Robust and Recoverable Maintenance Routing Schedules

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Introduction

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Some numbers

- ☐ Huge economical impact[1]
  - $1.7 billion loss of revenue for first week
  - $400 million a day for the first 4 days
  - 1.2 million affected passengers / day
- ☐ Spill out due to disrupted / blocked passengers

[1] *www.iata.org/pressroom*, Press release No 15, 21 April 2010

Why robustness appeals for airline scheduling

- Airlines have low profitability
  - < 2% profit margin (US, 2007)

- High delays and implied delay costs[2]
  - 4.3 Billion hours delay (US, 2008)
  - $41 Billion delay costs (US, 2008)

[2] *Your flight has been delayed again* (2008), Joint Economic Committee www.jec.senate.gov

Worse is still to come

- ☐ Growth:
  - 2.5% more flights annually
  - Every 1% additional flights incur an additional 5% delays (`Schaefer et al., 2005`)
  - => Yearly increase of delays of 12.5%
- ☐ Europe: 50% of flights in 2030 depart or land at congested airports
- ☐ Airlines must react – we try to help
  - Improve operations in a congested network

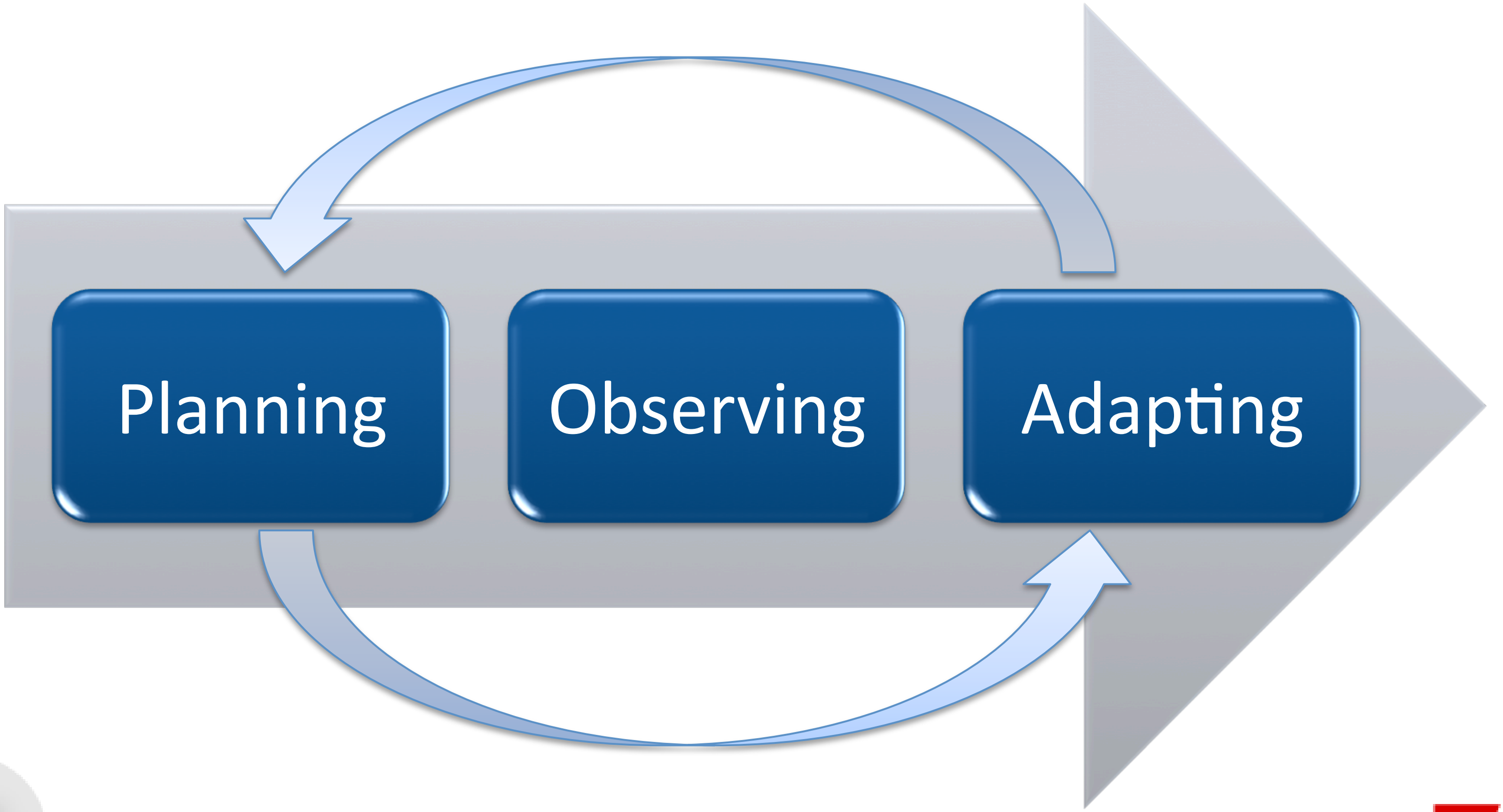
Outline

- ☐ Optimization under uncertainty
  - In general
  - In airline scheduling

- ☐ Robust Maintenance Routing Problem
  - Definitions
  - “Robust” and “Recoverable” models

- ☐ Simulation – preliminary results
  - Methodology to evaluate and compare robust solutions
  - Preliminary a priori and a posteriori results

General Optimization Problems



Planning

Observing

Adapting

Robustness: plan for stability and reliability

- Optimized solutions have
  - Highest "***expected***" revenue/yield/profit
  - Known to be sensitive to noise

- Robust solutions have
  - Lower expected revenue/yield/profit
  - Higher reliability
  - Both objectives are conflicting – requires ***trade-off***

Definition of robustness

❑ Unclear in literature

  - For more “***stable***” solutions (that remain feasible)
  - For more “***flexible”*** solutions
  - For solutions with lower “***operational costs”***

❑ How to determine what “more robust” means?

  - What metric to use?
  - Should it be a priori or a posteriori?

Other meanings of robustness

- ☐ Robustness is also used as a "***flexibility***" measure
  - Facilitates recovery
  - Reduces recovery costs

- ☐ We differentiate
  - **ROBUSTNESS** vs **RECOVERABILITY**

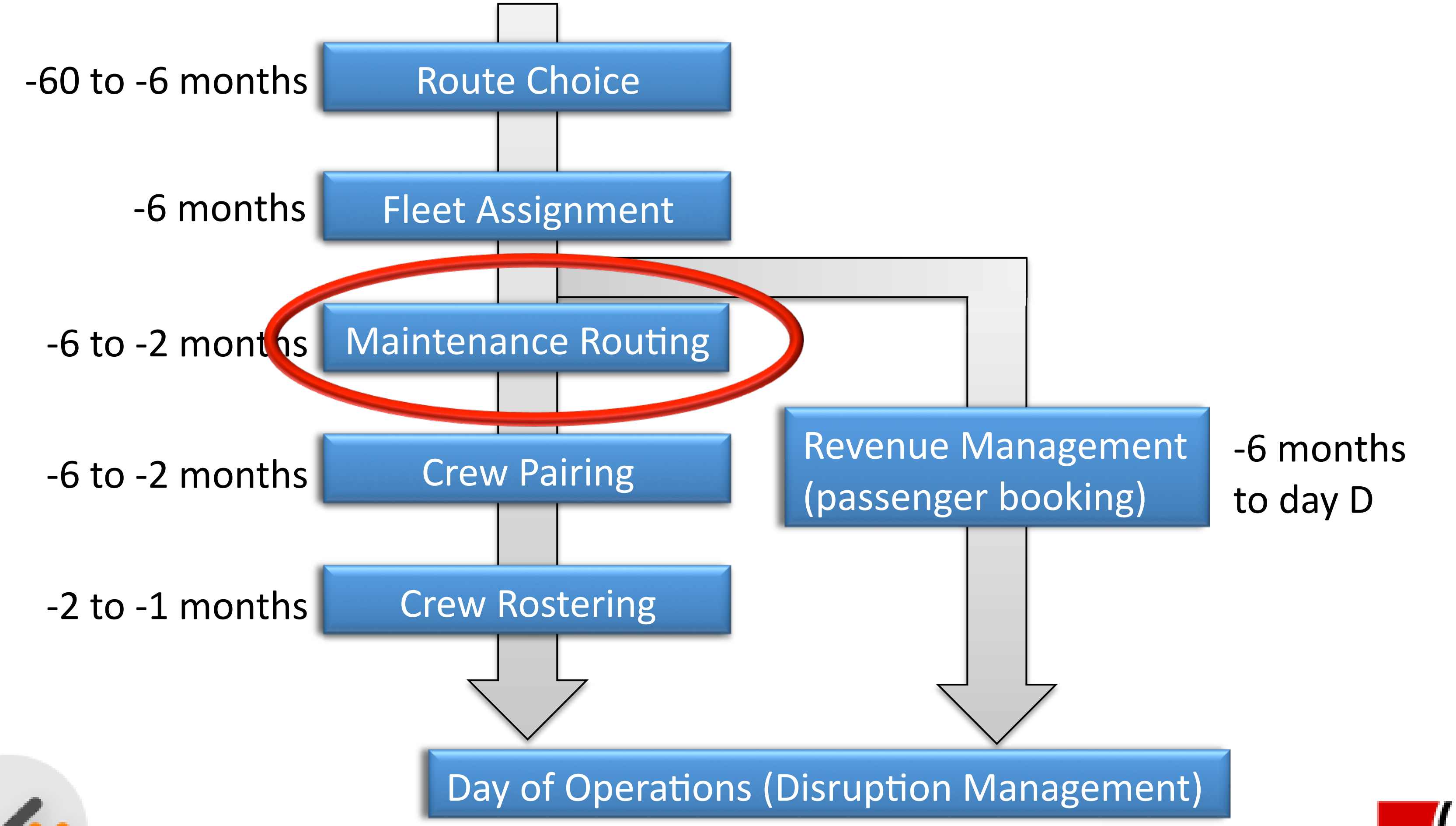
Our objectives

- Examine how robustness proxies and performance metrics are correlated

- Robustness proxies are structural a priori properties of the schedule
  - Expected propagated delay
  - Total slack in aircraft routes
  - Total passenger connection time
  - …

- Performance metrics are a posteriori metric
  - Observed propagated delay
  - Total passenger delay
  - Recovery costs
  - …

Airline Scheduling: An iterative Process



-60 to -6 months

Route Choice

-6 months

Fleet Assignment

-6 to -2 months

Maintenance Routing

-6 to -2 months

Crew Pairing

-2 to -1 months

Crew Rostering

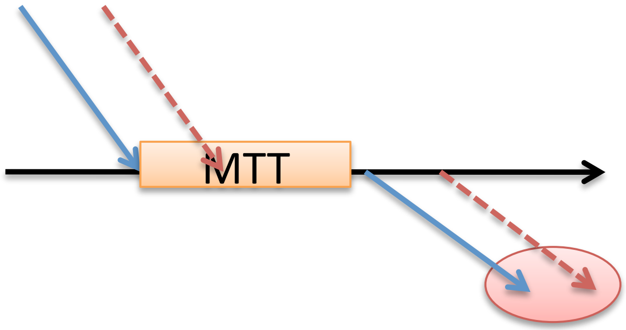
Revenue Management (passenger booking)

-6 months to day D

Day of Operations (Disruption Management)

Robustness in airline scheduling

- Robust airline schedules are
  - Operationally more efficient
  - Less sensitive to delay
    - i.e. with reduced delay propagation



Delay Propagation

- 2 types of delays for each flight
  - ***Independent*** delay: generated during a flight
    - At any stage (taxi, runway, landing,…)
  - ***Propagated*** delay
    - Delay due to previously delayed flight
    - Propagation is downstream (possibly to several flights)

- $Del(f) = ID(f) + PD(f)$
- Robustness proxy = expected PD
  - To be minimized

Robust Maintenance Routing Problem (MRP)

- Deterministically known
  - Original schedule (1 maintenance route/aircraft)
- To determine
  - New routes for each aircraft
  - And/or new departure times for each flight
- Constraints
  - Maintenance routes are feasible for each aircraft
  - All flights are covered exactly once
  - Each flight is retimed by at most ±15
  - Total retiming of all flights of at most *C* minutes (500 or 1000)
- Objective
  - Optimize robustness proxy

Used Uncertainty Feature Optimization (UFO)[3] Models

- ☐ Use different UFs:
  - IT: maximize total idle time
  - MIT: maximize sum of minimal idle time of each route
  - CROSS: maximize nbr plane crossings
  - PCON: maximize passenger idle connection time
  - MinPCON: maximize minimal PCON
- ☐ Solved with CG algorithm (COIN-OR – BCP package)

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[3] Eggenberg et al. (2010), *Uncertainty Feature Optimization: a implicit paradigm for problems with noisy data* (accepted for publication in Networks in June, 2010)

Benchmark

- Models from literature
  - EPD: minimize expected propagated delay (Lan et al., 2006)
    - No retiming
    - Allow only plane swaps
  - EPD2: minimize expected propagated delay (AhmadBeygi et al., 2008)
    - No plane swaps
    - Allow for retiming by ± 15 minutes
    - Total retiming bounded (500 or 1000 minutes)
- Solved with same CG algorithm (COIN-OR – BCP package) (Eggenberg et al., 2010)

Measuring Recoverability: Methodology

- Solve Robust MRP using different robust models
- Simulate different disruption scenarios
  - Differentiate *independent* and *propagated* delay
  - Update propagated delay according to schedule
- Solve the recovery problem
  - Using same recovery algorithm (Eggenberg et al., 2010)
- Evaluation with external recovery cost evaluator
  - Data and cost-evaluator provided by the *ROADEF Challenge 2009* (challenge.roadef.org/2009)

Planning

Observing

Adapting

Scenario Generation

- Use historical data of 2 year and separate it by season
  - Winter (October – March)
  - Summer (April – September)

- For each airport, we have arrival and departure delays

- Generate delays for flight f from A to B drawing from empirical distribution by

$$\text{Del} = 0.5 * [\ \text{depDel}(A) + \text{arrDel}(A)\ ]$$

Generated schedules

- UFO solutions are the same for Winter and Summer
  - UFs are non-predictive models
- EPD solutions are different
  - Solution depends on estimated delay distribution
  - Based on average delay of each flight, which is different in Winter and in Summer

Notation for models

- Model of Lan et al., 2006 (minimize expected propagated delay)
  - EPD_W: use average delay of Winter
  - EPD_S: use average delay of Summer

- Model of AhmadBeygi et al., 2008 (minimize expected propagated delay)
  - EPD2_W: use average delay of Winter
  - EPD2_S: use average delay of Summer

- Model name + "_*XXX*"
  - *XXX* is the value of *C* (maximum allowed retiming in min.)

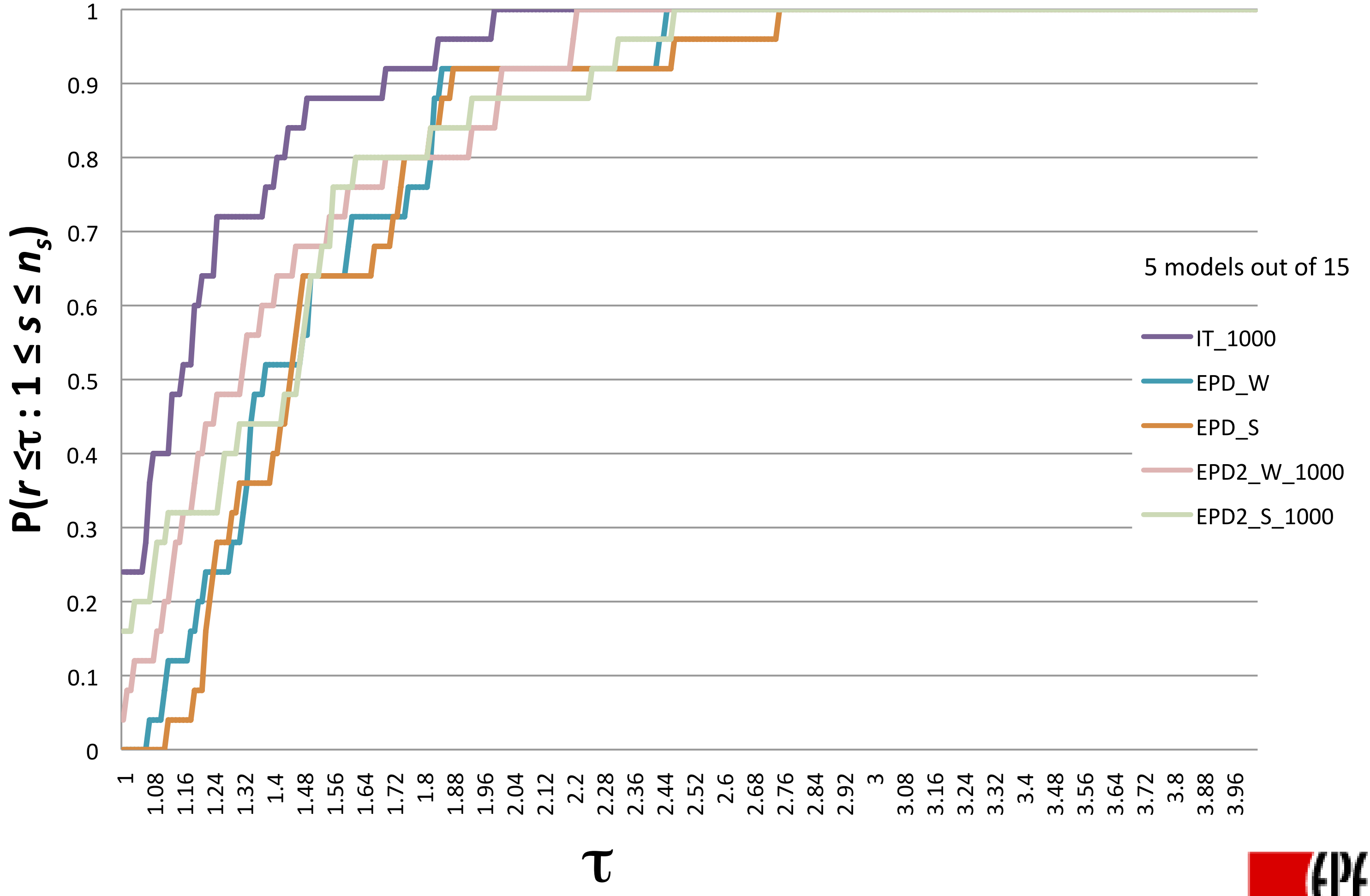
Simulation Overview – EPD and EPD2

Scenario/Schedules	**EPD_W & EPD2_W**	**EPD_S & EPD2_S**
Winter Scenarios	OK	WRONG DISTRIBUTION
Summer Scenarios	WRONG DISTRIBUTION	OK

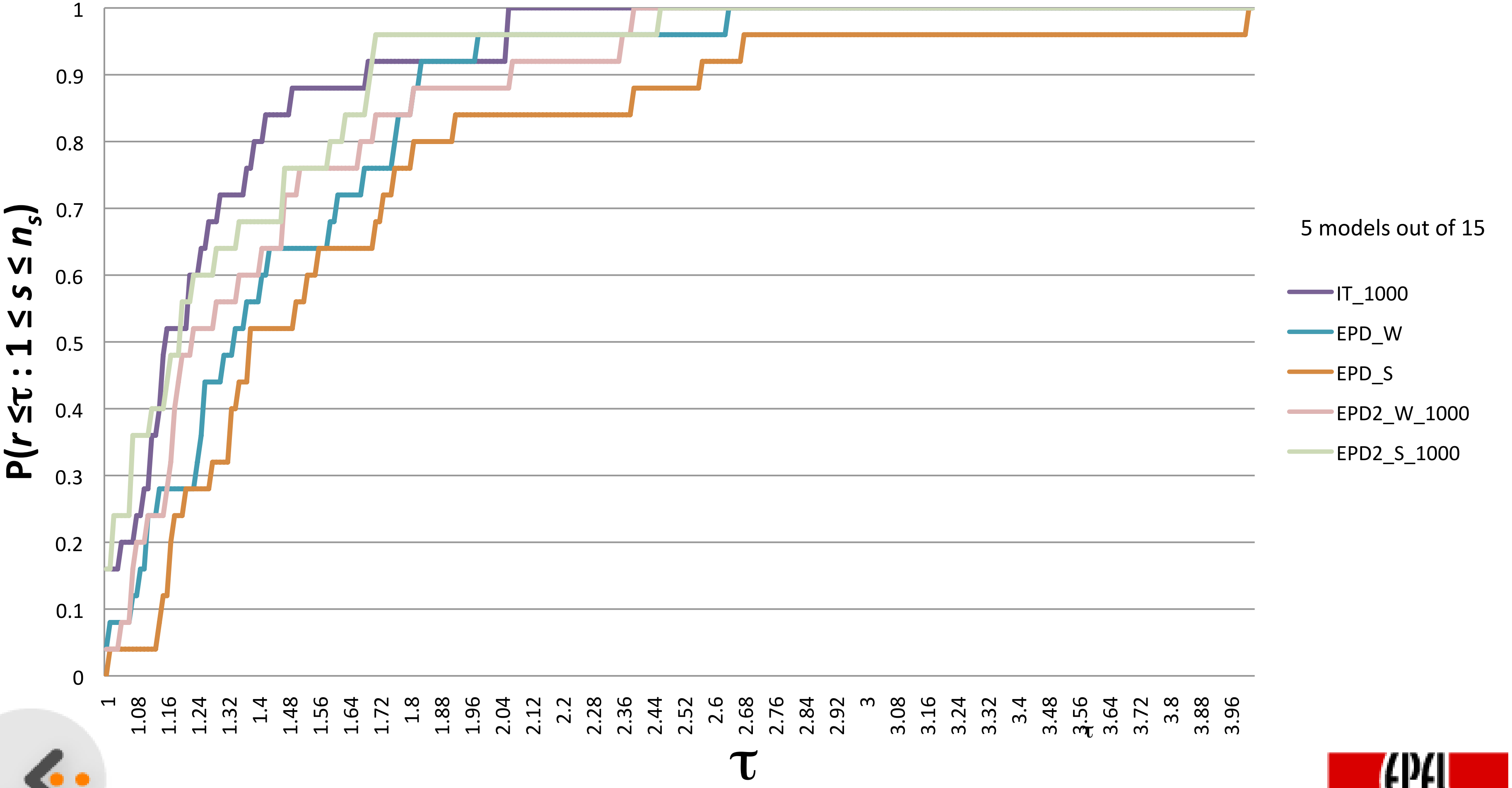
Used Instance – Derived from instance A01 of the Roadef Challenge 2009

- 608 flights
- 85 aircrafts
- 36010 passengers
- 1 day

Performance Profiles
Over all 25 instances (Winter only)



Performance Profiles
Over all 25 instances (Summer only)



Recovery Performance Metrics – Overall (Winter + Summer)

	Original	IT_1000	MIT_500	PCON_1000	EPD2_W_1000	EPD2_S_1000
Rec. Costs [k €]	249.2	**197.4**	241.1	249.6	248.6	239.8
Nbr Canc. Pax	137	**104**	123	137	139	129
Avg. Pax delay [min]	33.42	**31.55**	34.6	33.33	32.97	31.80
Nbr Cancelled Flights	2.98	**2.36**	3.08	2.98	2.84	2.94
Nbr Delayed Flights	53.7	50.6	55.2	53.8	53.1	**45.8**
Propagated Delay [min]	9405	7632	9732	9382	9069	**6108**

Recoverability: Correlation between a priori proxies and performance metrics

Overall	**Total Slack IT**	**Minimum Slack MIT**	**Passenger Connection Time PCON**	**Expected Propagated Delay EPD**
Recovery Costs	**-0.135**	-0.021	**-0.135**	**0.092**
# Cancelled Pax	**-0.135**	-0.016	**-0.134**	**0.082**
Average Pax Delay	**-0.084**	0.058	**-0.086**	**0.137**
# Cancelled Flights	**-0.072**	-0.014	**-0.073**	0.056
Propagated Delay	**-0.155**	**0.171**	-0.152	**0.409**

Bold values are significant with confidence level $\alpha = 0.05$

Conclusions

- We propose a methodology to evaluate the relevance of robustness proxies

- We show that these proxies are inter-correlated and indeed improve the ***recoverability*** of the schedule

- We show that expected propagated delay
  - is not a good indicator for recoverability
  - is sensitive to errors in the uncertainty model

Open Research Directions

- Exploit the correlation structure to combine the different robustness proxies

- Explore correlations on wider instance set with disruptions including
  - Imposed flight cancellations
  - Aircraft unavailability periods
  - Airport capacity modifications

- Study other proxies

- Evaluate performances using other recovery algorithms
  - To identify whether correlations are due to the recovery algorithm or if they are globally improving recoverability

The End

Thank you for your attention!