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

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Domino project
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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
Main events

1. FP Submission
2. Generate non-ATFM delay
3. Pushback Ready
4. Wait for pax
5. Pushback
6. Take-off
7. Flight Crossing Point
8. Landed
9. Flight Arrival
Airline cost function

- First group: passengers missing connections
- Second group: passengers missing connections
- Curfew missed

Graphs showing the cost of delay in euros as a function of delay in minutes.
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):

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

\[ \alpha \leq 1 \]

(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:

\[
\begin{align*}
x_t &= \phi_0^1 + \sum_{j=1}^{p} \phi_j^{11} x_{t-j} + \sum_{i=1}^{p} \phi_i^{12} y_{t-i} + \epsilon_t^1 \\
y_t &= \phi_0^2 + \sum_{j=1}^{p} \phi_j^{21} x_{t-j} + \sum_{i=1}^{p} \phi_i^{22} y_{t-i} + \epsilon_t^2
\end{align*}
\]

- 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