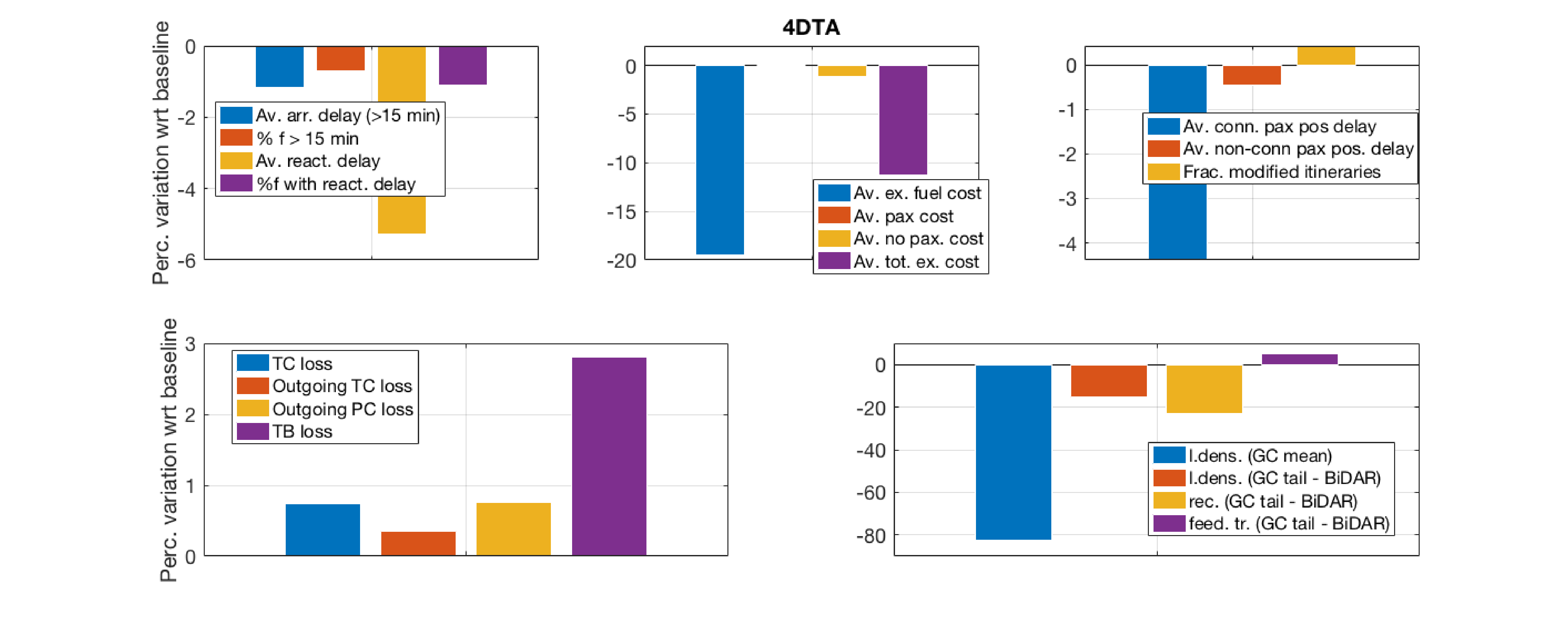
- Define extreme events at a node and see if they correlate with extreme events at another node



A use case from the Domino project

- Domino was a SESAR ER2 project in which these new approaches were tested
- Research question: how does letting airlines modify their speed dynamically and wait for passengers (4DTA) impact the system?
  - Standard KPIs?
  - Centrality loss?
  - Network tightness?
- Used the Mercury simulator to compute the KPIs (individual flights and pax simulated)
- Scenario: entire Europe for one day, with and without 4DTA.

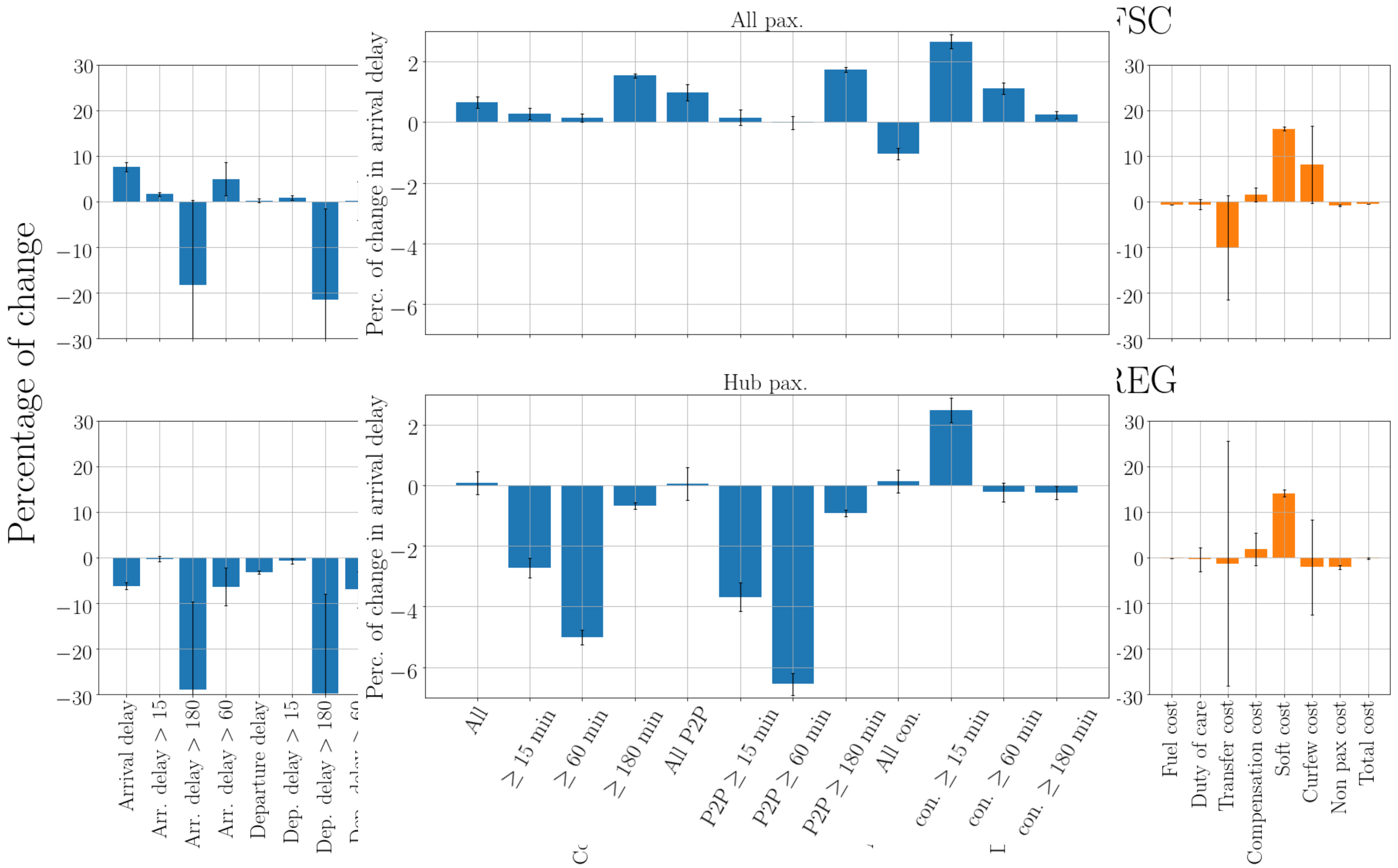
Results – major disruptions everywhere



- Loss of connectivity but network is slacker and delays/costs are decreased.

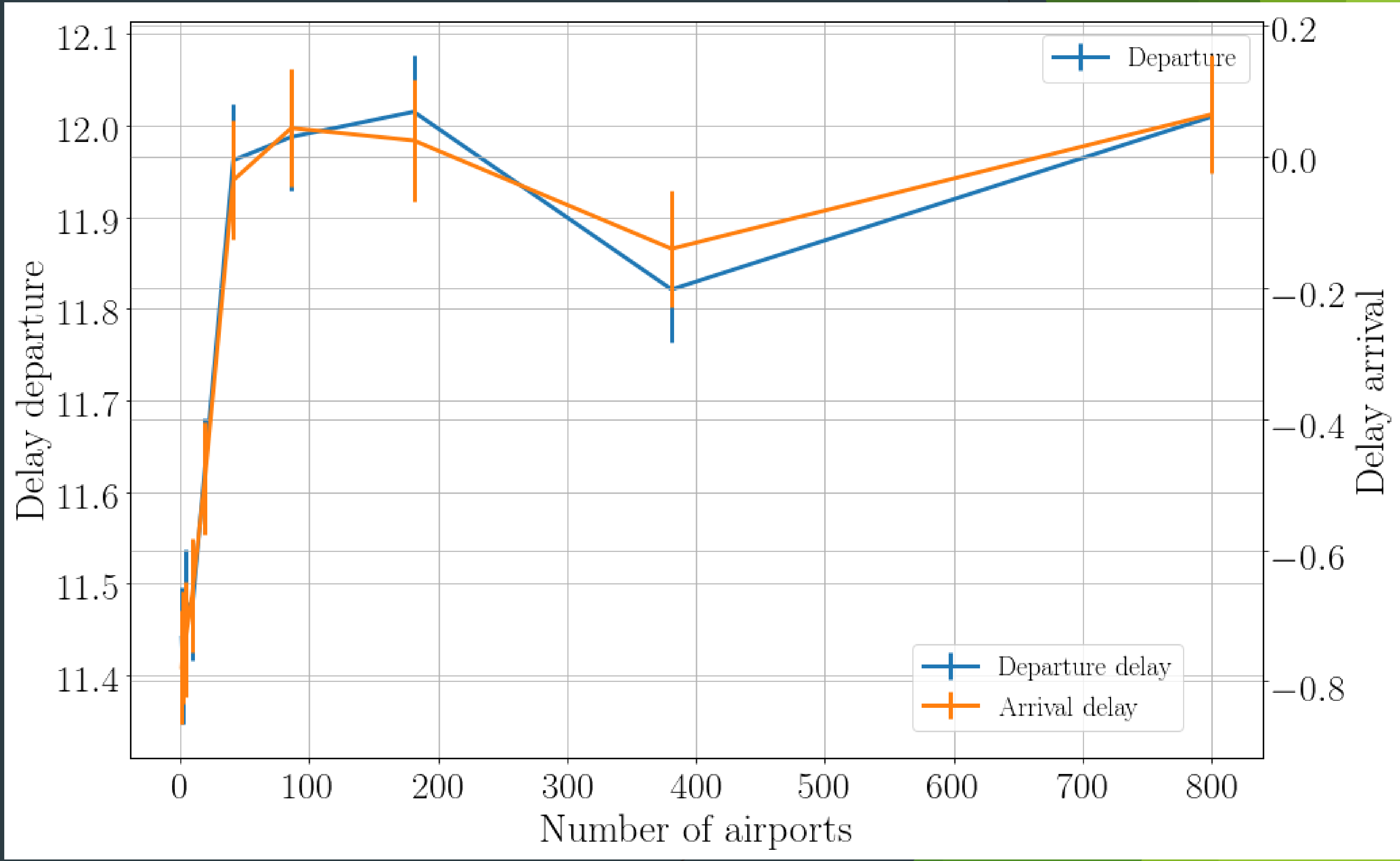
Results – disruptions at a few hubs

- Different stakeholders are impacted differently.



Results – emergence

- Network effects and emergence: interactions are important!



What about the future?

- Centrality and causality are intrinsic to the network, they contain information that is not available by other means (e.g. distribution of delay).
- But: their variations are not very informative: what about a reduction of 8% in causality? What does it say on the operations?
- More than targets, they may be more adapted as “alert” indicators, and used to pinpoint issues in the network (predictors).
- Centrality and causality metrics are very general, they could be used with many different subsystems, for instance crew + aircraft + gate etc.
- They may also help defining also indicators which are still fuzzy, like resilience or flexibility.
- Metrics “in tail” are crucial to assess the network. They condition most certainly the operations by having a disproportionate effect on the system and on stakeholders.

(Possible) interesting questions

- Should we embed the aversion of humans to extreme events within the performance framework?
- How to do simulation-based network-wide assessments for new solutions?
- In the era of predictive analytics, do we need indicators at all?

Thanks

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