Network modelling – performance, metrics, challenges

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Network modelling

– performance, metrics, challenges

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Overview

- Types & characterisation of networks
- Air transport performance & sampling
- POEM project (SESAR)
- Challenges ahead

Complexity Science in Air Traffic Management

Edited by Andrew Cook and Damián Rivas

Massimiliano Zanin

Seddik Belkoura

Europe in one slide

- European Commission
  - executive body of the European Union – manages its legislation, business activities and research funding; 28 member states
- EUROCONTROL
  - 41 member states; central flow management (Network Manager), central route charges, MUAC; regulation; research & coordination
- ‘Single European Sky’ initiative
  - launched in 2000 by Commission in response to increasing delays
- SESAR: Single European Sky ATM research (programme)
  - technological pillar of Single European Sky initiative; PPP
  - coordinates all EU research and development in ATM
- SESAR Joint Undertaking (SJU)
  - set up in 2007 to manage SESAR; now full representation

PRR 2010

Performance Review Report

An Assessment of Air Traffic Management in Europe
during the Calendar Year 2010

Performance Review Commission | May 2011

EUROCONTROL

Types & characterisation of networks

Types & characterisation of networks

Network	Node	Link	Flow	Disruption	Flow cost
generic	**collection**	**transport**	**assets**	**loss of capacity**	**E / $**

Biology/ecology					
mammalian brain	distinct grey-matter regions	white-matter fibre bundles	electrical impulses; neurotransmitters	breakage (e.g. disease)	**E**
animal ecology	habitat patch	landscape segment	species dispersal	road segment	**E**
fungal ecology	branch point, fusion, tip	cord (e.g. packed with hyphae)	aqueous nutrients; exploratory data	breakage (e.g. grazing)	**E**

Types & characterisation of networks

Network	Node	Link	Flow	Disruption	Flow cost
generic	**collection**	**transport**	**assets**	**loss of capacity**	**E / $**

Services/utilities					
water	plant, reservoir	pipe	water	pipe breakage	**E**
electricity	(sub)station	cable	electrons	cable breakage	**E**
telecoms	hub, router	wire / fibre	data packets: electrons/photons	cable breakage	**E**

Types & characterisation of networks

Network	Node	Link	Flow	Disruption	Flow cost
generic	**collection**	**transport**	**assets**	**loss of capacity**	**E / $**

Transportation					
goods	warehouse	road segment	goods	traffic congestion	**$**
urban (road)	junction	road segment	vehicles	bridge collapse	**$**
rail	station	track segment	trains (passengers)	signal failure (reactionary delay)	**$**
air – flight-centric	airport	flight	aircraft	reactionary delay	**$**
air – **pax-centric**	airport	flight(s)	passengers	missed connection	**$**

- Drivers of the focus of public transport flow disruption
  - business model / ownership of the operator
  - regulation

Types & characterisation of networks

- Real-world networks
  - often co-functional, sometimes (co-)disruptive
- Capacities
  - pipe diameters, cable bandwidths, (aircraft) seating configurations
- Telecommunications terminologies
  - (packet) scheduling, service denials, backbones, routing protocols, traffic delivery rates, traffic forecasts, diversions, hub-and-spoke
- Hub-and-spoke networks highly efficient *but* particularly susceptible to system failure or targeted attack
- Rerouting during disruption
  - common theme across many types of network
  - data (etc.) relatively insensitive to routing: unlike passengers
  - "resilience" many definitions … 'responsiveness during disruption'

Types & characterisation of networks

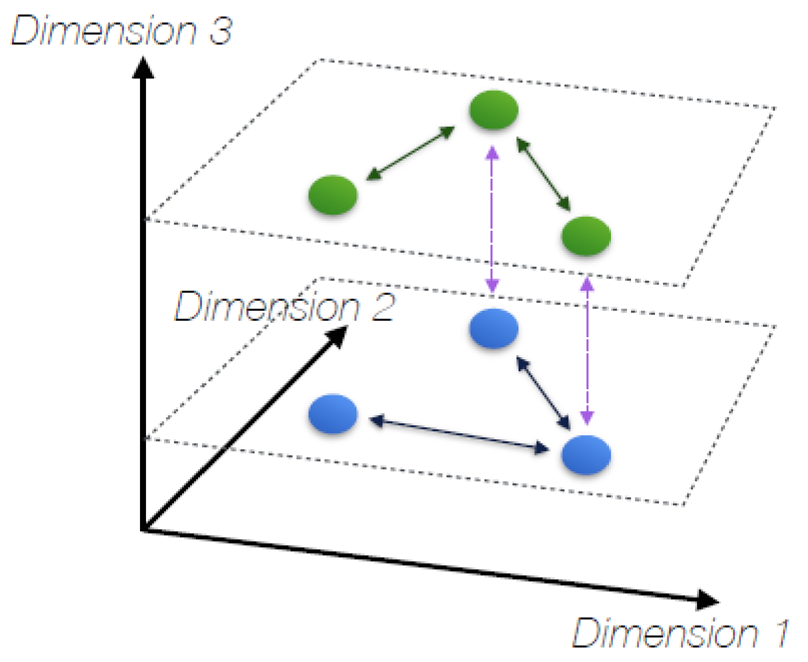
(Resilience – later session)

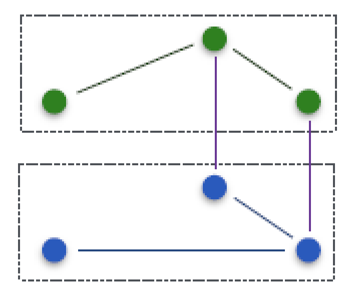
Terminology	Introduction	Field	State(s)	Key feature
engineering resilience	Hoffman (1948)	material testing	one stable state	inherent ability of the system to return to its original state
ecological resilience	Holling (1973)	ecology	multiple states	ability of the system to absorb disturbance
resilience engineering	Hollnagel (2006)	air transport	multiple states	safety-based design of socio-technical systems

Capacity	Key feature	Key association(s)	ATM focus
absorptive	network can withstand disruption	robustness; little or no change may be apparent	strategic
adaptive	flows through the network can be reaccommodated	change is apparent; often incorporates learning	strategic &/ tactical
restorative	recovery enabled within time and cost constraints	may focus on dynamics/targets; amenable to analytics	tactical

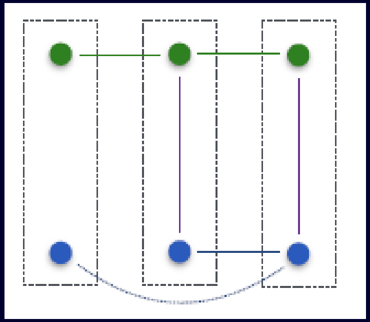
Source: Cook et al., Journal of Air Transport Management, 2016 (in press)

Types & characterisation of networks

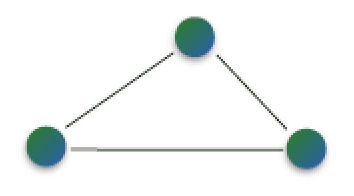




projection 1-2



projection 2-3



single-layer projection

Source: Belkoura, Cook, Peña and Zanin, 2016 (submitted paper)

Types & characterisation of networks

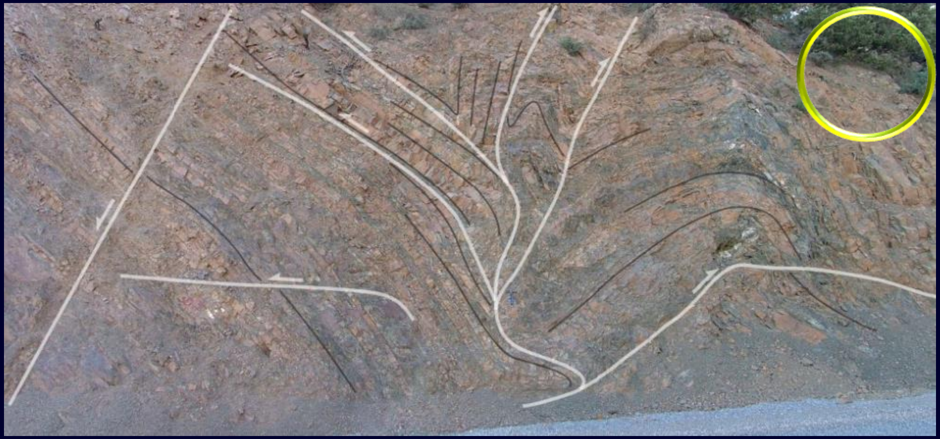
- Complex systems are usually multi-dimensional
  - how representative are various multi-layer projections?
    … c.f. a single-layer projection?
- Various layers may be considered
  - airlines
  - airports
    more typical
    (often data constrained)
  - aircraft types
  - time windows
  - crew
  - passengers
  - (reactionary) delay
- How safe is it to discard some dimensions?
  - estimating the associated information loss is challenging
  - equivalent to sampling according to hidden variables

Types & characterisation of networks

Types & characterisation of networks

Three scales commonly used for complex systems

	Geology	**Neuroscience**	**Air transport**
Macroscale	drainage basin	brain	air transport network
Mesoscale	positive flower structure – folds in fault plane	community of neurons, cooperatively processing a single stimulus	community of flights of a single airline
Microscale	crystal	single neurone	single flight



Mesoscale

- more elusive (more words)
- mesoscopic (condensed matter) physics (nm)
- subscales in meteorology (km)
- usefully captures 'in between'

Types & characterisation of networks

A selection of useful complexity metrics

clustering coefficient	CC	meso	node triplet	counts the number of triangles in the network (fraction of pairs of a node’s neighbours that are directly connected)
geodesic distance (mean)	G_m	macro	network	average number of steps needed to move between two nodes (generic distances topologically often called network ‘diameter’)
(global) efficiency	E	macro	network	ease of information flow between pairs of nodes (mean inverse of shortest paths)
eigenvector centrality	E_c	micro	node	centrality metric: proportional to the centralities of nodes to which it is connected (influence assigned to each node under a steady state)
entropy of degree distrib^N	E_{dd}	macro	network	heterogeneity of the network; minimum (zero) => all nodes have same degree (k)
link density	L_d	micro	network	$\frac{\text{number of links in the network}}{\text{max no. of links that could be present}}$

Types & characterisation of networks

- Many social/biological networks have different properties from purely random or regular graphs; simplifying somewhat:

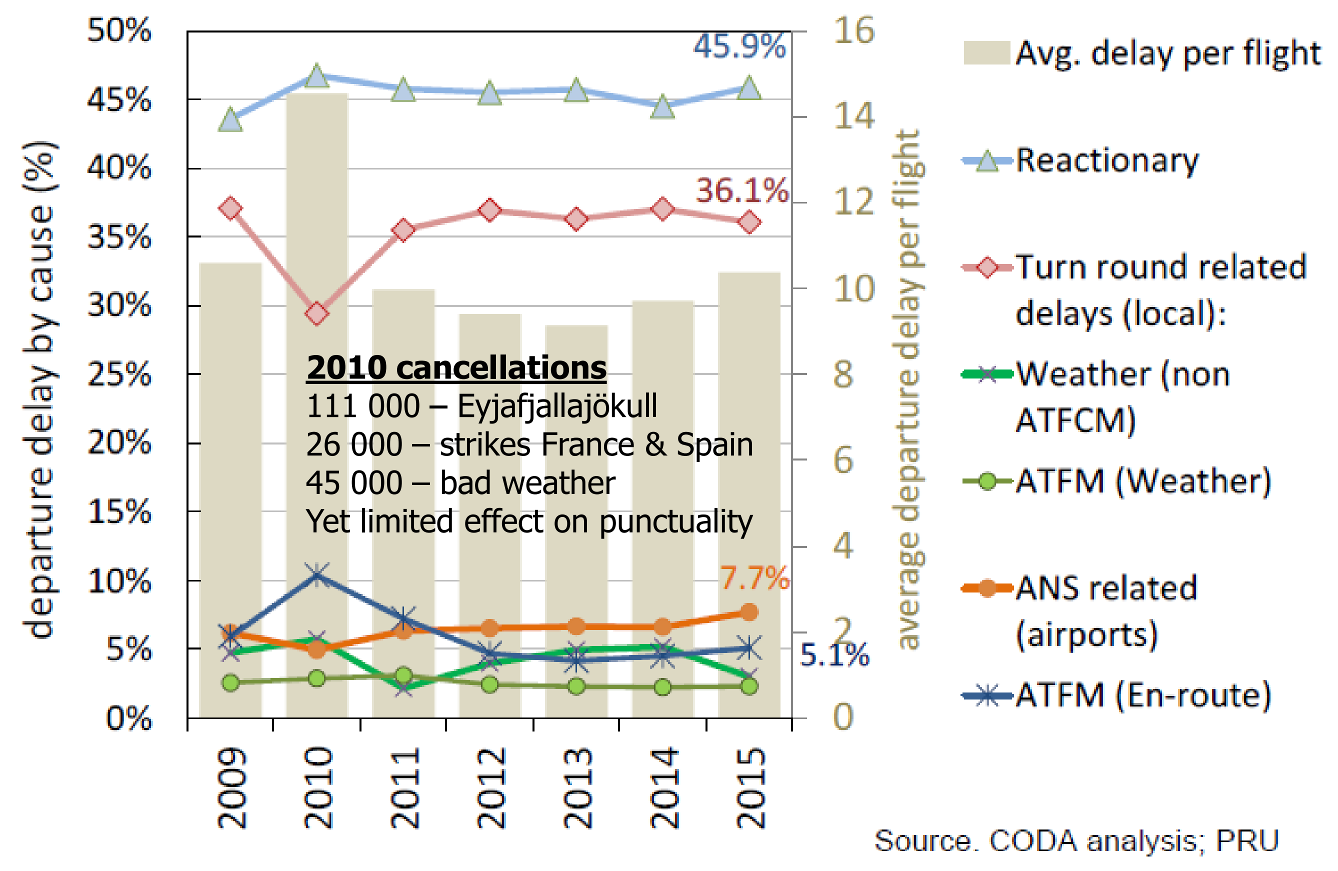
	Purely random	**Regular graph**	**Social /biological**
clustering coefficient	low	high	high
mean distance	low	(high)	(very) low
typical degree (k)	yes	yes	(no)

‘small-world’ networks

- Small-world networks made by ‘shortcuts’ (linkages or hubs)
- Scale-free networks ~ ‘ultra-small worlds’
  - created by presence of hubs (high degree nodes); $P(k) = ak^{-\gamma}$
  - no typical node, degree, or scale: hence ‘scale-free’ (c.f. some small-world networks may have fairly homogenous nodes)

Air transport performance & sampling

Air transport performance & sampling



2010 cancellations
111 000 – Eyjafjallajökull
26 000 – strikes France & Spain
45 000 – bad weather
Yet limited effect on punctuality

Source. CODA analysis; PRU

Sources: PRR 2010, 2015 (draft)

Air transport performance & sampling

metric	2000	2015
IFR flights	8.4M	9.8M
% flights arr. > 15 mins late	27%	18%
turnaround delay	? 33%	36%
reactionary delay	39%	46%
ATFM/ANS delay	23%	13%

Sources: PRR 2000, 2015 (draft)

NB1. SESAR target for 2020: > 95% of flights arrival delay ≤ 3 mins
(*Performance Target* and *Target Concept*) other 5%: average delay < 10 mins

NB2. Traffic in 2008: 10.1M (peak, start of slowdown and fall)

Air transport performance & sampling

- Literature demonstrates many sampling constraints
  - purposive, e.g. most connected airports / region of airspace
  - limited to data from a given airline (or alliance)
  - data quality/availability for smaller airports / smaller airlines/LCCs
  - data purchase cost
  - computational cost (including data cleaning; 14%)
- Clustering coefficient 0.07 – 0.42 for Italian airspace
- Sampling poorly addressed in AT c.f. several other fields
- We examined 10 reconstructed networks, all with long-tails (and some scale free): how should we selectively sample?
  1. static, sequential sampling of airports
  2. dynamical, sequential sampling of airports
  3. optimised sampling of airports
     (aircraft types, time windows, airline combinations)

Region	Dataset	Airports	Airlines	A/C types	Temporal[f]
Australia	OpenFlights[a]	112	12	No	No
Brazil	OpenFlights	119	12	No	No
Canada	OpenFlights	204	24	No	No
China	OpenFlights	185[d]	17	No	No
Europe	ALL-FT+[b]	**1854**	**100**	Yes	Yes
Europe	OpenFlights	**497**	**153**	No	No
India	OpenFlights	71	8	No	No
Russia	OpenFlights	104	36	No	No
USA	RITA[c]	**286[e]**	**16**	Yes	Yes
USA	OpenFlights	**595**	**81**	No	No

[a] Open source repository, flights and airport data, worldwide coverage; http://openflights.org

[b] Supplied by EUROCONTROL, all IFR flights in European airspace; planned and executed; detailed data

[c] On-Time Performance dataset, Research and Innovative Technology Administration, US DoT; executed flights, detailed data (reported by 16 US carriers accounting for at least 1% of domestic revenue.)

[d] Total reported as 442

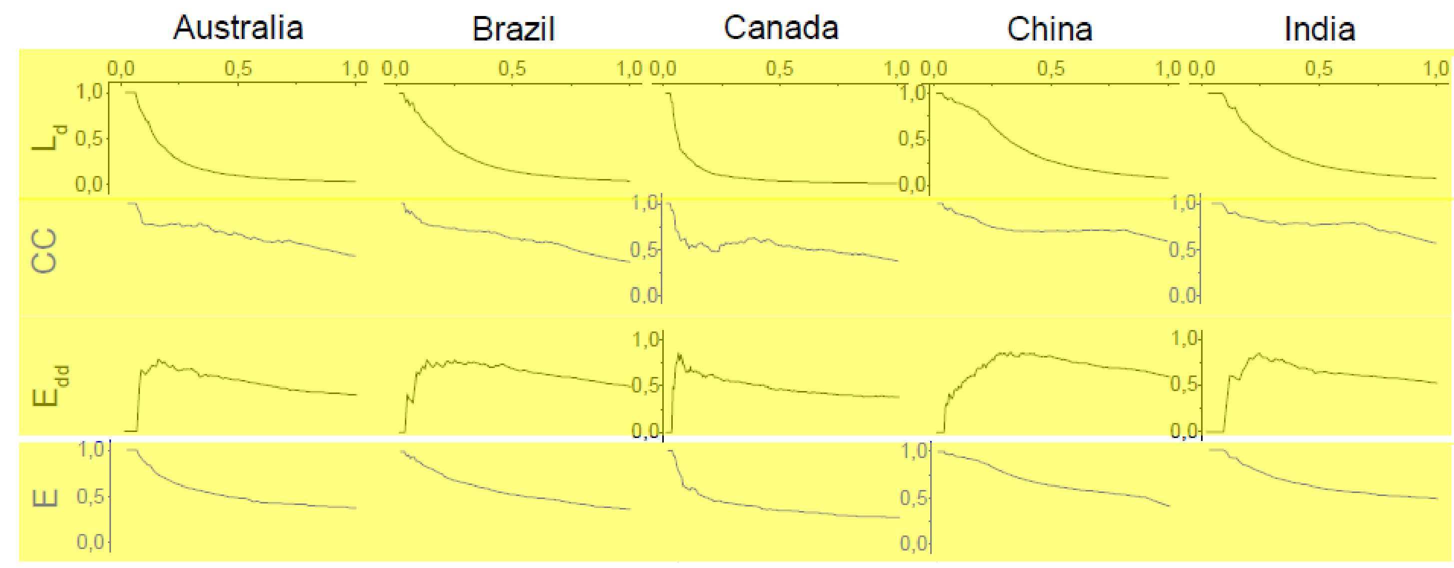
[e] Total reported as 5194

[f] Indicates availability of sampling by selected days. (*Total* period for (b) and (c): March through July 2011.)

Source: Belkoura, Cook, Peña and Zanin, 2016 (submitted paper)

Air transport performance & sampling

1. Static, sequential sampling of airports
   - airports sequentially added, by decreasing degree (connections)
   - simulates frequently observed sampling bias

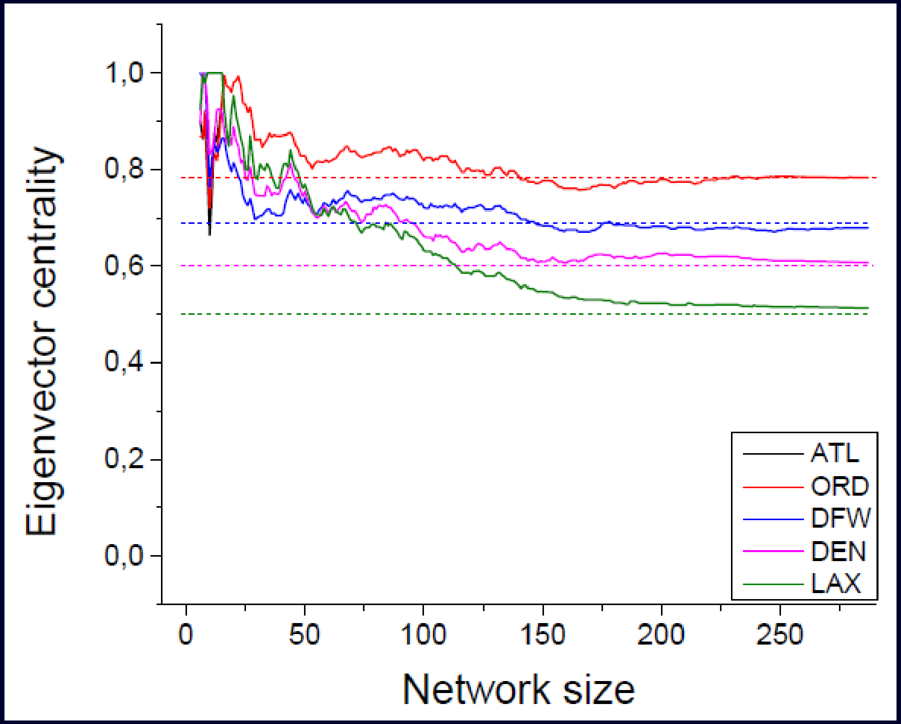


- high variation with fraction
- mostly monotonic
- don’t saturate
- non-monotonic
- don’t saturate

Source: Belkoura, Cook, Peña and Zanin, 2016 (submitted paper)

Air transport performance & sampling

2. Dynamical, sequential sampling of airports
   - delays generated at random at airports, propagated by flights
   - currently very simple (no reactionary effects or connectivities)

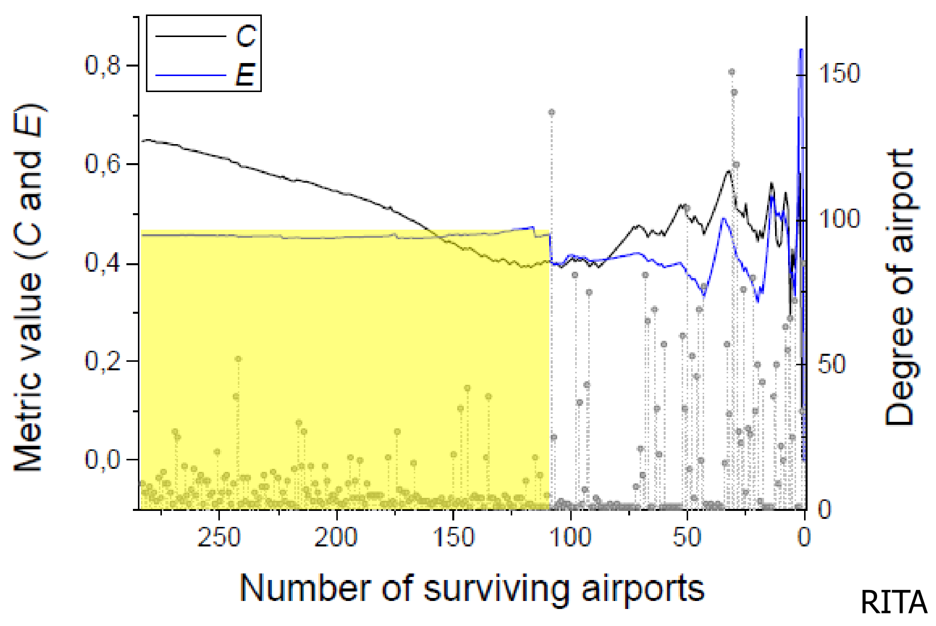


- study 5 most important US nodes (RITA)
- analyses weighted by flights
- adding largest first, left to right
- dynamically too, need >150

Source: Belkoura, Cook, Peña and Zanin, 2016 (submitted paper)

Air transport performance & sampling

3. Optimised sampling of airports
   - greedy optimisation algorithm; sequentially deletes nodes whose deletion introduces the least error for any given metric(s)
   - sampling by degree is poor; is by least error of E_{dd} any better?



- read from left to right
- grey circles: deleted airport degree (quite heterogeneous)
- E quite stable to 110;
- C comparable other optimisation
- minimising E_{dd} error quite good criterion for stratified sampling, appx. half the airports may suffice

Source: Belkoura, Cook, Peña and Zanin, 2016 (submitted paper)

POEM project (SESAR)

University of Westminster (London) & Innaxis (Madrid)

SESAR “Outstanding Project” Award, 2014

POEM project (SESAR)

Why are passengers so important?

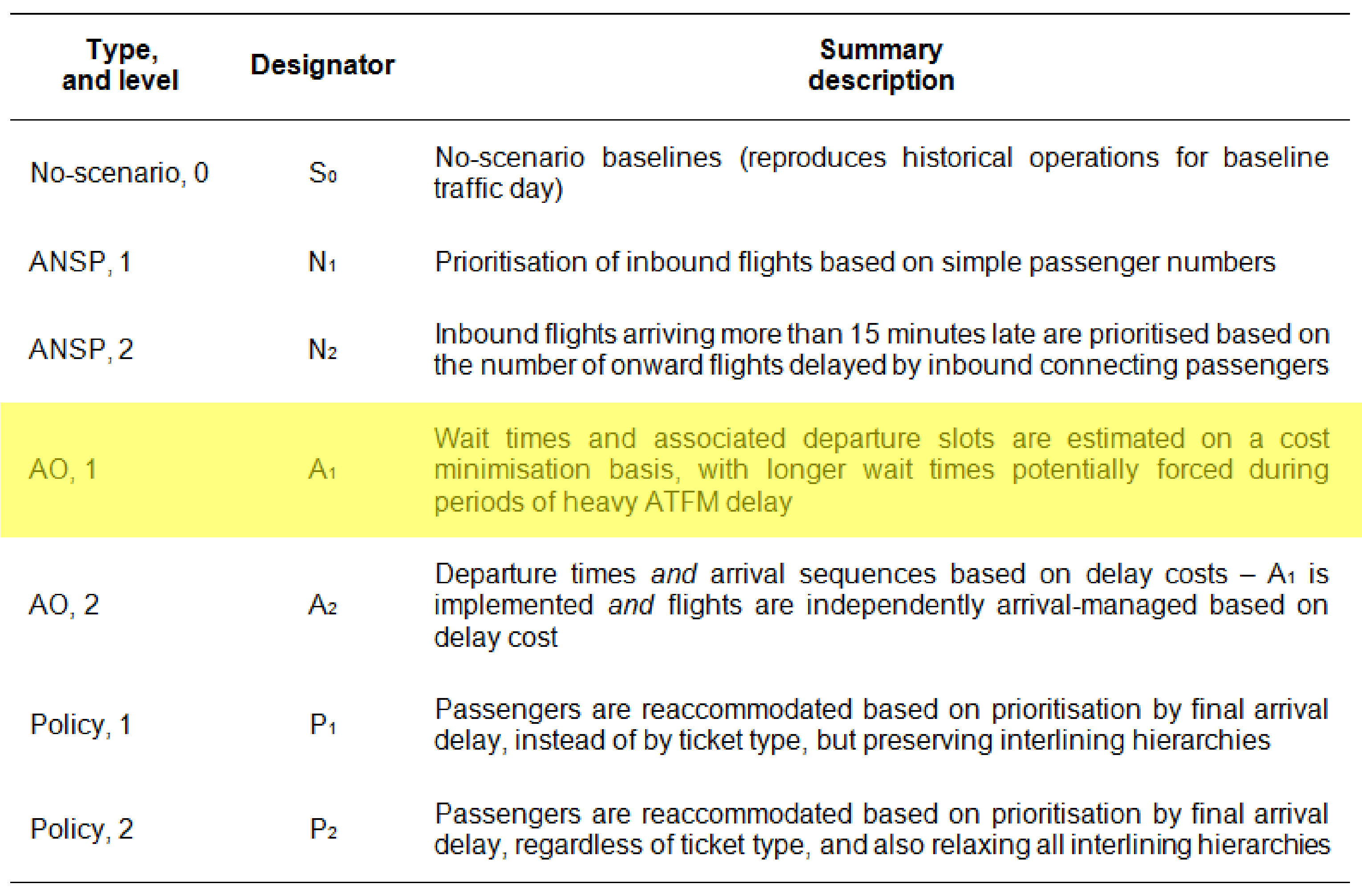
- Policy-driven motivation
  - ultimate performance delivery to the passenger
  - Commission's roadmap to a Single European Transport Area for 2050: pax mobility & network resilience
  - extension of passenger rights (e.g. review of Regulation 261)
  - 'Flightpath 2050', HLG on Aviation Research – 4 hours D2D
- Operational drivers
  - pax often dominate AO delay costs and therefore strongly influence AO behaviour in the network (strategically and tactically)
  - currently only using flight-centric metrics (Europe & US), although flight delay ≠ pax delay (US factors of 1.6 – 1.7)
- How can we measure specific progress without metrics?

POEM project (SESAR)

Unique European simulation model

- Evaluates different flight and pax prioritisation strategies
- Includes tactical costs to the airline (4 AO types)
- Key data-related characteristics
  - currently running 17SEP10 (busy day & month; 2010 c.f. 2012)
  - non-exceptional in terms of delays, strikes, weather
  - busiest 200 ECAC airports (cover 97% pax & 93% traffic for 2010)
  - 50 non-ECAC airports (based on pax flows in/out Europe)
  - extensive range and logic checks (e.g. speeds, registration seqs)
  - taxi-out unreliable; taxi-in missing; IOBT c.f. schedule
  - calibration (ind. sources, e.g. network delays (13.9±0.1) and LFs)
- Unique combination of PaxIS and PRISME data

POEM project (SESAR)



Type, and level	Designator	Summary description
No-scenario, 0	S_0	No-scenario baselines (reproduces historical operations for baseline traffic day)
ANSP, 1	N_1	Prioritisation of inbound flights based on simple passenger numbers
ANSP, 2	N_2	Inbound flights arriving more than 15 minutes late are prioritised based on the number of onward flights delayed by inbound connecting passengers
AO, 1	A_1	Wait times and associated departure slots are estimated on a cost minimisation basis, with longer wait times potentially forced during periods of heavy ATFM delay
AO, 2	A_2	Departure times *and* arrival sequences based on delay costs – A_1 is implemented *and* flights are independently arrival-managed based on delay cost
Policy, 1	P_1	Passengers are reaccommodated based on prioritisation by final arrival delay, instead of by ticket type, but preserving interlining hierarchies
Policy, 2	P_2	Passengers are reaccommodated based on prioritisation by final arrival delay, regardless of ticket type, and also relaxing all interlining hierarchies

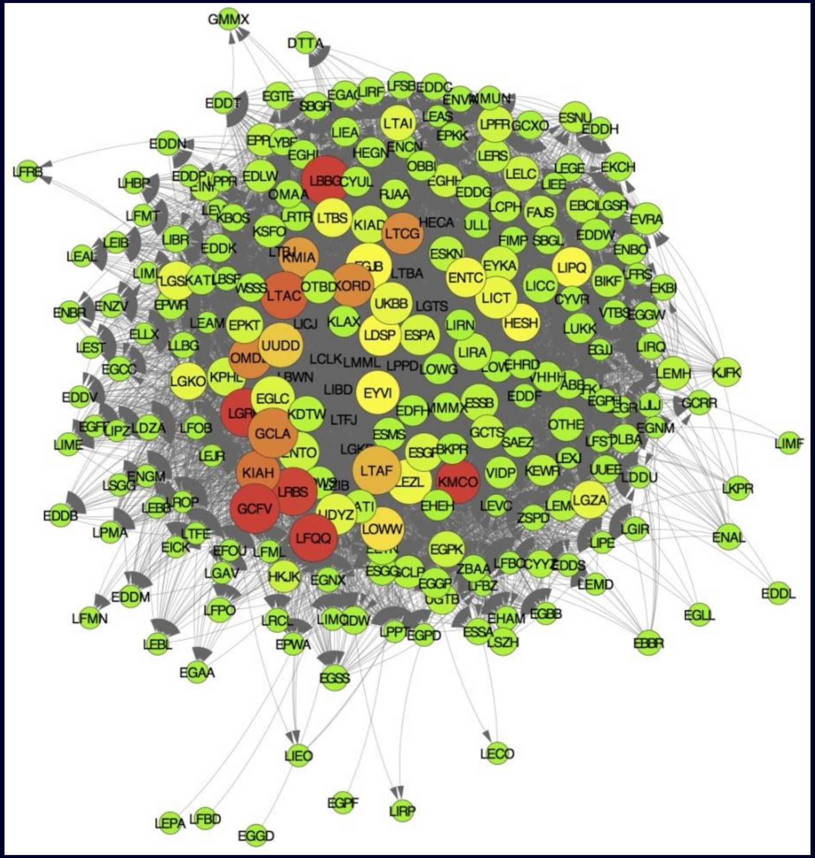
POEM project (SESAR)

- A_1 key results
  - no significant changes in current flight-centric metrics (all scenarios)
  - ⇩€39 avg. cost / flight (appx. €1.2m over whole network)
  - ⇩9.8 mins avg. arr. delay / delayed pax
  - ⇧ 2% reactionary delay …
  - … but focused on relatively few (waiting) aircraft (purposefully)
  - explicit estimations of reactionary delay: a significant advance
- Smaller airports implicated in delay propagation
  - more than hitherto commonly recognised
  - expedited turnaround; spare crew *(& a/c)*; connectivity & capacity
- Back-propagation important in persistence of network delay
  - CDG, MAD, FRA, LHR, ZRH, MUC: all > 100 hours (baseline day)

POEM project (SESAR)

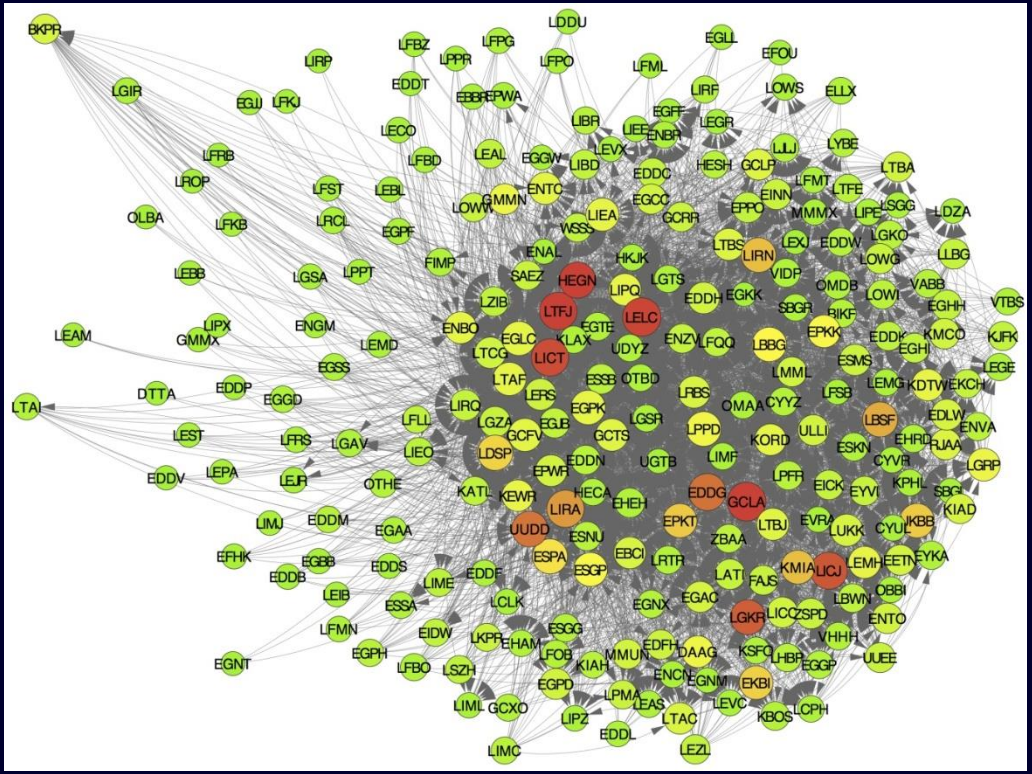
Metric	Pax S_0	Pax A_1	Flight S_0	Flight A_1	Implications
link density	0.17	0.16	0.13	0.08	Passenger delay propagation occurs more readily than for flights
entropy of degree distrib^N	5.1	4.8	5.5	4.2	A_1 network more homogeneous; nodes are more similar to each other, fewer of them highly connected
clustering coefficient	0.20	0.26	0.15	0.20	Clustering increases under A_1
efficiency	0.46	0.43	0.42	0.34	Delay connectedness reduces, i.e. A_1 improves the situation

Flight delay causality network for S_0



redder => higher connectedness; larger => more nodes 'forced'

Flight delay causality network for A_1



POEM project (SESAR)

- Main conclusions of Granger causality analyses
  - comparing eigenvector centrality rankings through Spearman rank correlation coefficients: all four layers almost completely different
  - i.e. airports play different roles in terms of flight and passenger delay propagation, and different again under A_1
- Main effects of A_1
  - delay propagation contained within smaller airport communities
  - … but these communities more susceptible to such propagation

    trade-off
  - largest persistent airports: Athens, Barcelona & Istanbul Atatürk

Challenges ahead

Challenges ahead

- Metrics – methods
  - more focus: costs (cancellation), pax service delivery, propagation
  - US analyses more advanced, several pax metrics proposed (data)
  - resilience is not a state: $\partial R/\partial t$, tipping points, pauses
  - greater use of CS to understand complex socio-technical nature
- Metrics – trade-offs
  - monetised v. non-monetised
  - regulatory v. market forces
  - KPAs, stakeholders: horizontal & vertical
  - local v. network
    - resilience engineering (CNT) evidence: ⇧ polycentric governance, better

Challenges ahead

- Data
  - how much of a network is ‘enough’?
  - more work ahead on sampling protocols; clearly need smaller airports
  - focus on particular airlines or routes is fine, but not a network proxy
  - accessibility (enabling research)
  - standardisation (enabling comparison)
- Collaboration
  - better industry adoption
    - integration with strategic & tactical tools (e.g. A-CDM, flight prioritisation)
    - improving models (e.g. ABMS rationality – intentions and elasticities)
    - better calibration (also a data issue)
    - building confidence (e.g. shadow-mode predictive analytics)
  - policy (AOs, SES) and mobility evaluation (4 hours door-to-door)
  - international scope

Thank you

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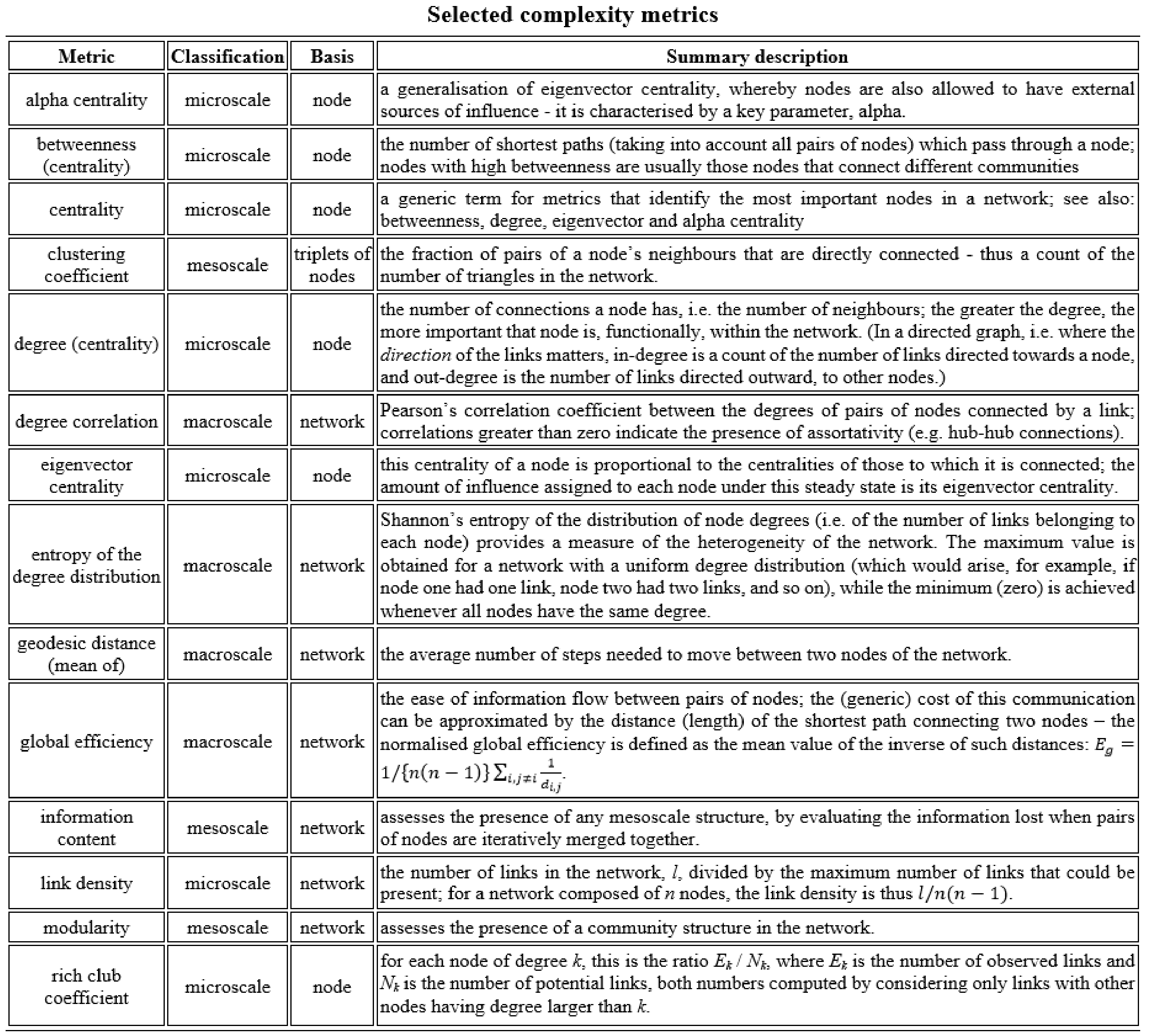
Stand-bys



Selected complexity metrics

Metric	Classification	Basis	Summary description
alpha centrality	microscale	node	a generalisation of eigenvector centrality, whereby nodes are also allowed to have external sources of influence - it is characterised by a key parameter, alpha.
betweenness (centrality)	microscale	node	the number of shortest paths (taking into account all pairs of nodes) which pass through a node; nodes with high betweenness are usually those nodes that connect different communities
centrality	microscale	node	a generic term for metrics that identify the most important nodes in a network; see also: betweenness, degree, eigenvector and alpha centrality
clustering coefficient	mesoscale	triplets of nodes	the fraction of pairs of a node's neighbours that are directly connected - thus a count of the number of triangles in the network.
degree (centrality)	microscale	node	the number of connections a node has, i.e. the number of neighbours; the greater the degree, the more important that node is, functionally, within the network. (In a directed graph, i.e. where the *direction* of the links matters, in-degree is a count of the number of links directed towards a node, and out-degree is the number of links directed outward, to other nodes.)
degree correlation	macroscale	network	Pearson's correlation coefficient between the degrees of pairs of nodes connected by a link; correlations greater than zero indicate the presence of assortativity (e.g. hub-hub connections).
eigenvector centrality	microscale	node	this centrality of a node is proportional to the centralities of those to which it is connected; the amount of influence assigned to each node under this steady state is its eigenvector centrality.
entropy of the degree distribution	macroscale	network	Shannon's entropy of the distribution of node degrees (i.e. of the number of links belonging to each node) provides a measure of the heterogeneity of the network. The maximum value is obtained for a network with a uniform degree distribution (which would arise, for example, if node one had one link, node two had two links, and so on), while the minimum (zero) is achieved whenever all nodes have the same degree.
geodesic distance (mean of)	macroscale	network	the average number of steps needed to move between two nodes of the network.
global efficiency	macroscale	network	the ease of information flow between pairs of nodes; the (generic) cost of this communication can be approximated by the distance (length) of the shortest path connecting two nodes – the normalised global efficiency is defined as the mean value of the inverse of such distances: $E_g = 1/\{n(n-1)\}\sum_{i,j\neq i}\frac{1}{d_{i,j}}$.
information content	mesoscale	network	assesses the presence of any mesoscale structure, by evaluating the information lost when pairs of nodes are iteratively merged together.
link density	microscale	network	the number of links in the network, l, divided by the maximum number of links that could be present; for a network composed of n nodes, the link density is thus $l/n(n-1)$.
modularity	mesoscale	network	assesses the presence of a community structure in the network.
rich club coefficient	microscale	node	for each node of degree k, this is the ratio E_k / N_k, where E_k is the number of observed links and N_k is the number of potential links, both numbers computed by considering only links with other nodes having degree larger than k.

Scale-free networks

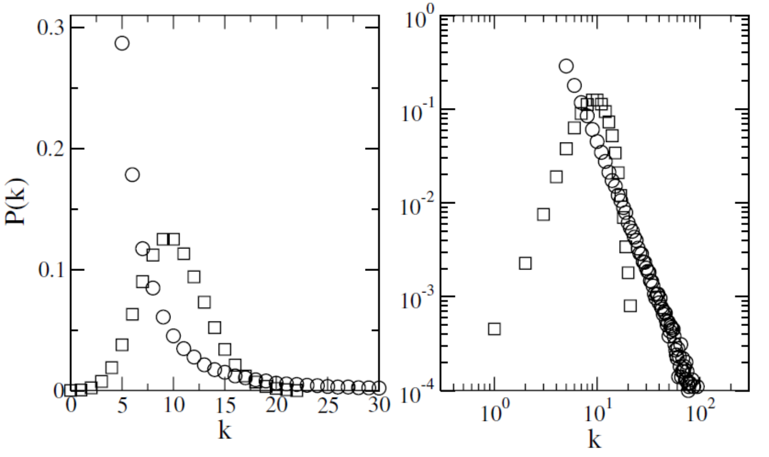
- Degree distribution P(*k*) follows a power law

  $P(k) = ak^{-\gamma}$; gives fraction of nodes with *k* = 1, 2, 3 etc.

  typically: $2 < \gamma < 3$; *a* such that $\int P(k) = 1$

  function => high diversity of node degrees, hence ‘scale-free’

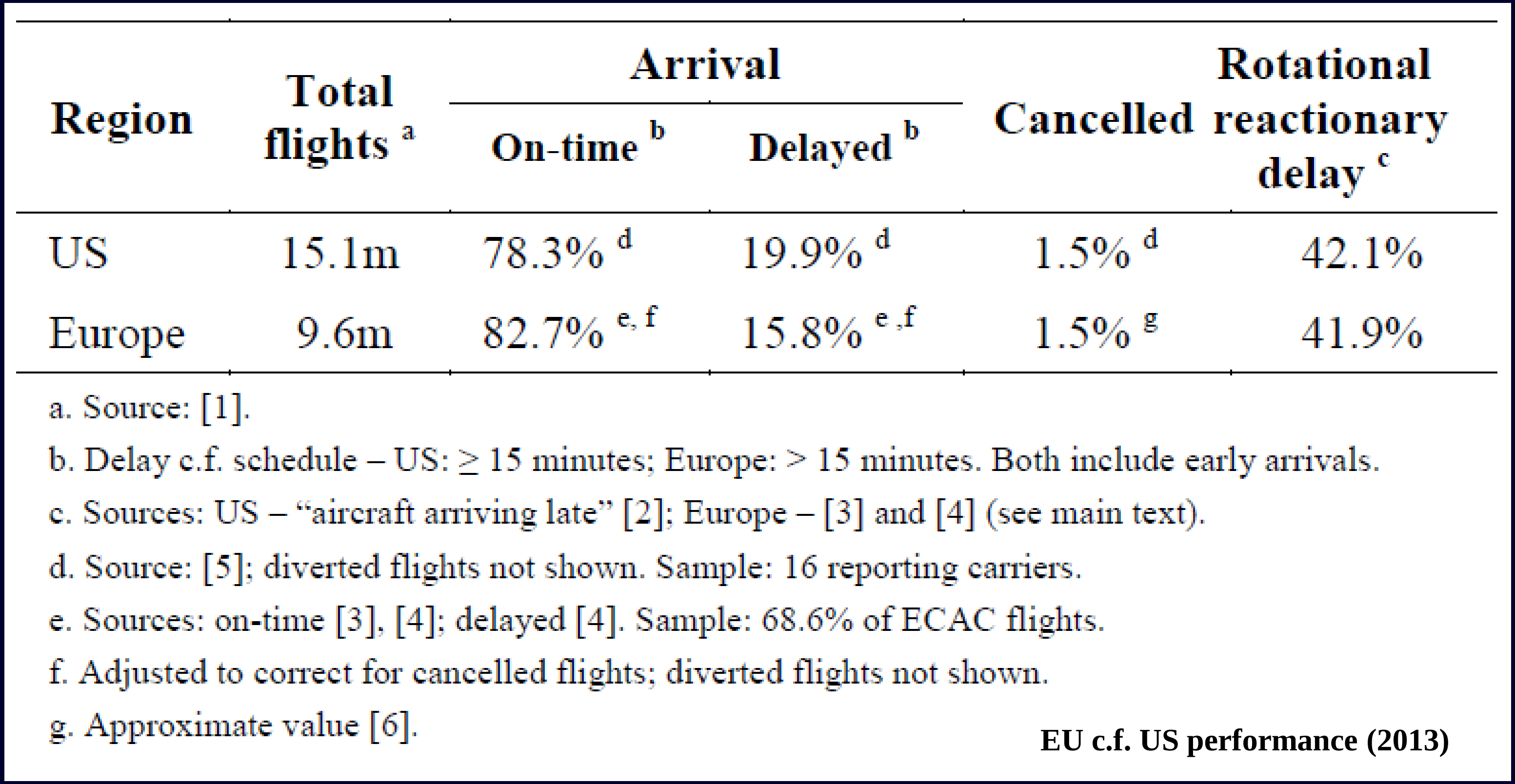
  built through ‘preferential attachment’



For the same number of links and edges: comparing random graphs (☐; peaks at average *k*) and scale-free networks (○; mostly small *k* and small number with very high *k* (hubs), but also every degree in between). Note that scale-free random graphs (i.e. with scale-free distributions but random in all other respects) can be constructed by scrambling degree-preserving versions of real networks.

Source: Albert (2005)

Air transport performance & sampling



Region	Total flights [a]	Arrival		Cancelled	Rotational reactionary delay [c]
		On-time [b]	Delayed [b]		
US	15.1m	78.3% [d]	19.9% [d]	1.5% [d]	42.1%
Europe	9.6m	82.7% [e, f]	15.8% [e, f]	1.5% [g]	41.9%

a. Source: [1].

b. Delay c.f. schedule – US: ≥ 15 minutes; Europe: > 15 minutes. Both include early arrivals.

c. Sources: US – "aircraft arriving late" [2]; Europe – [3] and [4] (see main text).

d. Source: [5]; diverted flights not shown. Sample: 16 reporting carriers.

e. Sources: on-time [3], [4]; delayed [4]. Sample: 68.6% of ECAC flights.

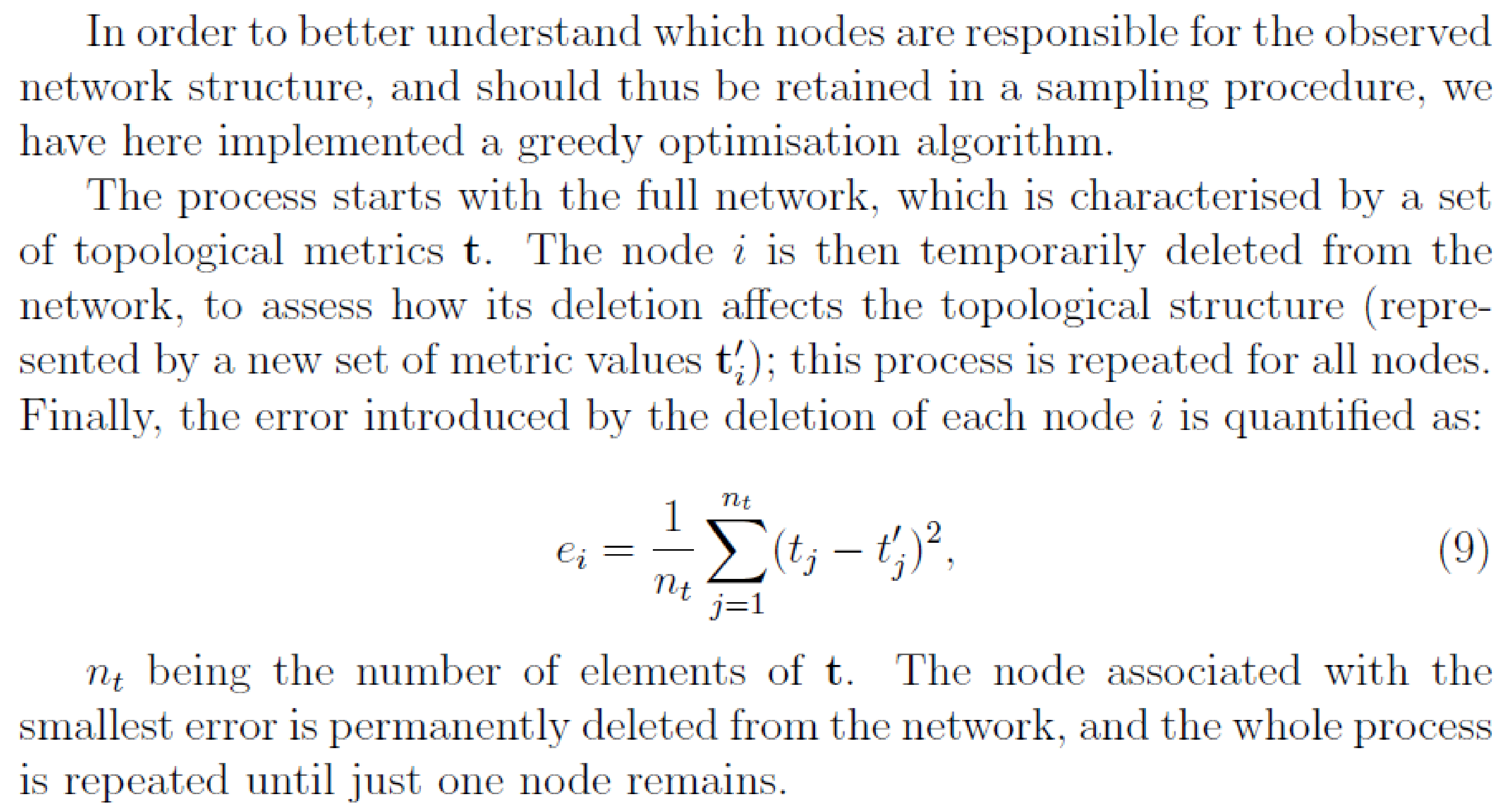
f. Adjusted to correct for cancelled flights; diverted flights not shown.

g. Approximate value [6].

EU c.f. US performance (2013)

Source: Cook, Tanner, Cristobal, Zanin, 2015. *Delay propagation – new metrics, new insights*.
Eleventh USA/Europe Air Traffic Management Research and Development Seminar (ATM2015), Lisbon, Portugal.

Optimisation algorithm



In order to better understand which nodes are responsible for the observed network structure, and should thus be retained in a sampling procedure, we have here implemented a greedy optimisation algorithm.

The process starts with the full network, which is characterised by a set of topological metrics $\mathbf{t}$. The node i is then temporarily deleted from the network, to assess how its deletion affects the topological structure (represented by a new set of metric values $\mathbf{t}'_i$); this process is repeated for all nodes. Finally, the error introduced by the deletion of each node i is quantified as:

$$e_i = \frac{1}{n_t} \sum_{j=1}^{n_t} (t_j - t'_j)^2, \tag{9}$$

n_t being the number of elements of $\mathbf{t}$. The node associated with the smallest error is permanently deleted from the network, and the whole process is repeated until just one node remains.

Source: Belkoura, Cook, Peña and Zanin, 2016 (submitted paper)

Further key sampling results

- Comparing two European & US data sources
  - all metric evolutions followed the same shape
  - however, when same no. of airports included, different metric values
- Sampling European aircraft types by no. of operations
  - need a very large sampling fraction before metrics stabilised
- Sampling European days
  - many studies only sample a day or a week
  - metrics did not stabilise until around 40-60 days
- Sampling airlines (all regions)
  - in contrast, to above, quite a low number of airlines often sufficient … sampling from largest no. of operations first (large rich clubs)
  - four of largest + one at random, also typically sufficient
  - relatively low no. of airlines captures good range of airports

Source: Belkoura, Cook, Peña and Zanin, 2016 (submitted paper)

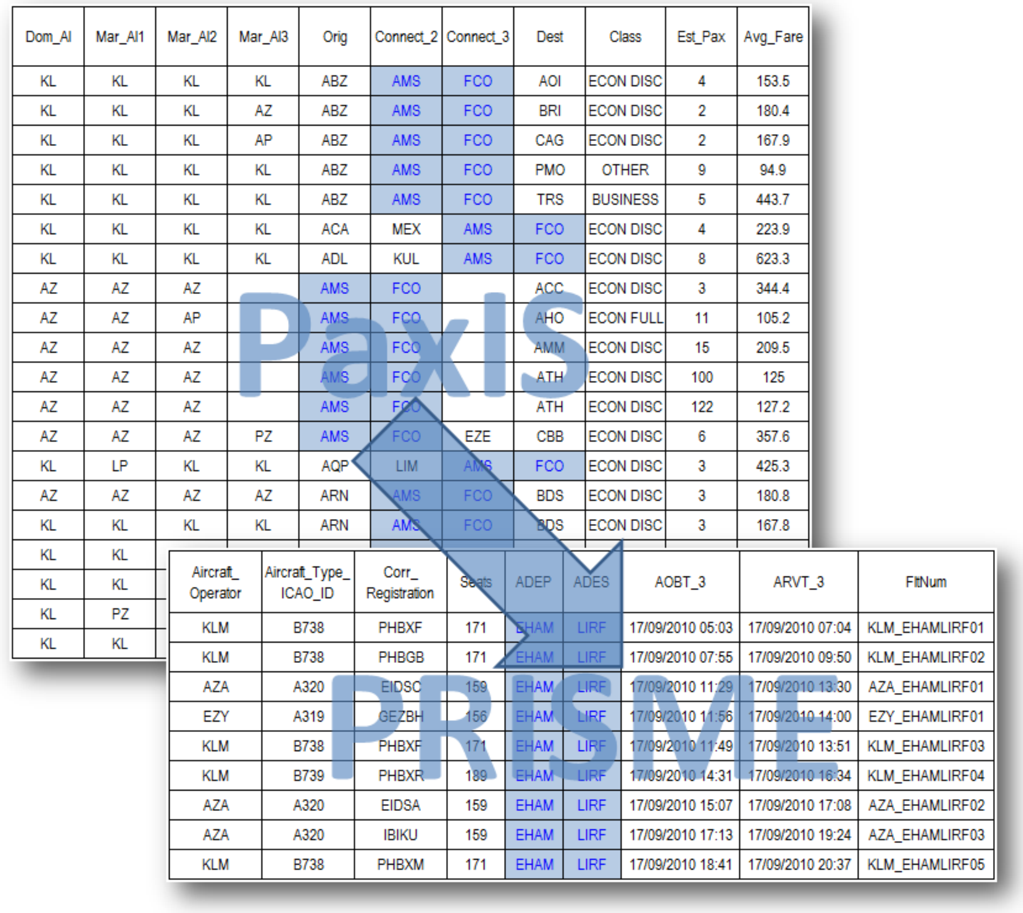
Key POEM model features

- Gate-to-gate aircraft rules, and pax connection rules
- Varying levels of fidelity, for example:

– Rule 23: en-route (some recovery, 5 min residual, wind)

– Rule 33: passenger reaccommodation
  - Regulation (EC) 261/2004; IATA (involuntary rerouting & proration rules)
  - trigger: pax late at gate (a/c not wait); cancellation; (*denied boarding)*
  - aircraft seat configuration data used with routing sub-rules
  - passenger prioritisation sub-rules (alliances, ticket flexibility, ties)
  - hard costs (rebooking, cost of care, overnight accommodation)
  - soft costs (dissatisfaction, market share; capped at 5 hours)
  - (passenger value of time)
  - multiple sources, including airline input and airline review

PaxIS + PRISME



Dom_Al	Mar_Al1	Mar_Al2	Mar_Al3	Orig	Connect_2	Connect_3	Dest	Class	Est_Pax	Avg_Fare
KL	KL	KL	KL	ABZ	AMS	FCO	AOI	ECON DISC	4	153.5
KL	KL	KL	AZ	ABZ	AMS	FCO	BRI	ECON DISC	2	180.4
KL	KL	KL	AP	ABZ	AMS	FCO	CAG	ECON DISC	2	167.9
KL	KL	KL	KL	ABZ	AMS	FCO	PMO	OTHER	9	94.9
KL	KL	KL	KL	ABZ	AMS	FCO	TRS	BUSINESS	5	443.7
KL	KL	KL	KL	ACA	MEX	AMS	FCO	ECON DISC	4	223.9
KL	KL	KL	KL	ADL	KUL	AMS	FCO	ECON DISC	8	623.3
AZ	AZ	AZ		AMS	FCO		ACC	ECON DISC	3	344.4
AZ	AZ	AP		AMS	FCO		AHO	ECON FULL	11	105.2
AZ	AZ	AZ		AMS	FCO		AMM	ECON DISC	15	209.5
AZ	AZ	AZ		AMS	FCO		ATH	ECON DISC	100	125
AZ	AZ	AZ		AMS	FCO		ATH	ECON DISC	122	127.2
AZ	AZ	AZ	PZ	AMS	FCO	EZE	CBB	ECON DISC	6	357.6
KL	LP	KL	KL	AQP	LIM	AMS	FCO	ECON DISC	3	425.3
AZ	AZ	AZ	AZ	ARN	AMS	FCO	BDS	ECON DISC	3	180.8
KL	KL	KL	KL	ARN	AMS	FCO	BDS	ECON DISC	3	167.8
KL	KL									
KL	KL									
KL	PZ									
KL	KL									

Aircraft_ Operator	Aircraft_Type_ ICAO_ID	Corr_ Registration	Seats	ADEP	ADES	AOBT_3	ARVT_3	FltNum
KLM	B738	PHBXF	171	EHAM	LIRF	17/09/2010 05:03	17/09/2010 07:04	KLM_EHAMLIRF01
KLM	B738	PHBGB	171	EHAM	LIRF	17/09/2010 07:55	17/09/2010 09:50	KLM_EHAMLIRF02
AZA	A320	EIDSC	159	EHAM	LIRF	17/09/2010 11:29	17/09/2010 13:30	AZA_EHAMLIRF01
EZY	A319	GEZBH	156	EHAM	LIRF	17/09/2010 11:56	17/09/2010 14:00	EZY_EHAMLIRF01
KLM	B738	PHBXF	171	EHAM	LIRF	17/09/2010 11:49	17/09/2010 13:51	KLM_EHAMLIRF03
KLM	B739	PHBXR	189	EHAM	LIRF	17/09/2010 14:31	17/09/2010 16:34	KLM_EHAMLIRF04
AZA	A320	EIDSA	159	EHAM	LIRF	17/09/2010 15:07	17/09/2010 17:08	AZA_EHAMLIRF02
AZA	A320	IBIKU	159	EHAM	LIRF	17/09/2010 17:13	17/09/2010 19:24	AZA_EHAMLIRF03
KLM	B738	PHBXM	171	EHAM	LIRF	17/09/2010 18:41	17/09/2010 20:37	KLM_EHAMLIRF05

- aggregated PaxIS (IATA ticket) pax data allocated onto individual flights (PRISME traffic data, from EUROCONTROL)
- assignment algorithms respecting aircraft seat configurations and load factor targets
- full pax itineraries built respecting MCTs and published schedules
- 30 000 flights
- 2.5 million pax
- 150 000 routings

flight-centric

new metrics

Core metric	Units	N_1 & N_2	P_1	P_2	A_1
		Inbound prioritisation based on: simple pax numbers, or on onward flights delayed	Passenger reaccommodated based on delay at final destination … … preserving interlining hierarchies	**… relaxing interlining hierarchies**	Departures times based on **cost minimisation** (& consideration of ATFM delay)
Flight departure delay	mins / flight	no significant changes in current flight-centric metrics: stresses need for passenger-centric metrics			
Flight arrival delay	mins / flight				
Departure delay of departure-delayed flights	mins / flight				
Arrival delay of arrival-delayed flights	mins / flight				
Pax departure delay	mins / pax			=	+0.4
Pax arrival delay	mins / pax			-0.4	-1.6
Departure delay of departure-delayed pax	mins / pax	no significant changes under simple inbound scenarios driven by passenger numbers, or by numbers of delayed onward flights	revised passenger re-booking rules produce only weak improvements whilst current airline interlining rules are preserved, c.f. →	=	=
Arrival delay of arrival-delayed pax	mins / pax			-2.2	-9.8
Passenger value of time	Euros / pax			-0.2	-0.7
Non-passenger costs	Euros / flight			=	=
Per-flight pax hard cost	Euros / flight			+26	-40
Per-flight pax soft cost	Euros / flight			=	=
Total flight cost	Euros / flight			+26	-39
Total flight cost per minute of departure delay	Euros / min			=	-7.8
Reactionary delay ratio	ratio			49%	51%

Granger causality

- time series, q, is considered to Granger-cause another time series, p, if inclusion of past values of q can improve forecasting of p
- two time series with a high correlation
- two time series ‘forced’ by a third system

] usually fail, as q doesn’t add new info for p

- built flight and pax networks for S_0 and A_1
- time series of arrival delay for node pairs (unweighted directed network)
- for each node, calculated eigenvector centrality: delay connectedness

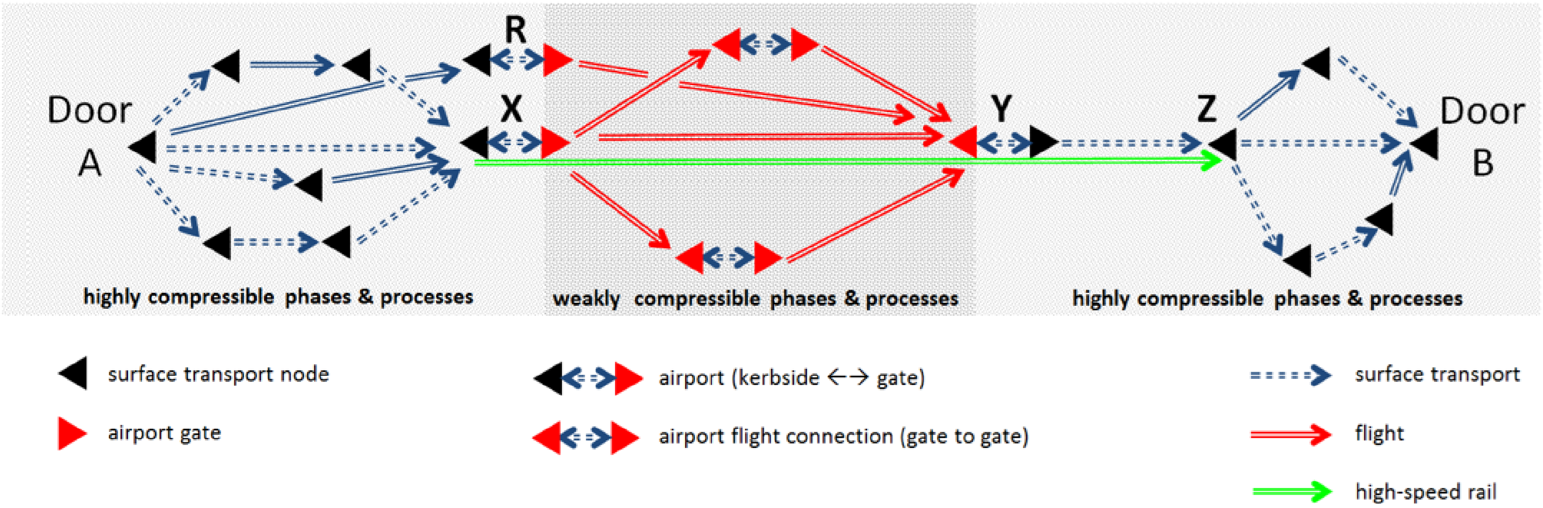
Delay cost elements

Element	Types of cost (in-house models, except fuel)
fleet	all fleet costs (depreciation, rentals & leases)
fuel	Lido/Flight, BADA, manufacturers
crew	schemes, flight hours, on-costs, overtime
maintenance	extra wear & tear powerplants/airframe
passenger	‘hard’ & ‘soft’ (not internalised costs)
ground handling	aircraft and passengers – penalty if late / delayed on gate
airport charges	various aeronautical charging manuals and policies consulted
en-route ATC charges	based on GCD entry/exit – requires significant re-route due delay
CO_2	considered allocated permits and CO_2 price; small % fuel variation

Delay cost elements

Element	Strategic	Tactical
fleet	= *f* (service hours)	≠ *f* (utilisation) = 0
fuel	= (e.g. no hedging between phases)	
crew	unit	marginal (0 … full o/t)
maintenance	unit	marginal (e.g. fixed LTOs)
passenger	0	dominate, non-linear

Flightpath 2050 – 4 hours D2D for 90% of pax?



>> ***Multiple D2D pathways:*** **some legs (= = =) are more compressible; regional / 2° options**

>> ***Airport access, process and egress particularly compressible***

- **road congestion; PT (priorities); interchange times / direct access; frequencies / capacities**
- **K2G (automation & smart systems): check-in (baggage); security / passport control; + MCTs**

>> ***Gate-to-gate (G2G) performance relatively pretty good***

- **82% of arrivals within 15mins (buffers); e/r ATFM = 0.73 mins/flt; hor. e/r ineff = 4.7% (2015)**

>> ***Compare 3h49 average CDG connections***