Airline Disruptions: Aircraft Recovery with Maintenance Constraints

Niklaus Eggenberg
Dr. Matteo Salani and Prof. Michel Bierlaire

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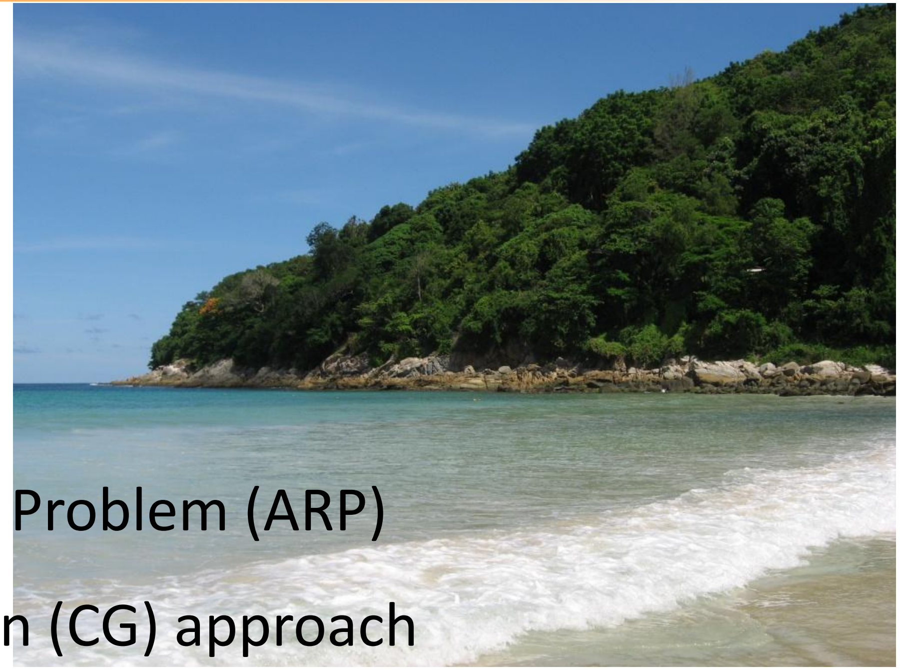
Dr. Matteo Salani

Prof. Michel Bierlaire



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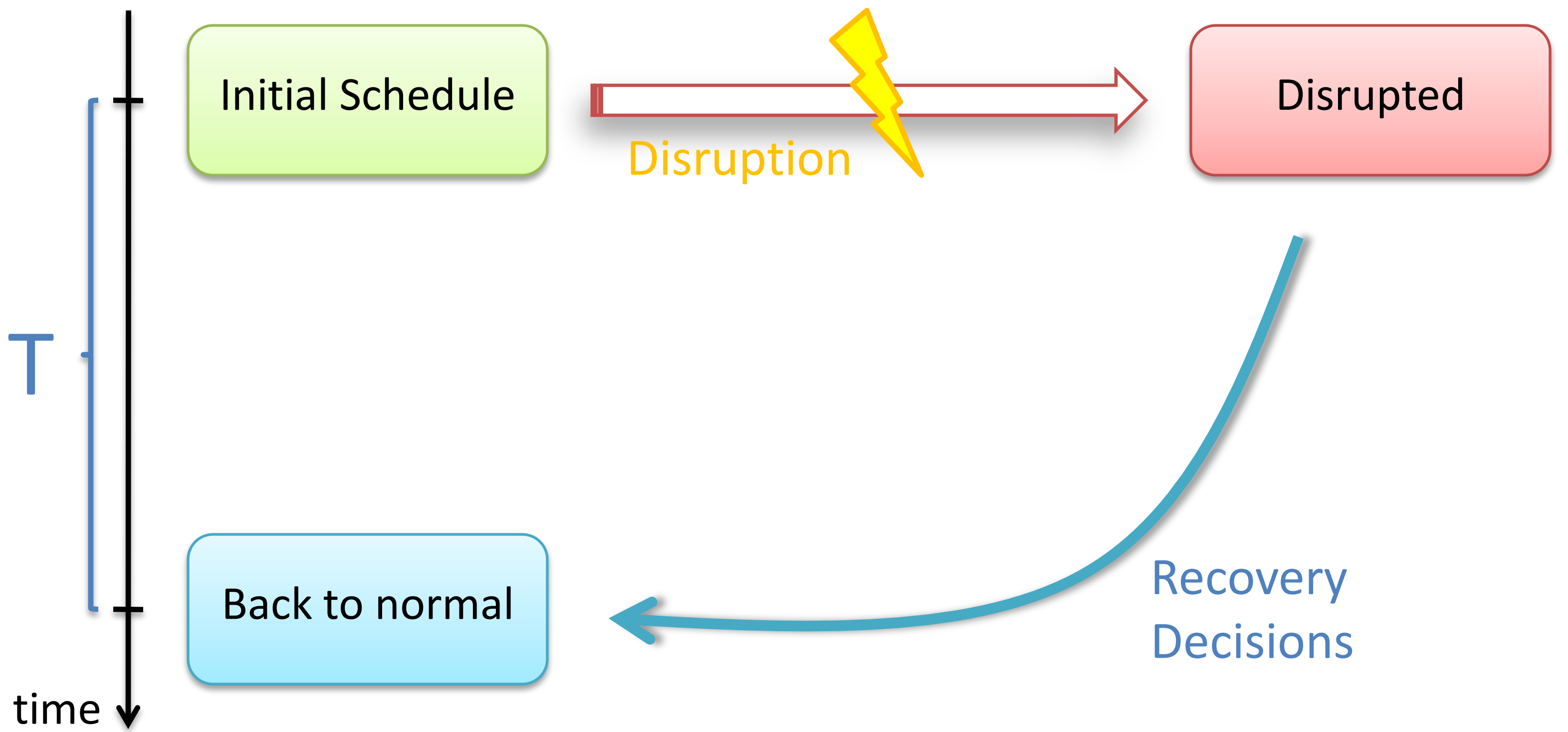
Airline Scheduling Approach

1. Route Choice
2. Fleet Assignment
3. Tail Assignment
4. Crew Pairing
5. Crew Roistering
6. Passenger Routing (catering)

Fleet Assignment and Tail Assignment: Technical Schedule

Disrupted Schedule and Recovery

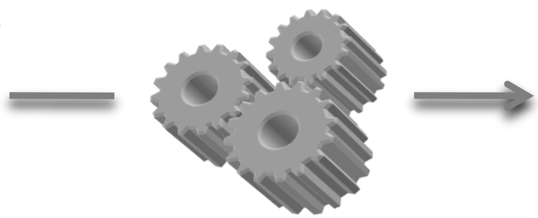


Survey: Kohl (2004)

The Airplane Recovery Problem (ARP)

Input

- Planes' States
- Initial Schedule
- Maintenances
- Cancelation Costs
- Delay Cost



Output

- T
- New schedule up to T
- Recovery cost

Multi-objective optimization:

Minimize both T and recovery costs

Strategy: for fixed T find optimal recovery plan

Give several recovery plans for different values of T (decision aid)

Definitions:

PLANES:

Initial State :	position, initial time, initial resource consumption
Final State:	position, expected time, expected resource consumption
Feasible Flight Set:	coverable flights
Feasible Final State Set:	coverable final states

AIRPORTS:

Activity Slots:	periods when take-off/landings are permitted
Maintenance Slots:	periods when given plane type can perform maintenance

Definitions (2):

Flights:

Origin and Destination

Scheduled Departure Time (SDT)

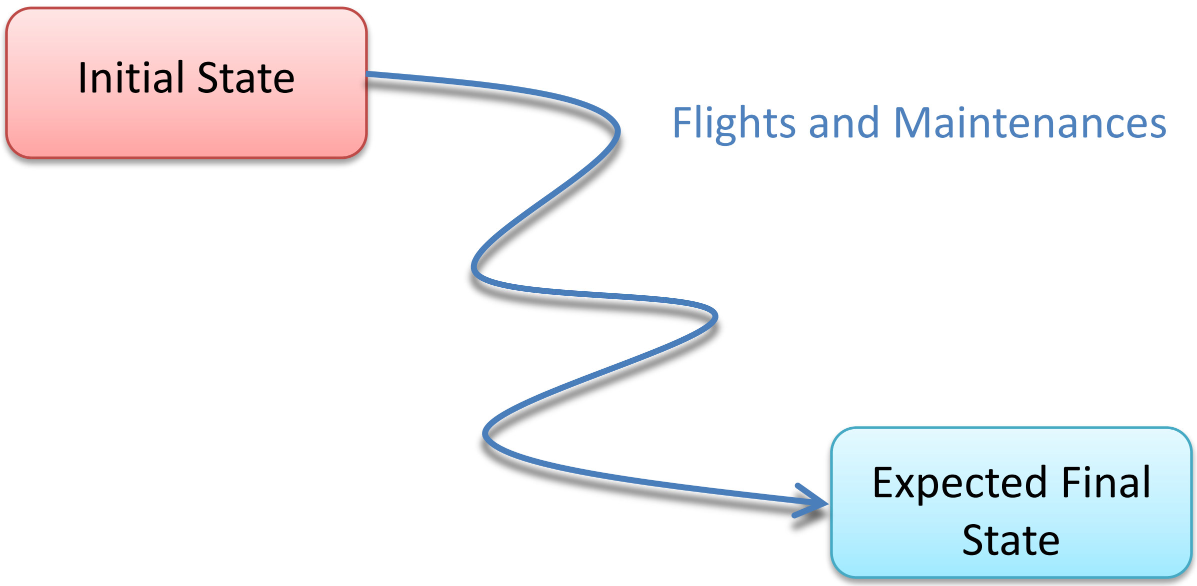
Flight Duration

Flight Cost

Cancelation Cost

Solution to the ARP:

A recovery scheme for each plane:



Example

f_1 GVA to AMS

f_2 AMS to BCN

f_3 BCN to GVA

f_4 MIL to BUD

f_5 BUD to MIL

f_6 BCN to MIL

Example (2)

- flights: $F = \{f_1, f_2, f_3, f_4, f_5, f_6\}$
- final states: $S = \{s^{GVA}, s^{MIL}\}$
- planes: $P = \{p_1, p_2\}$
- initial states: p_1 (*GVA*, 0, 0)

  p_2 (*MIL, 0, 0)*

Feasible Solution

Column Generation Approach

Find out optimal solution by combining individual recovery schemes $r \in R'$ (master problem) on a subset $R' \subseteq R$ of all feasible recovery schemes

Generate potentially improving recovery schemes $r \in R\text{-}R'$ dynamically for each plane (pricing problem)

Master Problem: MIP formulation

$$\min \quad z_{MP} = \sum_{r \in R} c_r x_r + \sum_{f \in F} c_f y_f + \sum_{s \in S} c_s z_s$$

$$s.c. \quad \sum_{r \in R} \boldsymbol{b}_r^f x_r + y_f = 1 \qquad \forall f \in F \quad (\lambda_f)$$

$$\sum_{r \in R} \boldsymbol{b}_r^s x_r + z_s = 1 \qquad \forall s \in S \quad (\eta_s)$$

$$\sum_{r \in R} \boldsymbol{b}_r^p x_r \leq 1 \qquad \forall p \in P \quad (\mu_p)$$

$$x_r \in \{0,1\} \qquad \forall r \in R$$

$$y_f \in \{0,1\} \qquad \forall f \in F$$

$$z_s \in \{0,1\} \qquad \forall s \in S$$

What is a column ?

- cost c_r
- vector $\boldsymbol{b}_r = \left(b_r^f, b_r^s, b_r^p \right)^T$

Where

- b_r^f = 1 if flight *f* is covered by column *r*
- b_r^s = 1 if final state *s* is covered by *r*
- b_r^p = 1 if column *r* is affected to plane *p*

Column examples

$$\boldsymbol{b}_1 = (0,0,0,0,0,0,1,0,1,0)^T$$

$$\boldsymbol{b}_2 = (1,1,1,0,0,0,1,0,1,0)^T$$

$$\boldsymbol{b}_3 = (0,0,0,1,1,0,0,1,0,1)^T$$

The Pricing Problem

Find new columns minimizing the reduced cost $\tilde{c}_r^p$:

$$\min_{r \in R} \ \tilde{c}_r^p = c_r^p - \sum_{f \in F} \boldsymbol{b}_r^f \lambda_f - \sum_{s \in S} \boldsymbol{b}_r^s \eta_s - \boldsymbol{b}_r^p \mu_p \qquad \forall\, p \in P$$

Recovery Networks (Argüello et al. 97)

1. Generate a recovery network for each plane
2. Update arc costs according to dual variables
3. Solve Resource Constrained Elementary Shortest Path (RCESPP)
4. Add Columns to *R'*
5. Resolve restricted LP until optimality and branch

Time – Space Network with

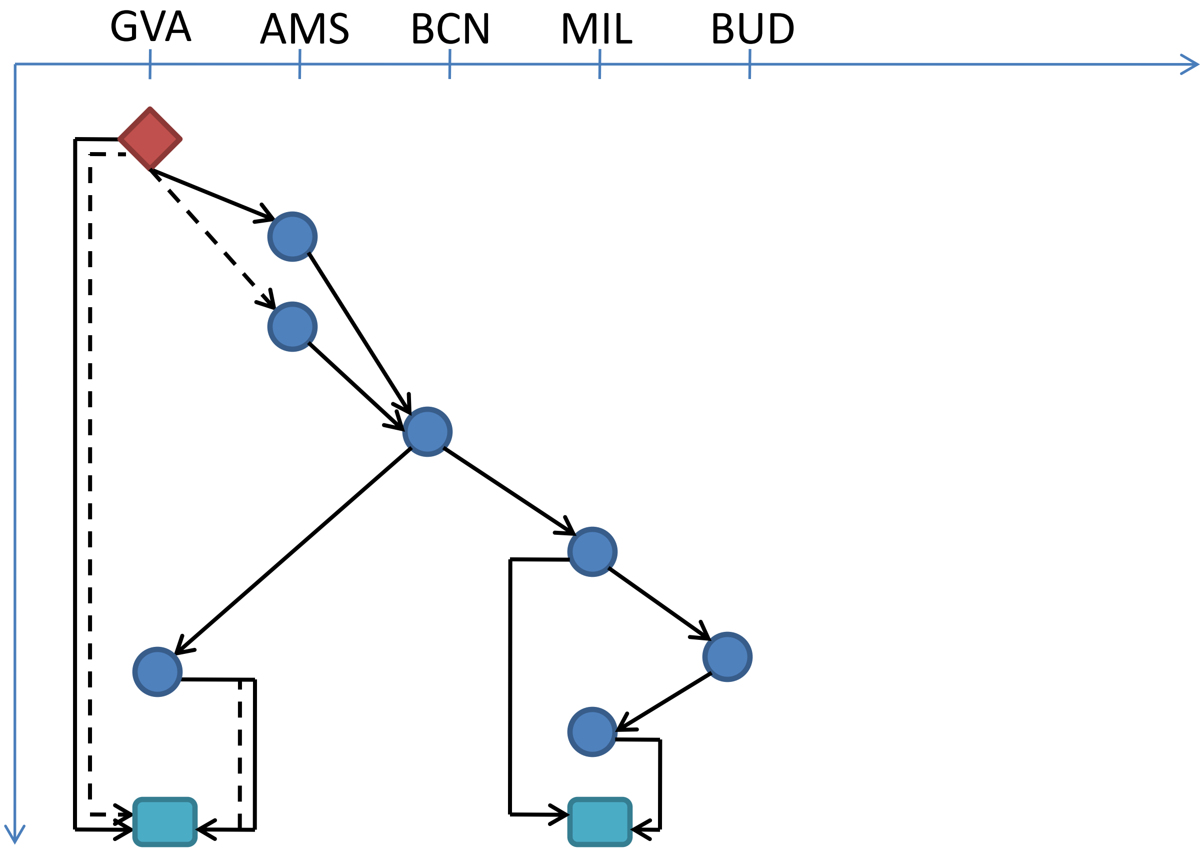
- source node n_0 = [t, m, $\boldsymbol{r}$]
- node n = [t, m, $\boldsymbol{r}$]
- sink s = [t,m,$\boldsymbol{r}$]

- flight arc [n, n']
- maintenance arc [n, n']
- termination arc [n,s]
- maintenance termination arc [n,s]

Example (continued)

- flights: $F = \{f_1, f_2, f_3, f_4, f_5, f_6\}$
- final states: $S = \{s^{GVA}, s^{MIL}\}$
- planes: $P = \{p_1, p_2\}$
- initial states: p_1 (*GVA*, 0, 0)
  p_2 grounded for the day
- only maintenances at GVA

Recovery Network of p_1



Generating Recovery Networks

- Create Source node n_0 (initial time, location, resource cons.)
- $S = \{n_0\}$
- While $S \neq \emptyset$:
  - Select $n \in S$, $S \leftarrow S - \{n\}$
  - For all feasible flights:
    - create flight and maintenance arcs
    - create destinations node n_f and n_m
    - $S = S \cup \{n_f, n_m\}$
- Clean network

Updating arc costs

- flight arcs: $c = c^f + c^d - \lambda_f$
- maintenance arcs: $c = c^f + c^d + c^M - \lambda_f$
- termination arcs: $c = -\eta_s$
- maintenance term. arcs : $c = -\eta_s + c^M$

Solve RCESPP on networks returns column minimizing the reduced cost!

Righini & Salani (2006), which is an extension of Desrochers et al. (1988)

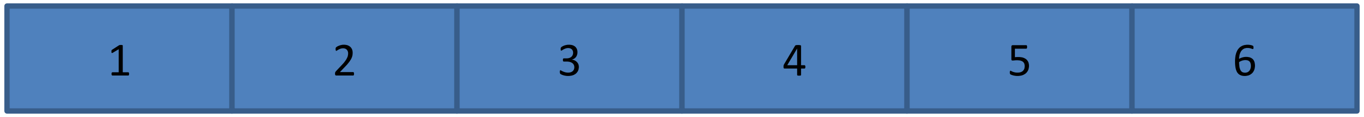
Some References

- Argüello et al. (1997): recovery without maintenance
  up to 27 planes, 162 flights, 30 airports
- Desrosiers et al. (1997): daily scheduling NOT recovery
  up to 91 planes, 383 flights, 33 airports; max delay of 30 minutes
- Clarke (1997): maintenances requirements but no decision on them
  up to 177 planes, 612 flights, 37 airports; only 0 or 30 min delay
- Kohl et al. (2004): Descartes project, good survey of state of the art
  no instance size mentioned for DAR
- Barnhart and Bratu (2006): passenger oriented recovery algorithm
  up to 302 planes, 1032 flights, 74 airports

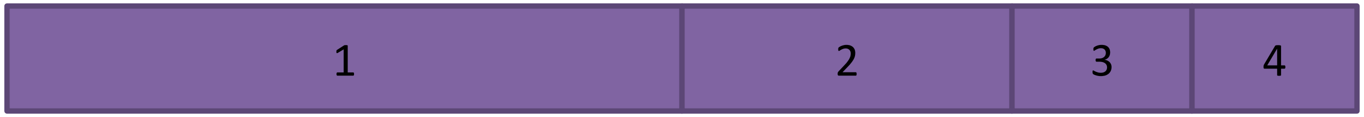
Implementation issues

- Implemented in C++ with COIN-OR BCP framework
- Used interior point methods to solve the LP
- Used linear time and logarithmical resource discretisation
- 2 phase pricing:
  - generation (keep also non optimal columns, heuristic pricing)
  - proving optimality (optimal column only, exact pricing)

Linear Time Discretization



Logarithmic Resource Discretization



Real Instances

- Got real schedules from Thomas Cook Airlines (APM's main customer)
- Solved original schedules up to 250 flights (algorithm validation)
- Generated disruption scenarios
  - delayed planes (initial states)
  - grounded planes (initial states)
  - airport closures (activity slots)
  - forced maintenances (initial resource consumption)

Solved Instances (2): Problem Sizes

Instance	2D_5AC	2D_5AC_1del	2D_10AC	2D_10AC_1del	2D_10AC_2del
# planes	5	5	10	10	10
# flights	38	38	75	75	75
# delayed planes	0	1	0	1	2
# cancelled flts	0	2	0	2	2
# delayed flts	0	4	0	4	5
total delay [min]	0	969	0	969	989
max delay [min]	0	370	0	370	370
cost	380(*)	21175(*)	750(*)	21545(*)	21745(*)
tree size	1	1	1	1	1
run time [s]	< 0.1	< 0.1	0.7	0.7	1.0

Instance	3D_10AC	4D_10AC	5D_5AC	5D_10AC	7D_16AC
# planes	10	10	5	10	16
# flights	113	147	93	184	242
# delayed planes	0	0	0	0	0
# cancelled flts	0	0	0	0	0
# delayed flts	0	0	0	0	11
total delay [min]	0	0	0	0	310
max delay [min]	0	0	0	0	45
cost	1130(*)	1470(*)	930(*)	1840(*)	5600
tree size	1	1	1	5	2033
run time [s]	3.0	6.5	1.0	29.1	3603

Solved Instances (3): Behavior against disruptions

Instance	Den2del	Den2grd	Den4del	Den4grd	Den2del2grd	Den6del	Den6grd
# delayed planes	2	0	4	0	2	6	0
# grounded planes	0	2	0	4	2	0	6
# affected flights	1	4	3	8	5	5	16
# cancelled flts	0	2	0	8	4	0	16
# delayed flts	1	4	7	2	7	13	2
total delay	10	920	230	380	490	640	380
max delayed flight	10	275	85	200	200	100	200
cost	36100(*)	83200(*)	38300(*)	163800(*)	84900(*)	42400(*)	251800(*)
tree size	1	1	1	1	1	41	1
run time	0.7	0.5	0.6	0.3	0.5	1.6	0.2

Instance	Den3del3grd	Den_3x100	Den_1x300	Den_Storm1	Den_Storm2
# delayed planes	3	0	0	0	0
# grounded planes	3	0	0	0	0
# affected flights	9	11	7	3	6
# cancelled flts	6	0	4	0	0
# delayed flts	12	11	11	6	6
total delay	950	675	2560	350	1550
max delayed flight	200	90	385	140	340
cost	127500(*)	42750(*)	125600(*)	39500(*)	51500(*)
tree size	1	1	35	1	3
run time	0.4	0.3	0.8	0.5	0.5

Average results of 10 randomly generated instances

Instance	No maintenance	Dummy maintenance	Maintenance optimization
# cancelled flts	63.3	5.4	4.8
# delayed flts	4.3	3.1	1.1
# uncovered final states	2.2	0.5	0.3
total delay [min]	508	103.3	36.6
max delay [min]	222.2	35.7	31.6
cost	397214.5	36581.5	33074
optimality gap [%]	0.35	0.28	1.01
tree size	29.2	23	12
run time [s]	20.3	57.9	41.8

Considering maintenances is crucial!!!

Example of instance

Instance	No maintenance	Dummy maintenance	Maintenance optimization
# cancelled flts	57	2	0
# delayed flts	9	2	2
total delay [min]	546	61	79
max delay [min]	191	34	50
cost	339195	13310(*)	5760(*)
tree size	5	1	1
run time [s]	8.8	30.5	47.0

Future Work

- Benchmark solutions against practitioners
- Allow repositioning flights and early departures
- Extend Pricing Solver for acceleration
- Include in APM solutions

Conclusions

- Developed a flexible and fast algorithm
- Solutions are very promising
- Maintenance planning is an added value


THANKS for your attention!
Any Questions?