

Stakeholder Cooperation for Improved Predictability and Lower Cost Remote Services

Joen Dahlberg, Tatiana Polishchuk, Valentin Polishchuk, **Christiane Schmidt**





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 - ➔ In extreme case in Sweden: simultaneous movements at all five airports
 - ➔ Each airport needs separate RTM
- ➔ **Possibilities to perturb flight schedules?** (current flight schedules consider only the single airport, ATCO might have to put a/c on hold anyhow...)

Problem Formulation

- Input: Aircraft movements at each airport from Demand Data Repository (DDR) hosted by EUROCONTROL

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- ➔ Input matrix F:

	04:00												05:00												06:00												
	<i>0</i>	<i>5</i>	<i>10</i>	<i>15</i>	<i>20</i>	<i>25</i>	<i>30</i>	<i>35</i>	<i>40</i>	<i>45</i>	<i>50</i>	<i>55</i>	<i>0</i>	<i>5</i>	<i>10</i>	<i>15</i>	<i>20</i>	<i>25</i>	<i>30</i>	<i>35</i>	<i>40</i>	<i>45</i>	<i>50</i>	<i>55</i>	<i>0</i>	<i>5</i>	<i>10</i>	<i>15</i>	<i>20</i>	<i>25</i>	<i>30</i>	<i>35</i>	<i>40</i>	<i>45</i>	<i>50</i>	<i>55</i>	
AP1	0	0	1	1	0	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0
AP2	0	0	1	0	1	0	0	1	0	1	1	0	1	1	0	1	0	1	0	0	0	1	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0
AP3	0	0	0	0	0	1	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	1	0	0	0	1	0	1	0	1	0	0	0	0	0
AP4	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	1	1	1	0
AP5	0	0	1	1	0	0	0	1	0	0	1	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0

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	0	5	10	15	20	25	30	35	40	45	50	55	0	5	10	15	20	25	30	35	40	45	50	55	0	5	10	15	20	25	30	35	40	45	50	55
AP1	0	0	1	1	0	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0
AP2	0	0	1	0	1	0	0	1	0	1	1	0	1	1	0	1	0	1	0	0	0	1	0	0	0	0	0	0	1	1	0	1	0	0	0	0
AP3	0	0	0	0	0	1	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	1	0	0	0	1	0	1	0	0	0	0	0	0
AP4	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	1	1	1	0
AP5	0	0	1	1	0	0	0	1	0	0	1	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0

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AP1	0	0	1	1	0	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0
AP2	0	0	1	0	1	0	0	1	0	1	1	0	1	1	0	1	0	1	0	0	0	1	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0
AP3	0	0	0	0	0	1	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	1	0	0	0	1	0	1	0	1	0	0	0	0	0
AP4	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	1	1	1	0
AP5	0	0	1	1	0	0	0	1	0	0	1	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0

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AP1	0	0	1	1	0	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0
AP2	0	0	1	0	1	0	0	1	0	1	1	0	1	1	0	1	0	1	0	0	0	1	0	0	0	0	0	0	1	1	0	1	0	0	0	0
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AP4	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	1	1	1	0
AP5	0	0	1	1	0	0	0	1	0	0	1	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0

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AP2	0	0	1	0	1	0	0	1	0	1	1	0	1	1	0	1	0	1	0	0	0	1	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0
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AP4	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	1	1	1	0
AP5	0	0	1	1	0	0	0	1	0	0	1	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0

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AP2	0	0	1	0	1	0	0	1	0	1	1	0	1	1	0	1	0	1	0	0	0	1	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0
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AP5	0	0	1	1	0	0	0	1	0	0	1	0	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0

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AP2	0	0	1	0	1	0	0	1	0	1	1	0	1	1	0	1	0	1	0	0	0	1	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0
AP3	0	0	0	0	0	1	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	1	0	0	0	1	0	1	0	1	0	0	0	0	0
AP4	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	1	1	1	0
AP5	0	0	1	1	0	0	0	1	0	0	1	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0

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AP1	0	0	1	1	0	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0
AP2	0	0	1	0	1	0	0	1	0	1	1	0	1	1	0	1	0	1	0	0	0	1	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0
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AP4	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	1	1	1	0
AP5	0	0	1	1	0	0	0	1	0	0	1	0	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0

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Conflict count	AP1	AP2	AP3	AP4	AP5
AP1		1058	621	366	339
AP2	1058		6473	3400	3021
AP3	621	6473		2603	2517
AP4	366	3400	2603		1449
AP5	339	3021	2517	1449	

Conflict days	AP1	AP2	AP3	AP4	AP5
AP1		341	316	278	285
AP2	341		366	363	365
AP3	316	366		362	362
AP4	278	363	362		359
AP5	285	365	362	359	

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 - ❖ Maximum slot shift Δ (in minutes; multiple of 5, as we shift only by whole slots)
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- MAP = maximum number of airports per module

Formal problem definition:

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Flights Rescheduling and Airport-to-Module Assignment (FRAMA)

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- Maximum total number of allowable shifts, S

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- Maximum allowable shift of a flight
- Maximum total number of allowable shifts, S
- Maximum number of airports per RTM, MAP

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Given:

- Flight slots in a set of airports (the matrix F)
- Maximum allowable shift of a flight
- Maximum total number of allowable shifts, S
- Maximum number of airports per RTM, MAP
- Total number of modules, M

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Flights Rescheduling and Airport-to-Module Assignment (FRAMA)

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- Flight slots in a set of airports (the matrix F)
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- Maximum total number of allowable shifts, S
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Find: New slots for the flights and an assignment of airports to RTMs such that

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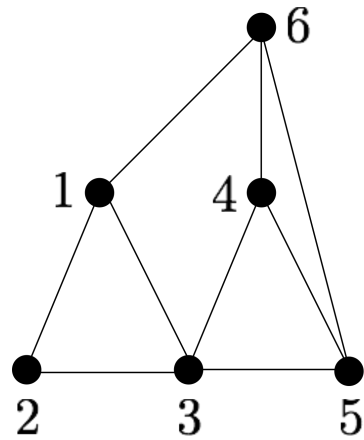
For us: Minimize number M of used RTMs, while respecting the bounds Δ , S , MAP

Problem Complexity

Theorem: FRAMA is NP-complete, even if $\Delta = 0$ and $\text{MAP} = 3$.

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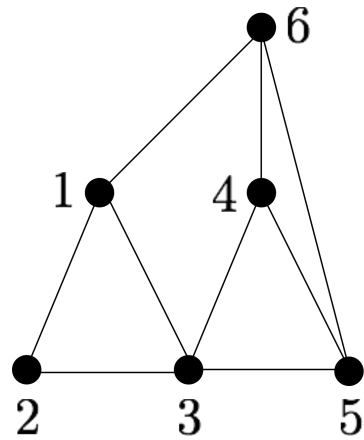
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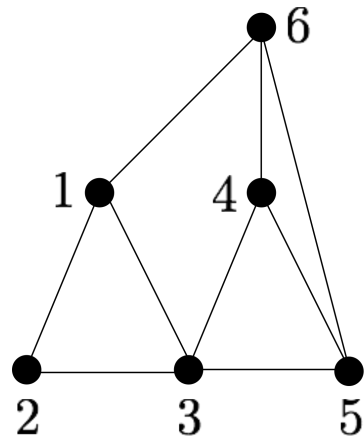
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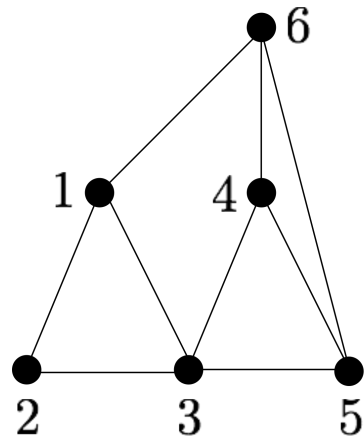


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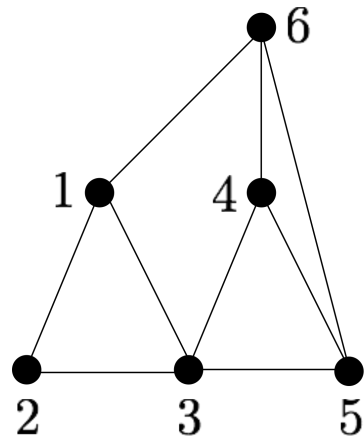
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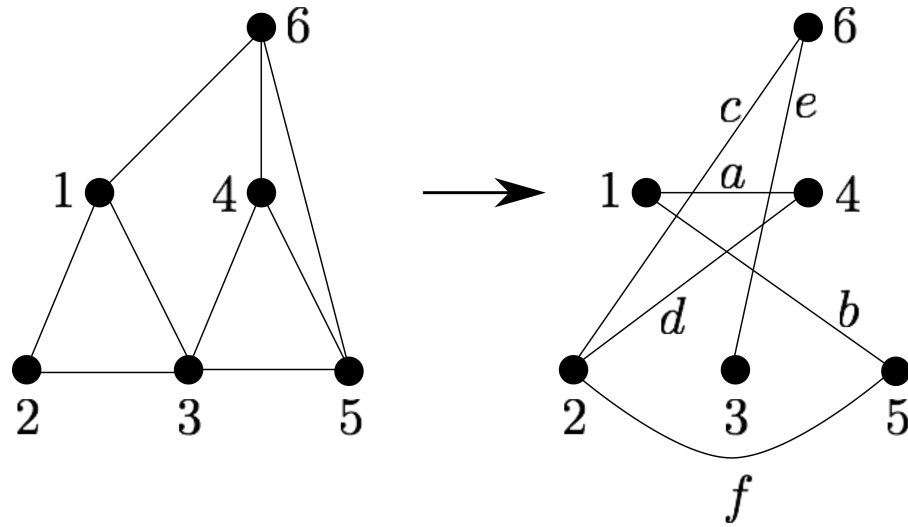
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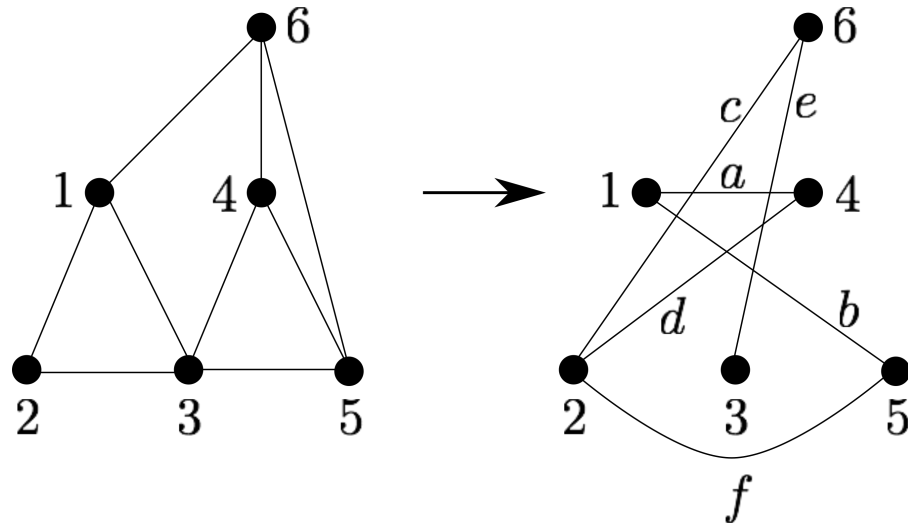
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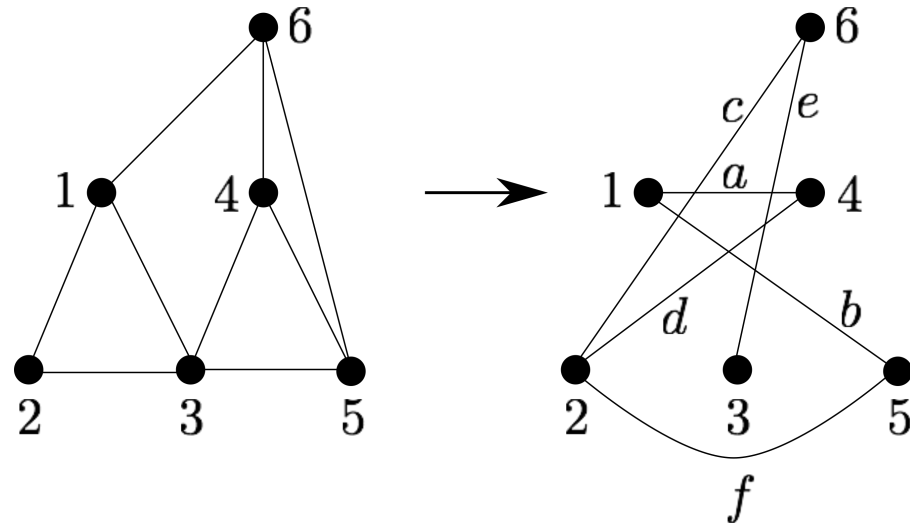
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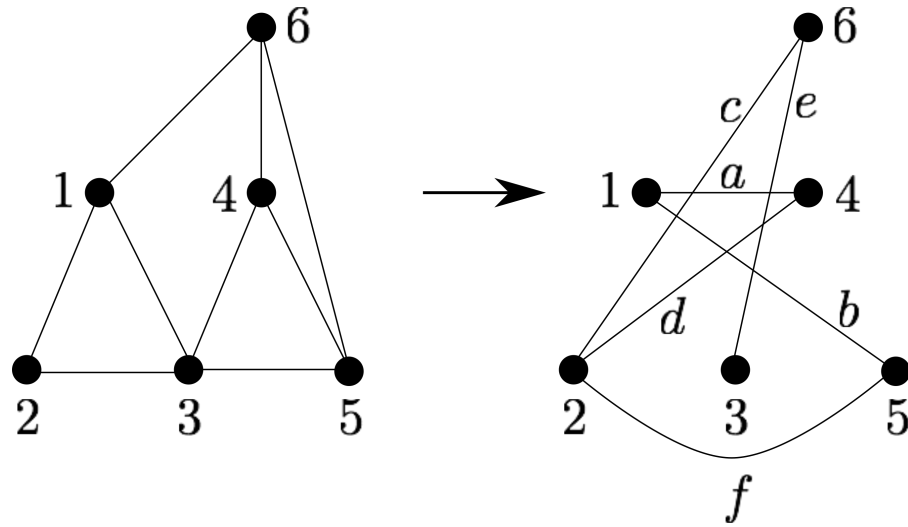
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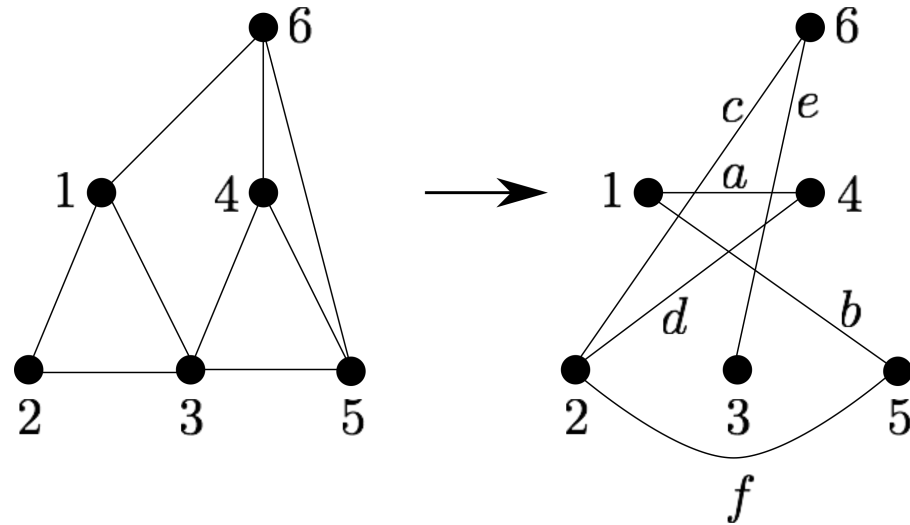
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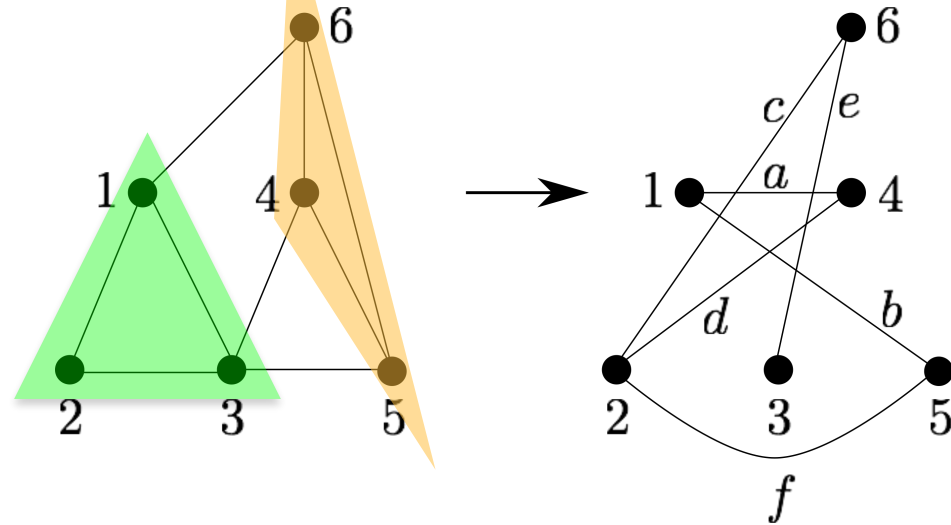
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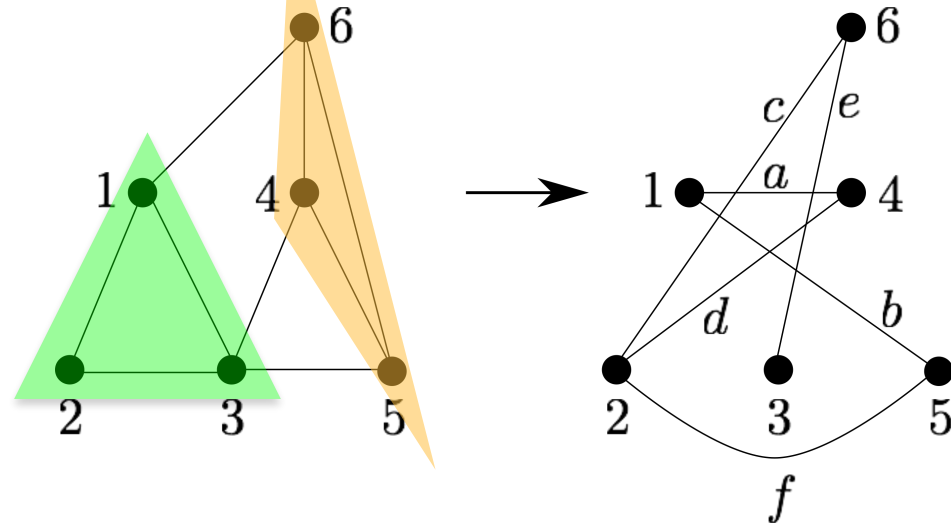
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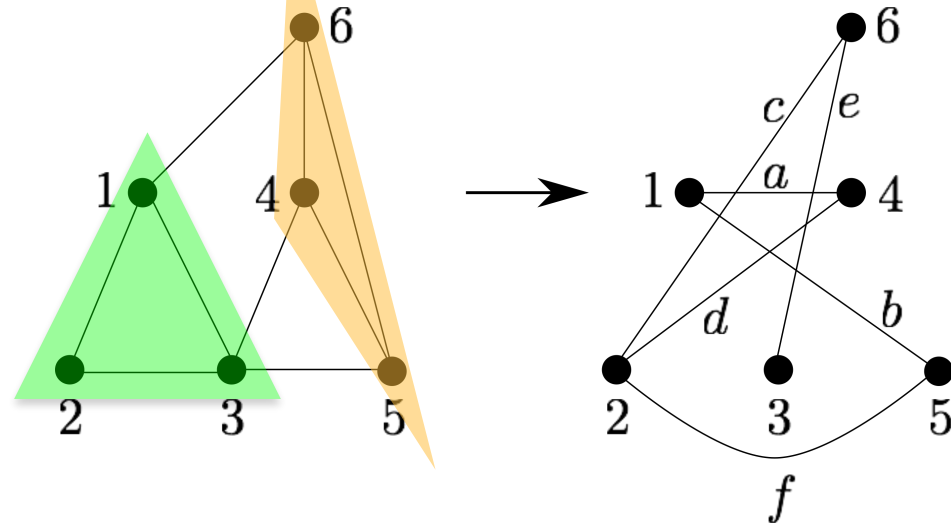
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Solution to FRAMA with $\Delta=0$ (and, thus, $S=0$) and $\text{MAP}=3$ can be verified in polytime.

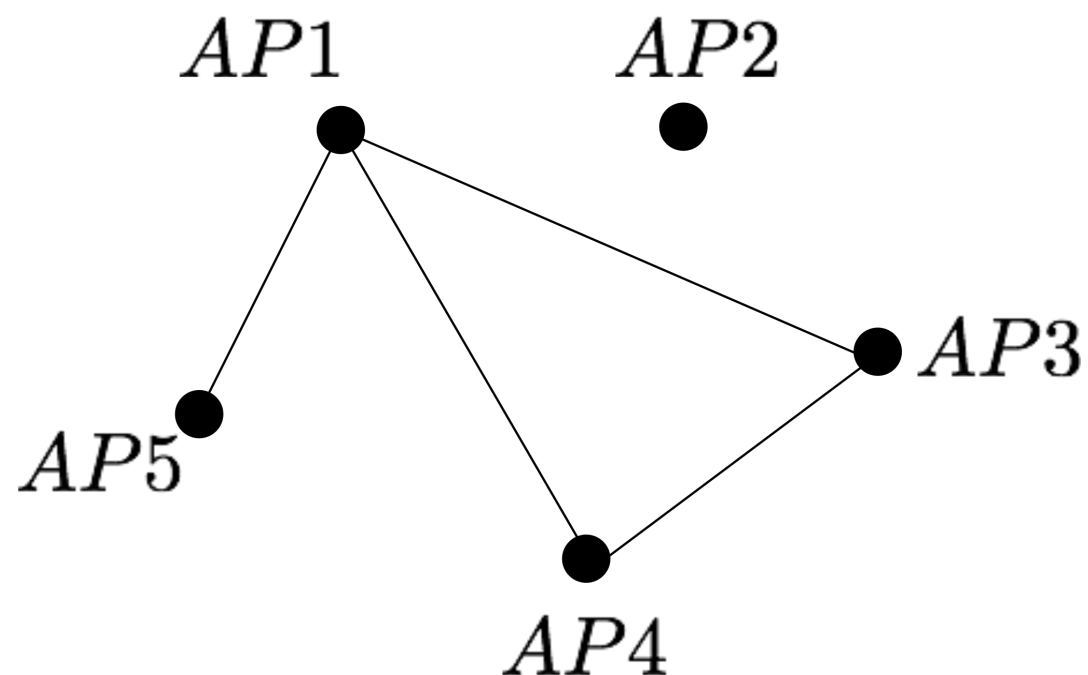
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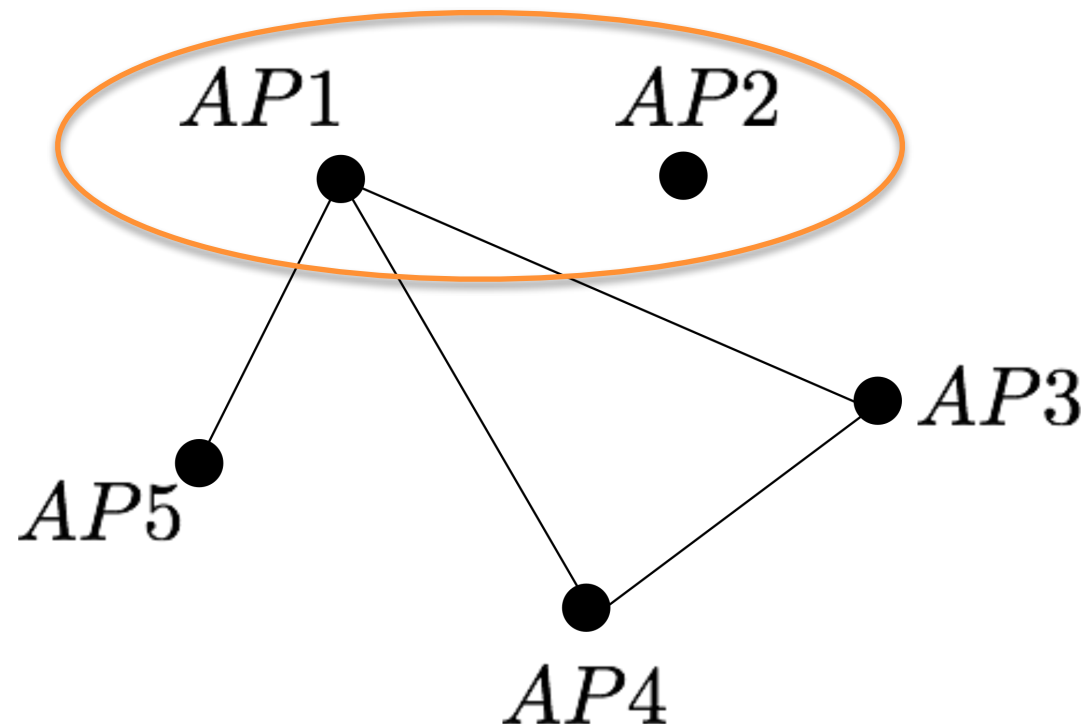
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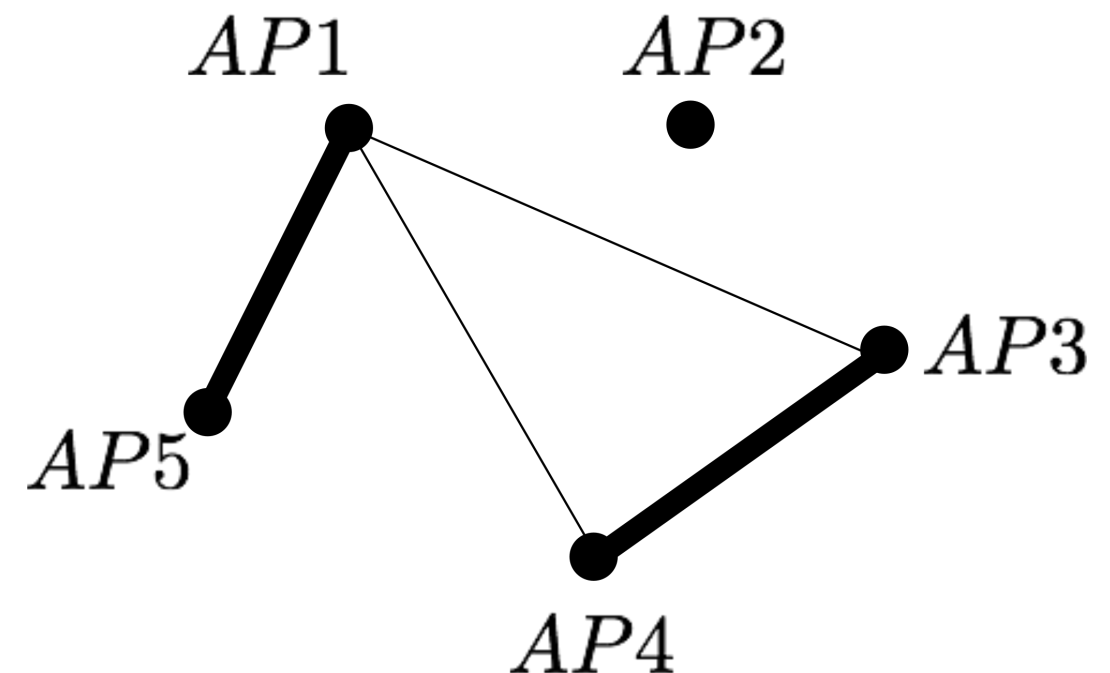
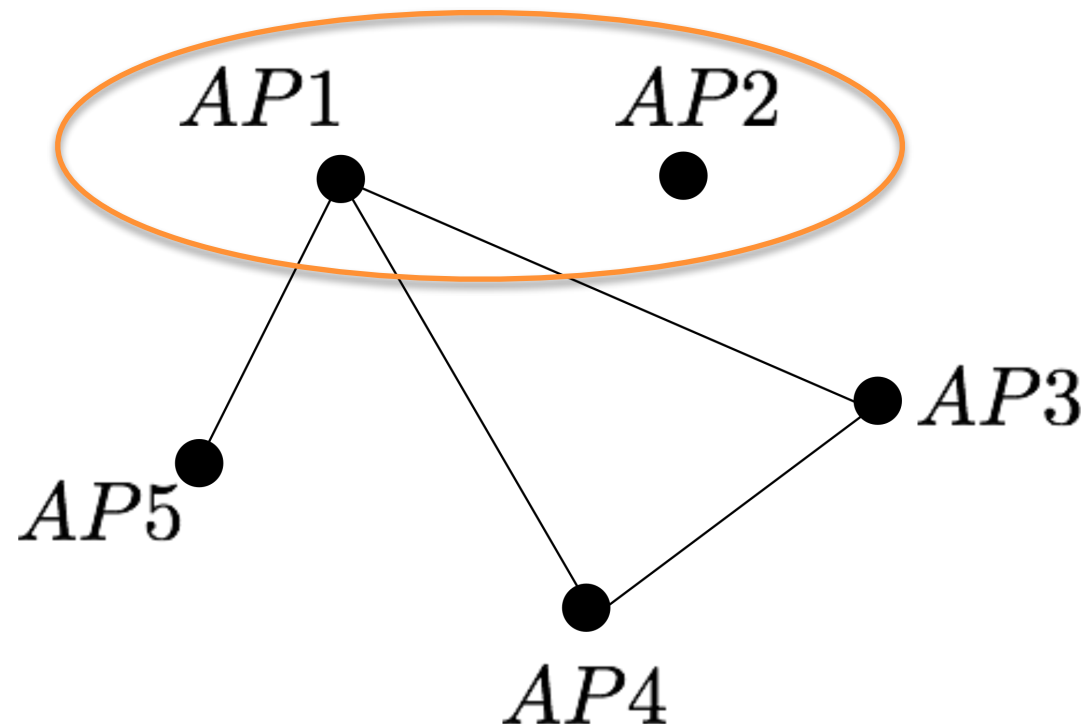
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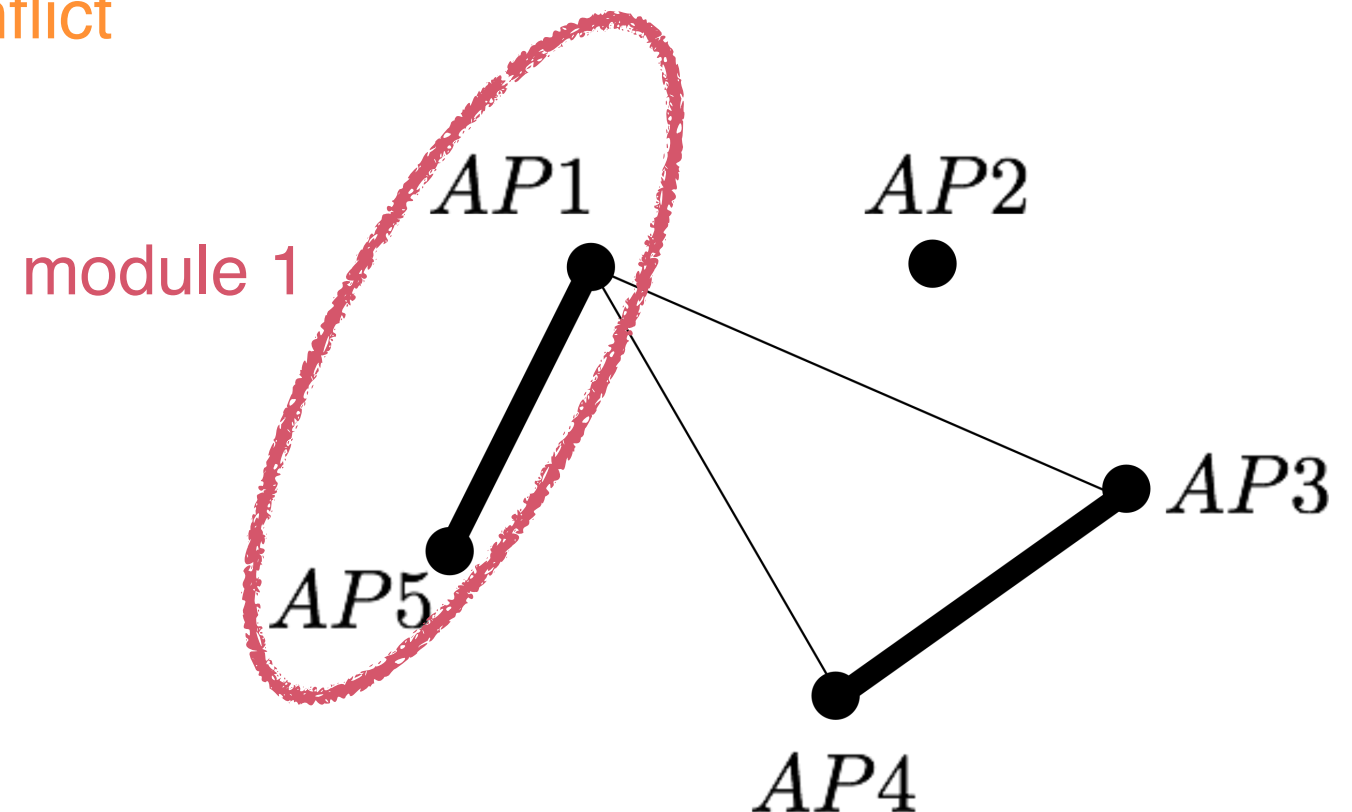
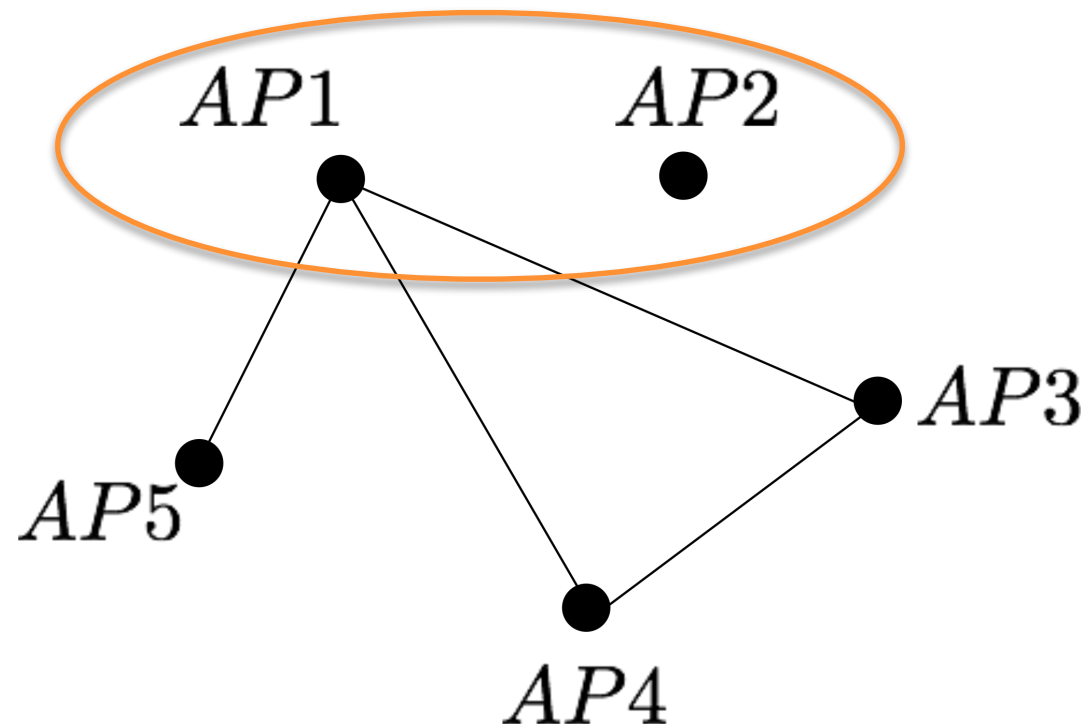
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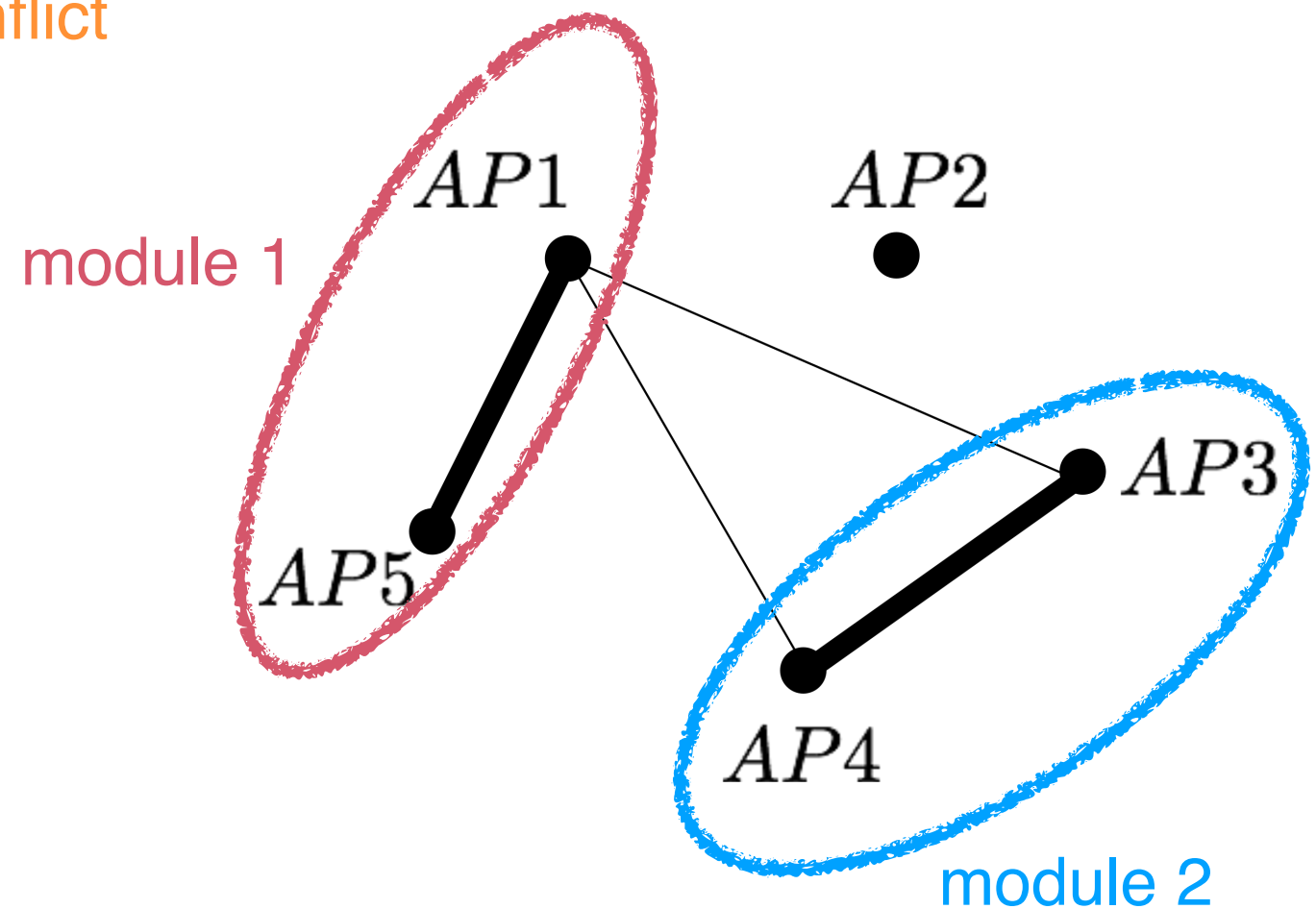
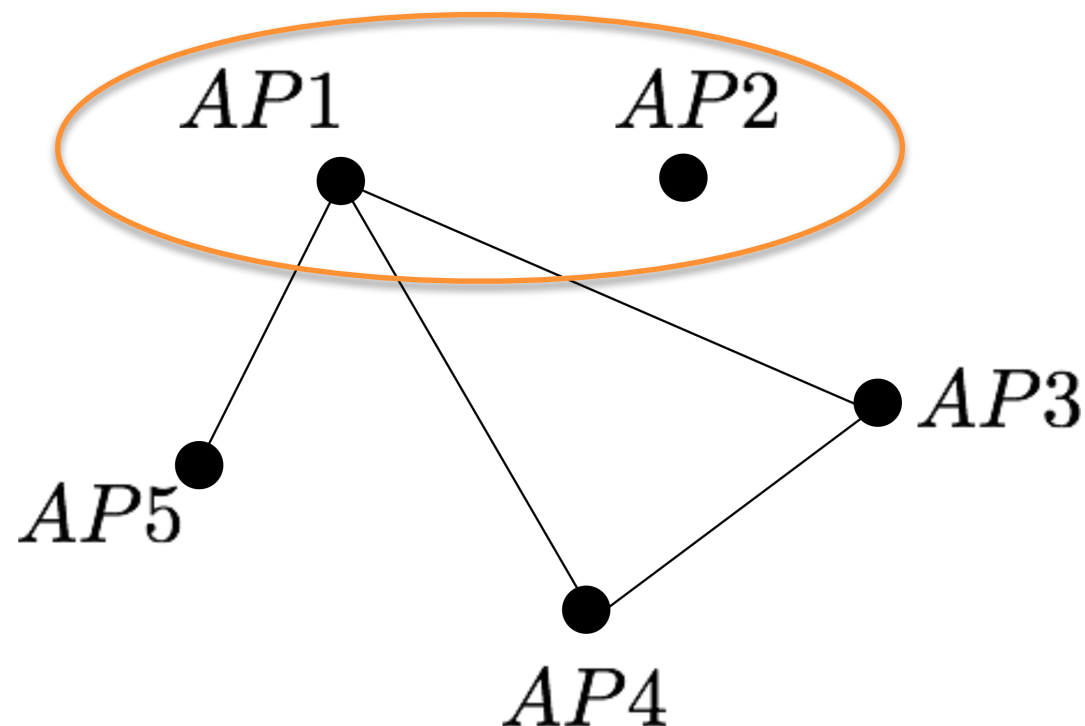
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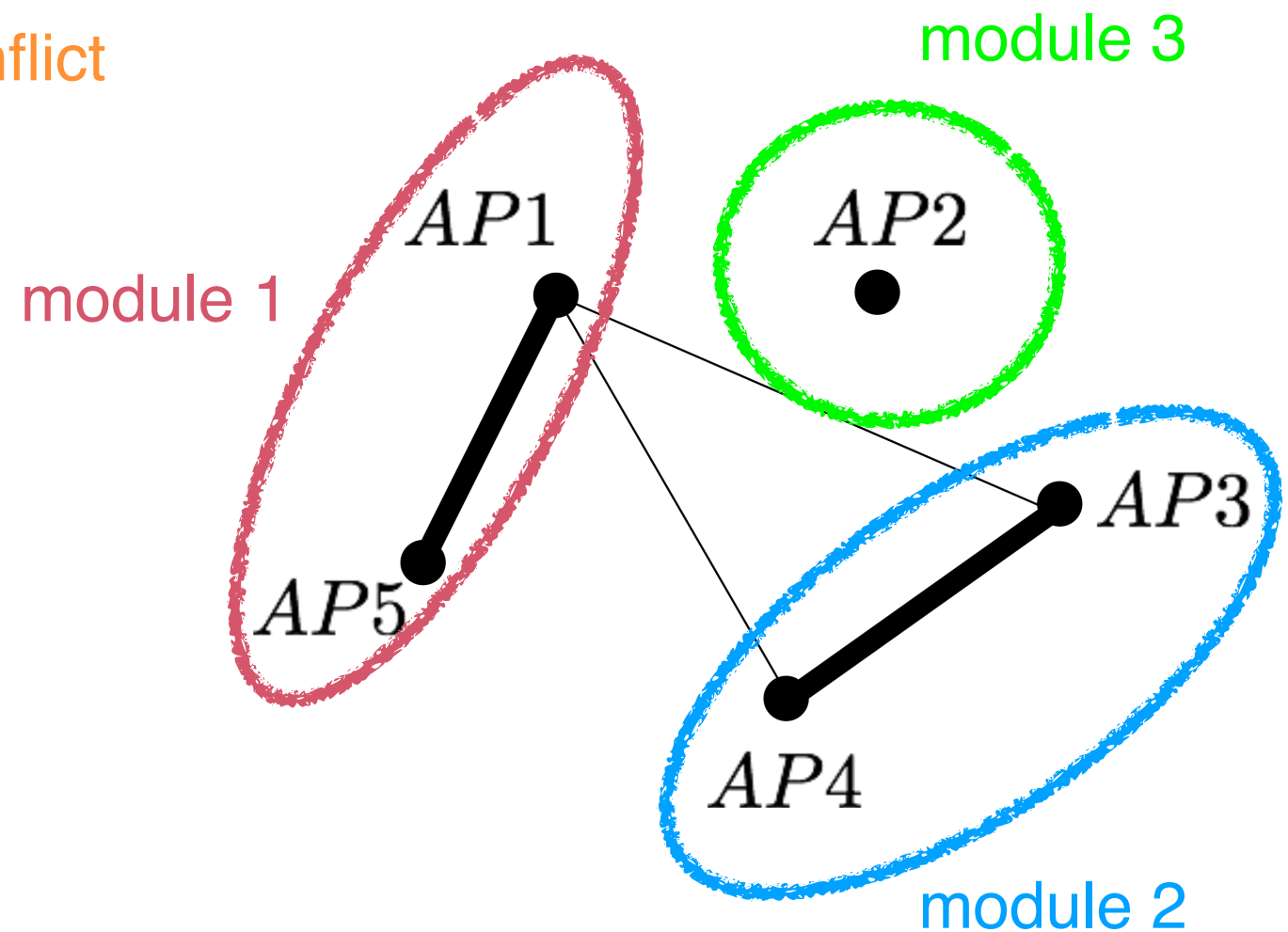
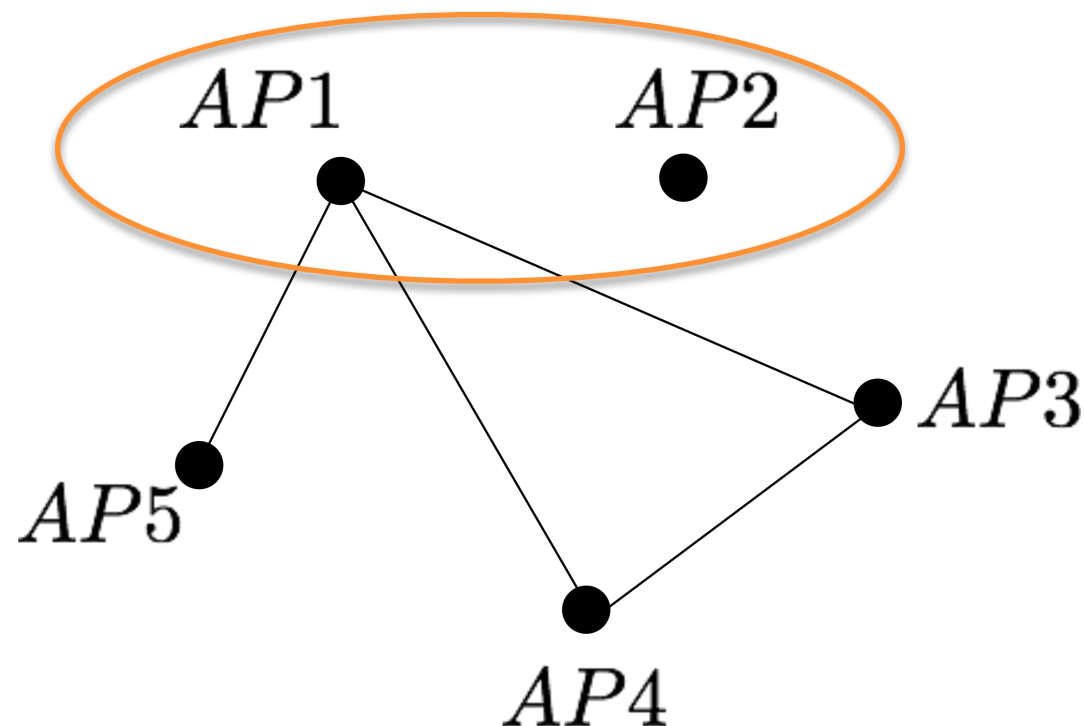
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➔ How to deconflict flight schedule?

We can reduce deconfliction problem to matching:

Complexity for $\Delta > 0$ and MAP=2 unknown.

Possible heuristic:

- First remove all conflicts
- Then assign airports to RTMs

➔ Solve rescheduling and assignment problem separately

Assignment problem is trivial in the absence of conflicts (the airports are arbitrarily packed into the RTMs, with MAP airports per module)

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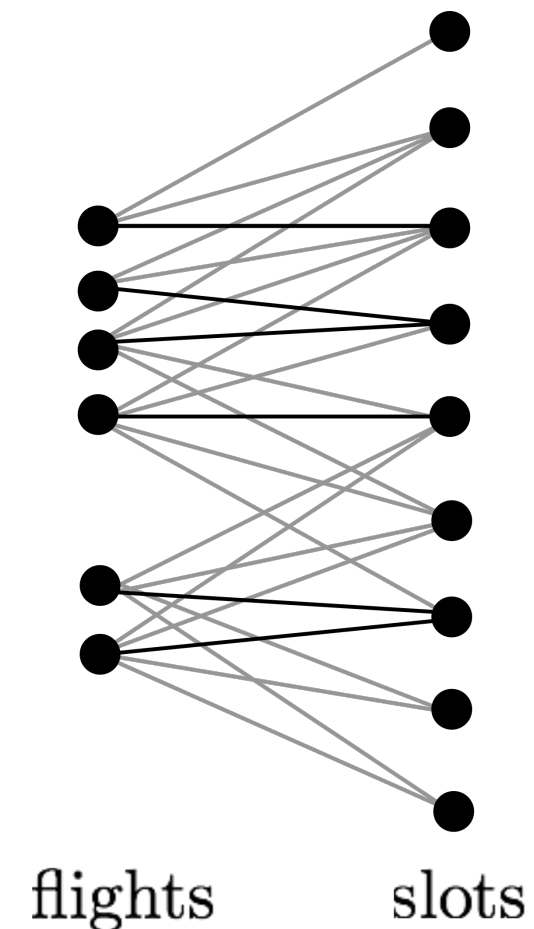
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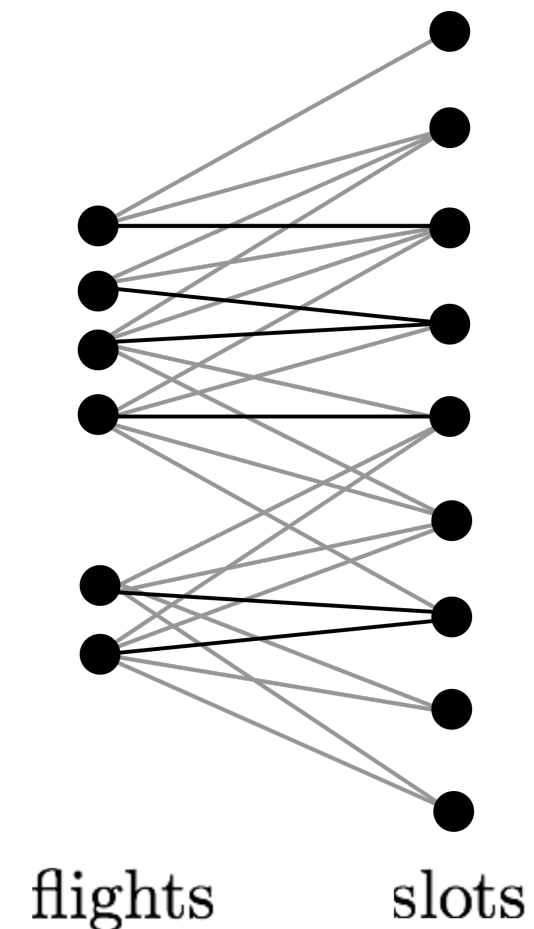
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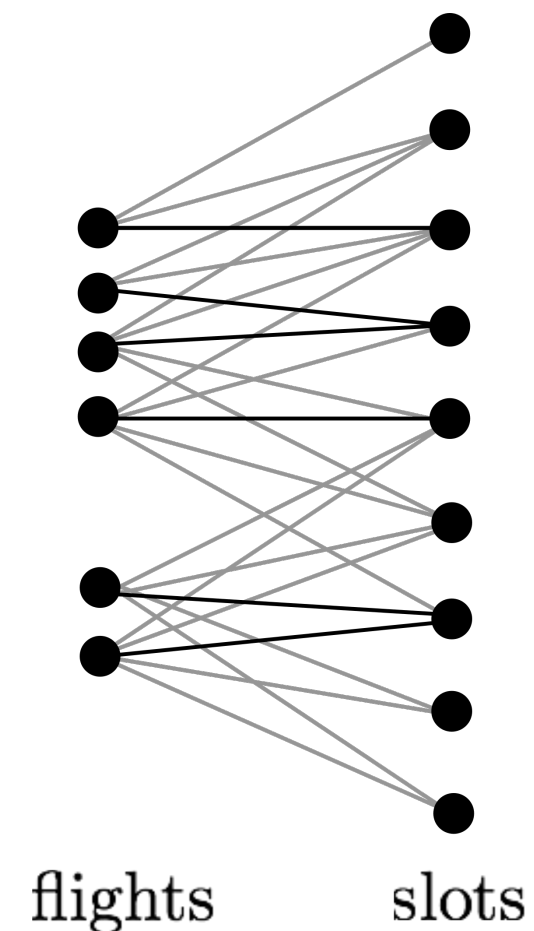
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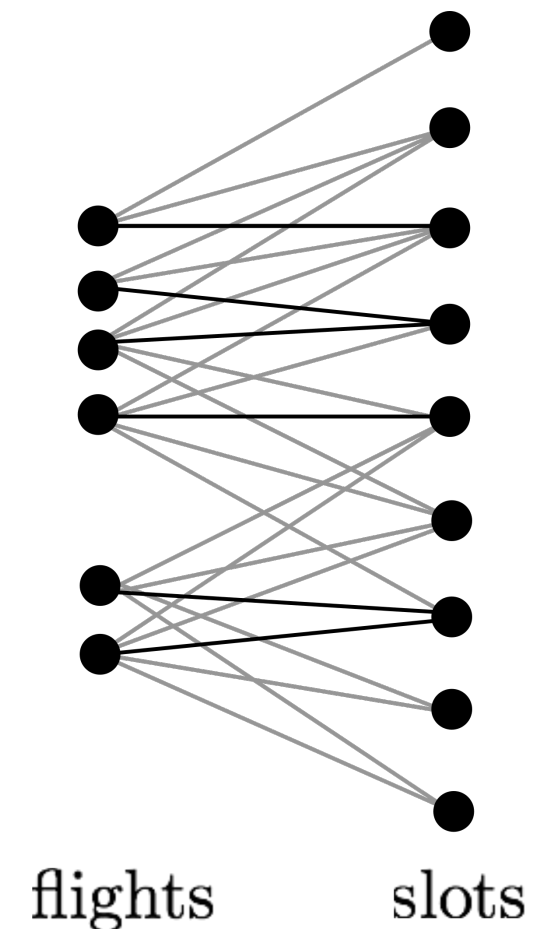
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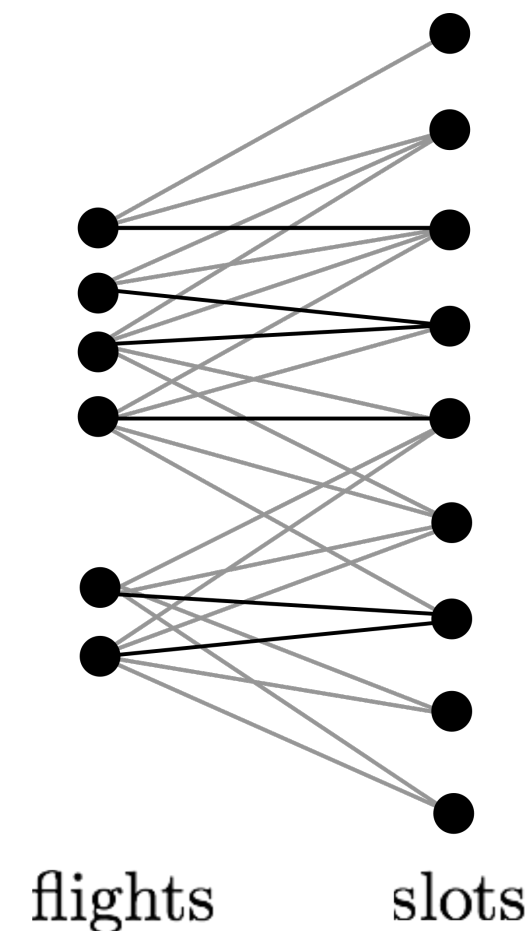
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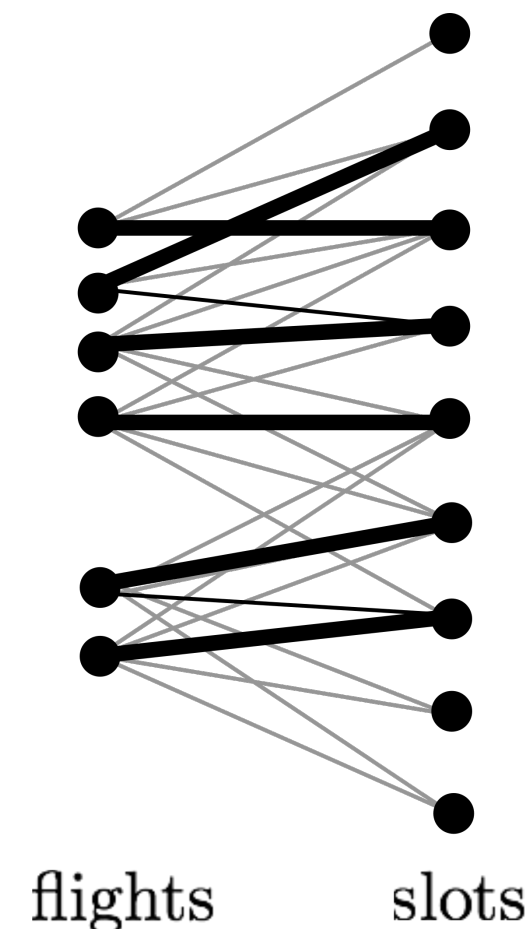
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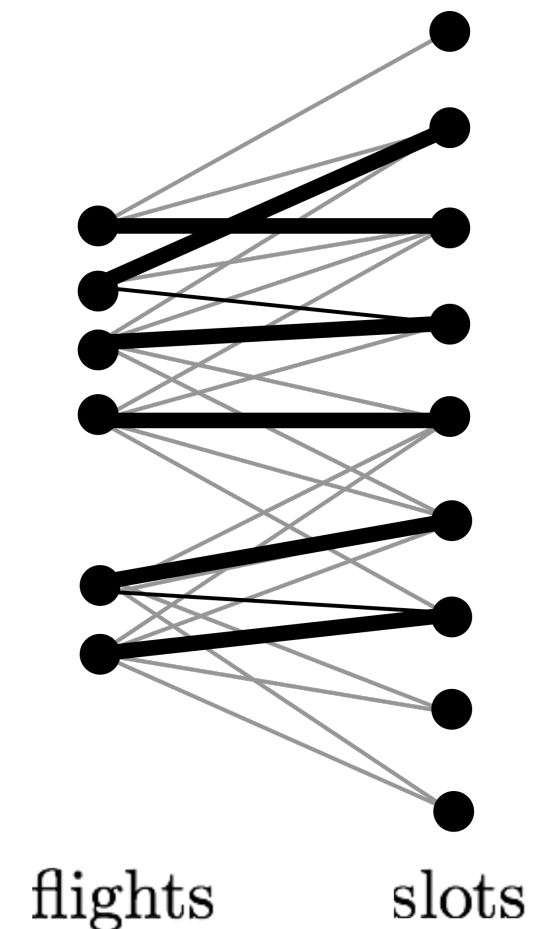
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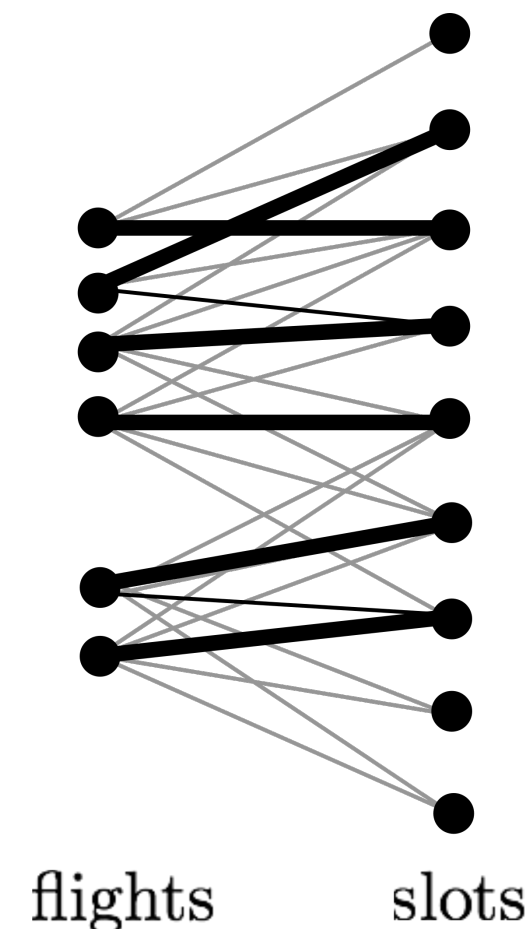
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Runs in polynomial time, but may find suboptimal solutions to FRAMA (not necessary to remove all the conflicts)



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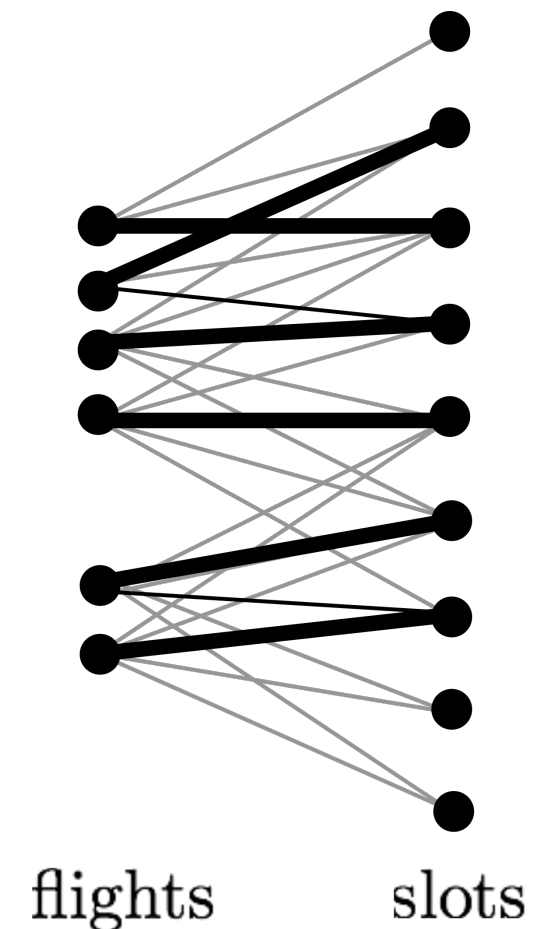
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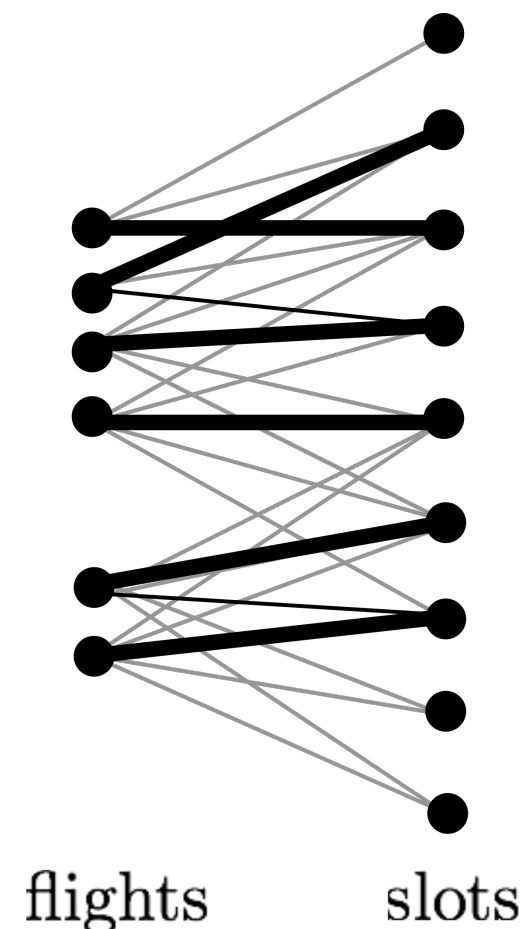
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For a small number of airports: enumerate all pairs of airports

completely eliminate all conflicts for the given pairs (matching) with a given $\Delta > 0$



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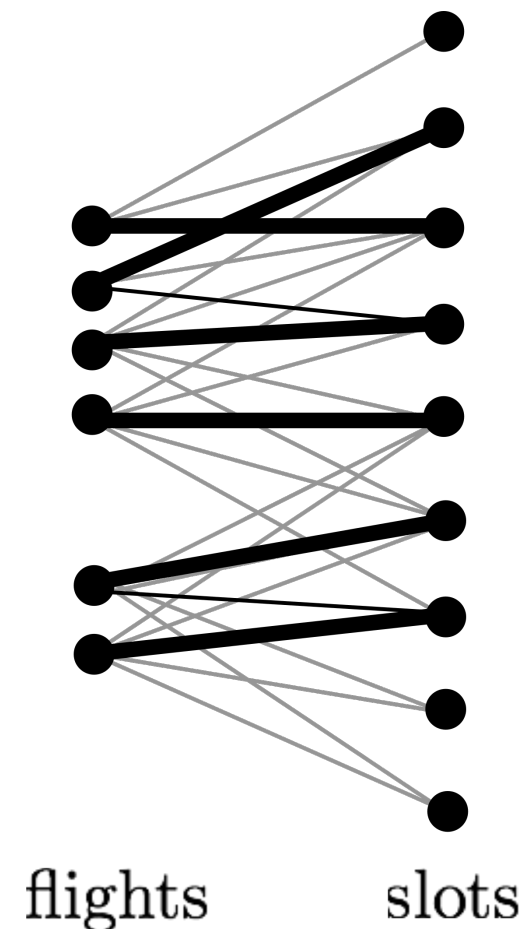
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For a small number of airports: enumerate all pairs of airports

completely eliminate all conflicts for the given pairs (matching) with a given $\Delta > 0$
chose combination with minimum possible number of modules



IP for FRAMA

Decision variables

x_{am} : airport a assigned to module m

z_m : module m is used

y_{atf} : flight f arrives/departs at/from airport a in time slot t

w_{ab} : conflict between airport a and airport b (some t)

A = set of airports

M = set of modules

T = set of time slots

V_a = flights at airport a

p_{atf} = cost to move flight f at airport a to time slot t

s_{af} = scheduled time for flight f at airport a

δ maximum shift distance for scheduled aircraft in terms of time slots: $\delta = \Delta / 5$.

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min # shifts: $p_{atf}=1$ if $t \neq s_{af}$; $p_{atf}=0$ if $t=s_{af}$

min total amount of shifts: $p_{atf}=|t-s_{af}|$

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$$\min c_1 \sum_{m \in M} z_m + c_2 \sum_{a \in A} \sum_{t \in T} \sum_{f \in V_a} p_{atf} y_{atf} \quad (1)$$

$$s.t. \quad x_{am} \leq z_m \quad \forall (a, m) \in A \times M \quad (2)$$

$$\sum_{m \in M} x_{am} = 1 \quad \forall a \in A \quad (3)$$

$$\sum_{f \in V_a} y_{atf} \leq 1 \quad \forall (a, t) \in A \times T \quad (4)$$

$$\sum_{t=\max(1, s_{af}-\delta)}^{\min(|T|, s_{af}+\delta)} y_{atf} = 1 \quad \forall (a, f) \in A \times V_a \quad (5)$$

$$\sum_{f \in V_a} y_{atf} + \sum_{f \in V_b} y_{btf} \leq 1 + w_{ab} \quad \forall (a, b, t) \in A \times A \times T, a < b \quad (6)$$

$$x_{am} + x_{bm} \leq 2 - w_{ab} \quad \forall (a, b, m) \in A \times A \times M, a < b \quad (7)$$

$$\sum_{a \in A} x_{am} \leq \text{MAP} \quad \forall m \in M \quad (8)$$

$$x, y, w, z \quad \text{binary} \quad (9)$$

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(1) $c_1^* \# \text{modules} + c_2^* \text{ sum of shifts}$

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Some airport assigned to module m

(2) $\rightarrow$ module m used

(3)

(4)

(5)

(6)

(7)

(8)

(9)

$$s.t. \quad x_{am} \leq z_m \quad \forall (a, m) \in A \times M$$

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(4)

(5)

(6)

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(8)

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(1) $c_1 * \# \text{modules} + c_2 * \text{sum of shifts}$

Some airport assigned to module m

(2) $\rightarrow$ module m used

(3) Each airport assigned to 1 module

(4) At most 1 flight arrives/departs at airport time slot t

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Experimental Study

Additional airports considered for remote operation in Sweden:

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- **Airport 1 (AP1):** Small airport with low traffic, few scheduled flights per hour, non-regular helicopter traffic, sometimes special testing activities.
- **Airport 2 (AP2):** Low to medium-sized airport, multiple scheduled flights per hour, regular special traffic flights (usually open 24/7, with exceptions).
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One optimization problem for each pair (Δ , MAP)

MAP=5

δ	# of modules	# of shifts $= S$	maximum shift (in mins) $= \Delta$
0	5	0	-
1	2	32	5
2	2	27	10
3	2	26	15
4	2	26	-
5	2	26	-
6	2	26	-
7	1	118	35
8	1	108	40
9	1	99	45
10	1	91	50
11	1	85	55
12	1	83	60
13	1	81	65
14	1	79	70
15	1	78	75
16	1	75	80
17	1	75	85
18	1	75	90
19	1	74	95
20	1	74	100
21	1	73	105

We have $12 \times 24 = 288$ slots for flight movements

➔ with sufficiently large shifts 233 flight movements in single module

MAP=5

δ	# of modules	# of shifts $= S$	maximum shift (in mins) $= \Delta$
0	5	0	-
1	2	32	5
2	2	27	10
3	2	26	15
4	2	26	-
5	2	26	-
6	2	26	-
7	1	118	35
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19	1	74	95
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21	1	73	105

No rescheduling allowed: need 5 RTMs

We have $12 \times 24 = 288$ slots for flight movements

➔ with sufficiently large shifts 233 flight movements in single module

MAP=5

δ	# of modules	# of shifts $= S$	maximum shift (in mins) $= \Delta$
0	5	0	-
1	2	32	5
2	2	27	10
3	2	26	15
4	2	26	-
5	2	26	-
6	2	26	-
7	1	118	35
8	1	108	40
9	1	99	45
10	1	91	50
11	1	85	55
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13	1	81	65
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16	1	75	80
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No rescheduling allowed: need 5 RTMs
Reschedule at most ± 5 minutes: 2 RTMs

We have $12 \times 24 = 288$ slots for flight movements

➔ with sufficiently large shifts 233 flight movements in single module

MAP=5

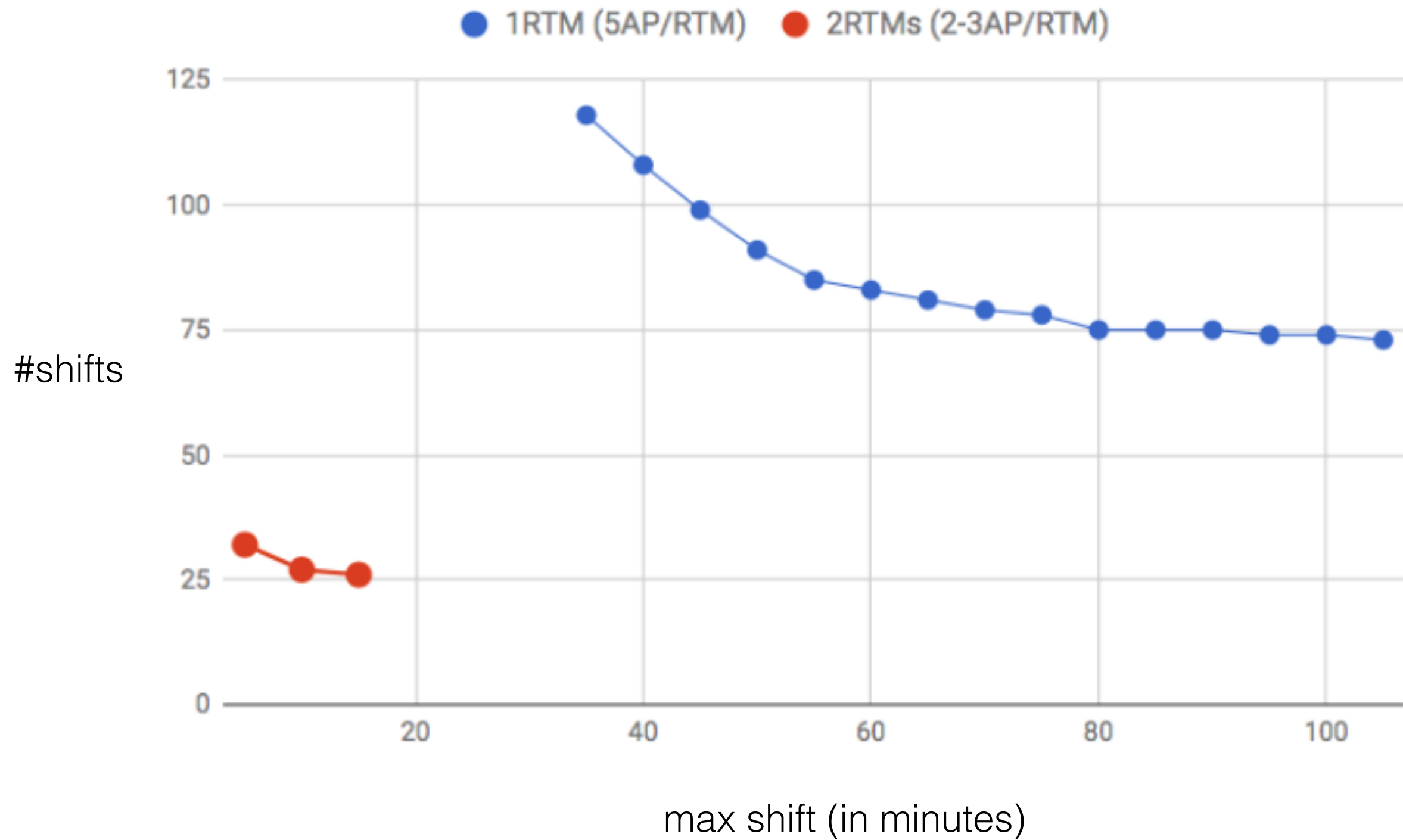
δ	# of modules	# of shifts $= S$	maximum shift (in mins) $= \Delta$
0	5	0	-
1	2	32	5
2	2	27	10
3	2	26	15
4	2	26	-
5	2	26	-
6	2	26	-
7	1	118	35
8	1	108	40
9	1	99	45
10	1	91	50
11	1	85	55
12	1	83	60
13	1	81	65
14	1	79	70
15	1	78	75
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No rescheduling allowed: need 5 RTMs
Reschedule at most ± 5 minutes: 2 RTMs

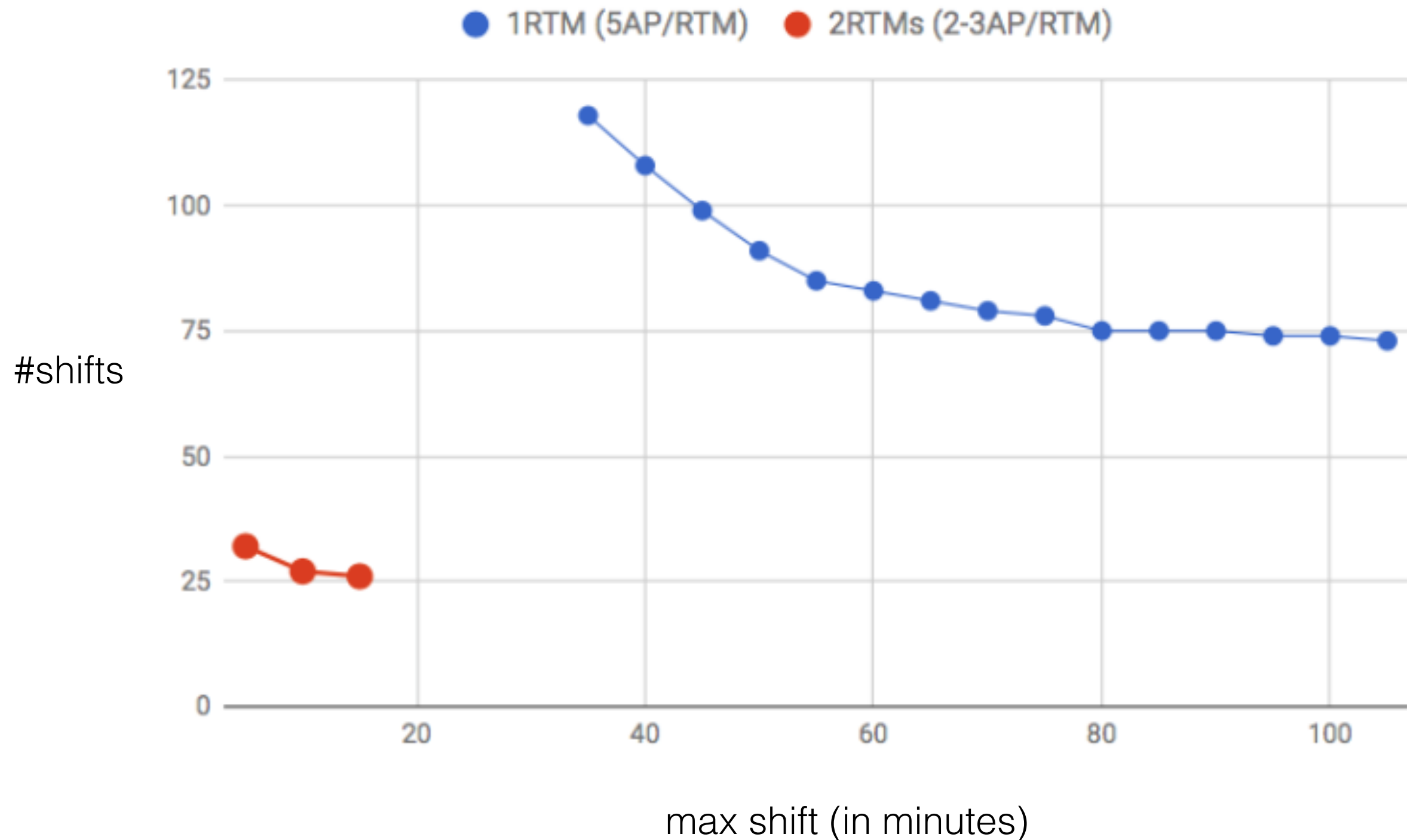
For 1 RTM: we need to reschedule by ± 35 mins

We have $12 \times 24 = 288$ slots for flight movements

➔ with sufficiently large shifts 233 flight movements in single module



Shows tradeoffs: more shifts — larger shifts (more minutes) — more APs/module



MAP=4

δ	M	S
0	5	0
1	2	32
2	2	27
3	2	26

MAP=3

δ	M	S
0	5	0
1	2	32

MAP=2

δ	# of modules	# of shifts
0	5	0
1	3	7

In case of a self-induced conflict: model shifts either of them

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➔ we start with possible more than one flight movement per time slot and airport

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- ➔ $\delta=0$ infeasible by definition

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➔ $\delta=0$ infeasible by definition

MAP=5

δ	M	S
0	infeasible	infeasible
1	infeasible	infeasible
2	2	103
3	2	80
4	2	79
36	2	79
37	1	158
38	1	154

In case of a self-induced conflict: model shifts either of them

➔ we start with possible more than one flight movement per time slot and airport

➔ $\delta=0$ infeasible by definition

MAP=5

δ	M	S
0	infeasible	infeasible
1	infeasible	infeasible
2	2	103
3	2	80
4	2	79
36	2	79
37	1	158
38	1	154

For 233 movs 2 RTMs were enough for $\delta=1$, now $\delta=2$

In case of a self-induced conflict: model shifts either of them

➔ we start with possible more than one flight movement per time slot and airport

➔ $\delta=0$ infeasible by definition

MAP=5

δ	M	S
0	infeasible	infeasible
1	infeasible	infeasible
2	2	103
3	2	80
4	2	79
36	2	79
37	1	158
38	1	154

For 233 movs 2 RTMs were enough for $\delta=1$, now $\delta=2$

For 233 movs 1RTM was enough for $\delta=7$, now $\delta=37$

In case of a self-induced conflict: model shifts either of them

➔ we start with possible more than one flight movement per time slot and airport

➔ $\delta=0$ infeasible by definition

MAP=5

δ	M	S
0	infeasible	infeasible
1	infeasible	infeasible
2	2	103
3	2	80
4	2	79
36	2	79
37	1	158
38	1	154

For 233 movs 2 RTMs were enough for $\delta=1$, now $\delta=2$

For 233 movs 1RTM was enough for $\delta=7$, now $\delta=37$

MAP=4

δ	M	S
0	infeasible	infeasible
1	infeasible	infeasible
2	2	103
3	2	80
4	2	79
288	2	79

In case of a self-induced conflict: model shifts either of them

➔ we start with possible more than one flight movement per time slot and airport

➔ $\delta=0$ infeasible by definition

MAP=5

δ	M	S
0	infeasible	infeasible
1	infeasible	infeasible
2	2	103
3	2	80
4	2	79
36	2	79
37	1	158
38	1	154

For 233 movs 2 RTMs were enough for $\delta=1$, now $\delta=2$

For 233 movs 1RTM was enough for $\delta=7$, now $\delta=37$

MAP=4

δ	M	S
0	infeasible	infeasible
1	infeasible	infeasible
2	2	103
3	2	80
4	2	79
288	2	79

MAP=3

δ	M	S
0	infeasible	infeasible
1	infeasible	infeasible
2	2	103
3	2	80
4	2	79
288	2	79

In case of a self-induced conflict: model shifts either of them

➔ we start with possible more than one flight movement per time slot and airport

➔ $\delta=0$ infeasible by definition

MAP=5

δ	M	S
0	infeasible	infeasible
1	infeasible	infeasible
2	2	103
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4	2	79
36	2	79
37	1	158
38	1	154

For 233 movs 2 RTMs were enough for $\delta=1$, now $\delta=2$

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MAP=4

δ	M	S
0	infeasible	infeasible
1	infeasible	infeasible
2	2	103
3	2	80
4	2	79
288	2	79

MAP=3

δ	M	S
0	infeasible	infeasible
1	infeasible	infeasible
2	2	103
3	2	80
4	2	79
288	2	79

MAP=2

δ	M	S
0	infeasible	infeasible
1	infeasible	infeasible
2	3	61
3	3	61
4	3	60
288	3	60

We solve two optimisation with $c_2 = 0$ and $c_1 = 0$ respectively and fix the $\sum z_k$ to the optimal number of modules used when solving the second optimization problem.

We solve two optimisation with $c_2 = 0$ and $c_1 = 0$ respectively and fix the $\sum z_k$ to the optimal number of modules used when solving the second optimization problem.

MAP=5

δ	# of modules	# of shifts = S	computation time in sec
0	infeasible	-	-
1	infeasible	-	-
2	2	103	1,40
3	2	80	1,26
4	2	79	1,79
36	2	79	7,97
37	1	158	8,42
38	1	154	9,34
39	1	151	40,84
40	1	149	46,61
41	1	147	45,12
42	1	144	38,10
43	1	141	40,20
44	1	139	43,57
45	1	137	9,24
46	1	136	106,31
47	1	135	148,79
48	1	134	100,03
49	1	133	94,08
50	1	132	479,12
51	1	130	433,79
52	1	128	348,83
53	1	126	11,65
288	1	126	46,49

We solve two optimisation with $c_2 = 0$ and $c_1 = 0$ respectively and fix the $\sum z_k$ to the optimal number of modules used when solving the second optimization problem.

MAP=5

δ	# of modules	# of shifts = S	computation time in sec
0	infeasible	-	-
1	infeasible	-	-
2	2	103	1,40
3	2	80	1,26
4	2	79	1,79
36	2	79	7,97
37	1	158	8,42
38	1	154	9,34
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41	1	147	45,12
42	1	144	38,10
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50	1	132	479,12
51	1	130	433,79
52	1	128	348,83
53	1	126	11,65
288	1	126	46,49

MAP=4

δ	# of modules	# of shifts = S	computation time in sec
0	infeasible	-	-
1	infeasible	-	-
2	2	103	1,31
3	2	80	1,06
4	2	79	1,22
288	2	79	60,92

We solve two optimisation with $c_2 = 0$ and $c_1 = 0$ respectively and fix the $\sum z_k$ to the optimal number of modules used when solving the second optimization problem.

MAP=5

δ	# of modules	# of shifts = S	computation time in sec
0	infeasible	-	-
1	infeasible	-	-
2	2	103	1,40
3	2	80	1,26
4	2	79	1,79
36	2	79	7,97
37	1	158	8,42
38	1	154	9,34
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40	1	149	46,61
41	1	147	45,12
42	1	144	38,10
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44	1	139	43,57
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49	1	133	94,08
50	1	132	479,12
51	1	130	433,79
52	1	128	348,83
53	1	126	11,65
288	1	126	46,49

MAP=4

δ	# of modules	# of shifts = S	computation time in sec
0	infeasible	-	-
1	infeasible	-	-
2	2	103	1,31
3	2	80	1,06
4	2	79	1,22
288	2	79	60,92

MAP=3

δ	# of modules	# of shifts = S	computation time in sec
0	infeasible	-	-
1	infeasible	-	-
2	2	103	1,36
3	2	80	1,28
4	2	79	1,09
288	2	79	51,79

We solve two optimisation with $c_2 = 0$ and $c_1 = 0$ respectively and fix the $\sum z_k$ to the optimal number of modules used when solving the second optimization problem.

MAP=5

δ	# of modules	# of shifts = S	computation time in sec
0	infeasible	-	-
1	infeasible	-	-
2	2	103	1,40
3	2	80	1,26
4	2	79	1,79
36	2	79	7,97
37	1	158	8,42
38	1	154	9,34
39	1	151	40,84
40	1	149	46,61
41	1	147	45,12
42	1	144	38,10
43	1	141	40,20
44	1	139	43,57
45	1	137	9,24
46	1	136	106,31
47	1	135	148,79
48	1	134	100,03
49	1	133	94,08
50	1	132	479,12
51	1	130	433,79
52	1	128	348,83
53	1	126	11,65
288	1	126	46,49

MAP=4

δ	# of modules	# of shifts = S	computation time in sec
0	infeasible	-	-
1	infeasible	-	-
2	2	103	1,31
3	2	80	1,06
4	2	79	1,22
288	2	79	60,92

MAP=3

δ	# of modules	# of shifts = S	computation time in sec
0	infeasible	-	-
1	infeasible	-	-
2	2	103	1,36
3	2	80	1,28
4	2	79	1,09
288	2	79	51,79

MAP=2

δ	# of modules	# of shifts = S	computation time in sec
0	infeasible	-	-
1	infeasible	-	-
2	3	61	0,55
3	3	61	1,09
4	3	60	0,98
288	3	60	100,30

Duplicate each of the original flight movements

Duplicate each of the original flight movements
Shift randomly by plus/minus one hour

Duplicate each of the original flight movements
Shift randomly by plus/minus one hour
Shift again, randomly, by plus/minus 15 minutes

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If two flight movements end up in the same slot, one of the movements is deleted

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“2x” data created from all data of the year 2016

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“2x” data created from all data of the year 2016

➡ shifted duplicates of flights from October 18, 2016 and October 20, 2016 may now happen on October 19, 2016

Duplicate each of the original flight movements

Shift randomly by plus/minus one hour

Shift again, randomly, by plus/minus 15 minutes

If two flight movements end up in the same slot, one of the movements is deleted

“2x” data created from all data of the year 2016

- ➡ shifted duplicates of flights from October 18, 2016 and October 20, 2016 may now happen on October 19, 2016
- ➡ Not exactly twice the number of movements

Duplicate each of the original flight movements

Shift randomly by plus/minus one hour

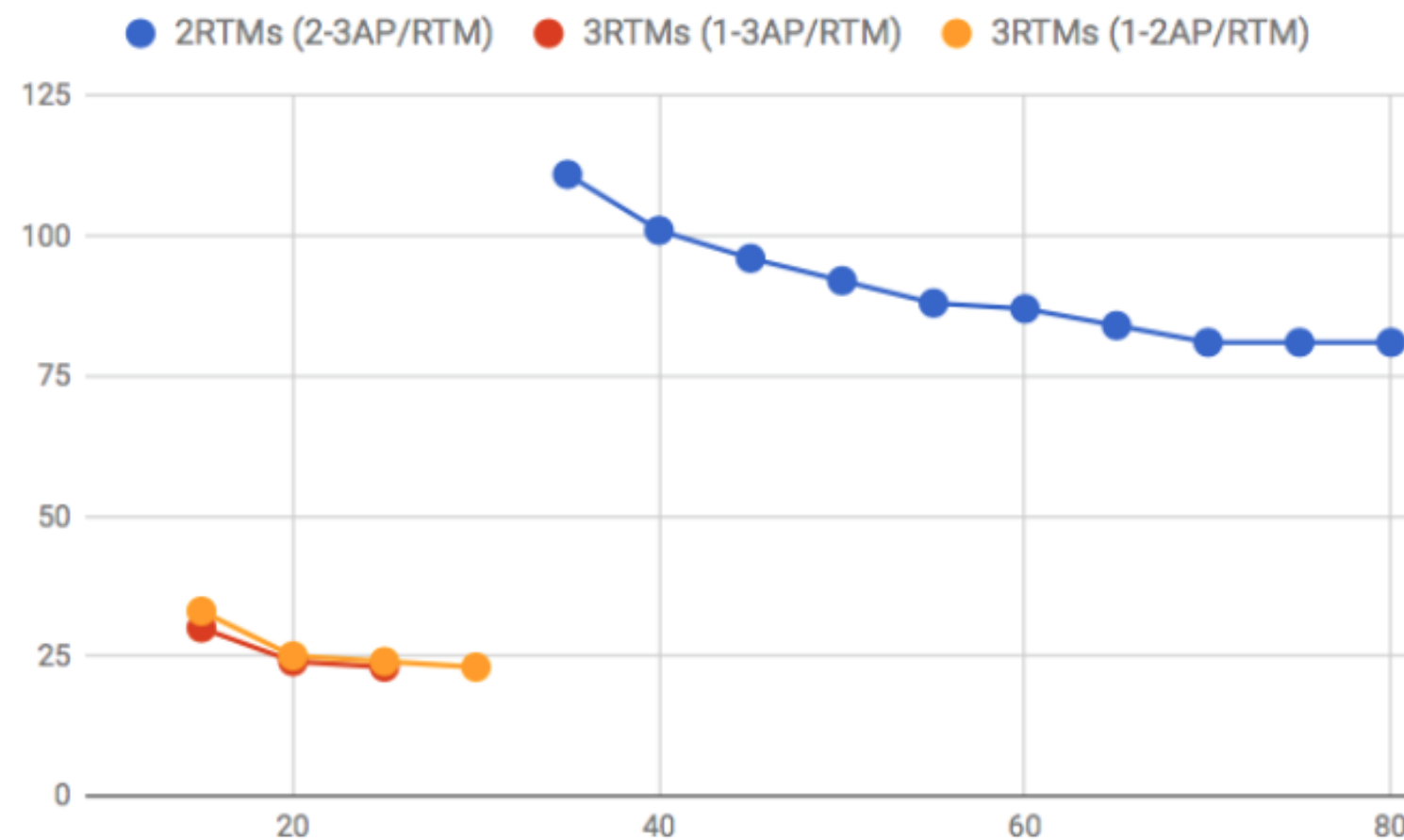
Shift again, randomly, by plus/minus 15 minutes

If two flight movements end up in the same slot, one of the movements is deleted

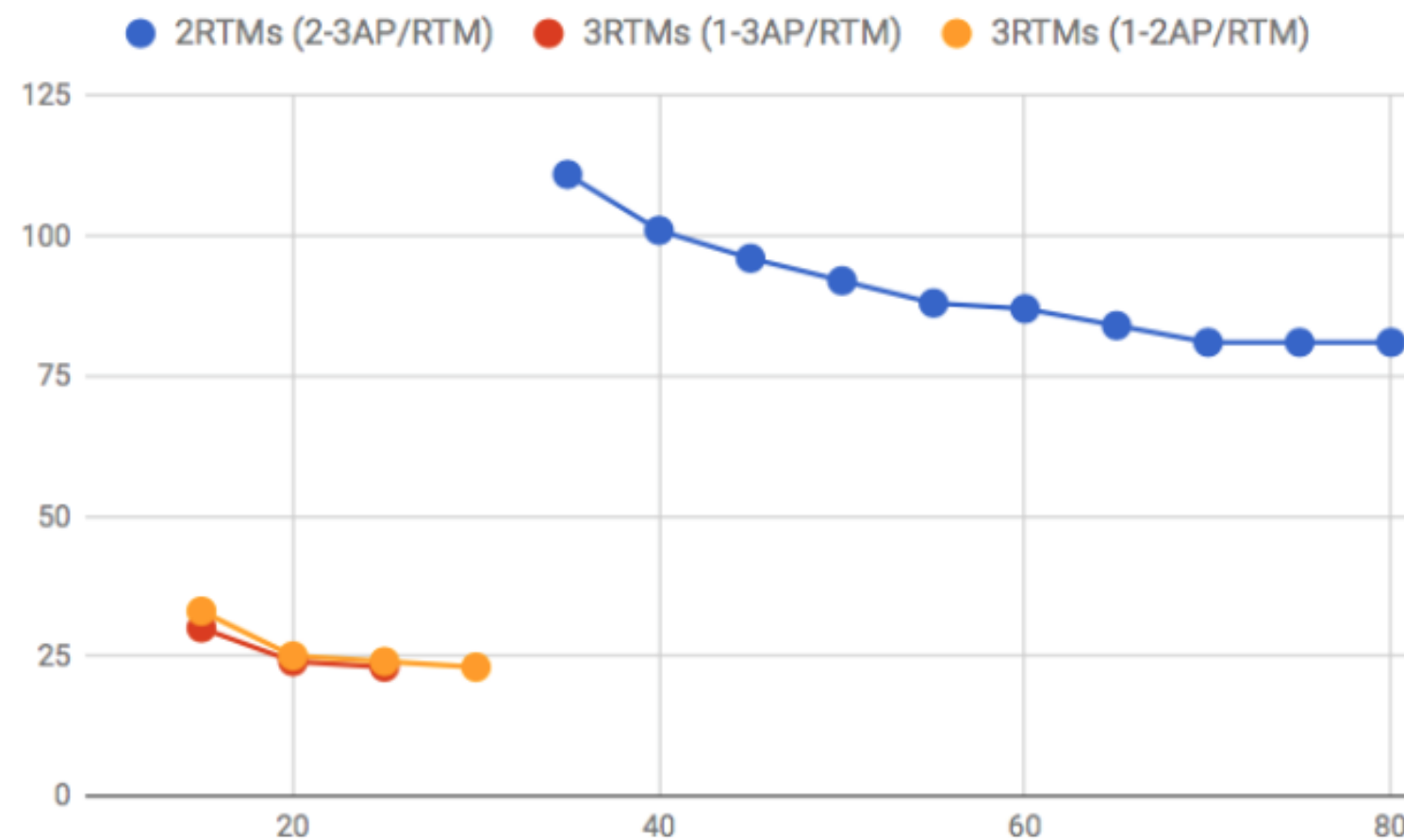
“2x” data created from all data of the year 2016

- ➡ shifted duplicates of flights from October 18, 2016 and October 20, 2016 may now happen on October 19, 2016
- ➡ Not exactly twice the number of movements
 - October 19: data set has 416 flight movements (after deleting double movements in time slots) out of 575 flight movements (all of the movements from 2016 that the duplication and shifting process produces)

δ	# of modules	S	Δ	S for 3RTMs (1-3AP/RTM)	S for 3RTMs (1-2AP/RTM)
0	5	0	-	-	-
1	3	30	5	30	33
2	3	24	10	24	25
3	3	23	15	23	24
4	3	23	20	-	23
5	2	111	25	-	-
6	2	101	30	-	-
7	2	96	35	-	-
8	2	92	40	-	-
9	2	88	45	-	-
10	2	87	50	-	-
11	2	84	55	-	-
12	2	81	60	-	-
13	2	81	65	-	-
14	2	81	70	-	-
15	2	81	75	-	-
16	2	80	80	-	-



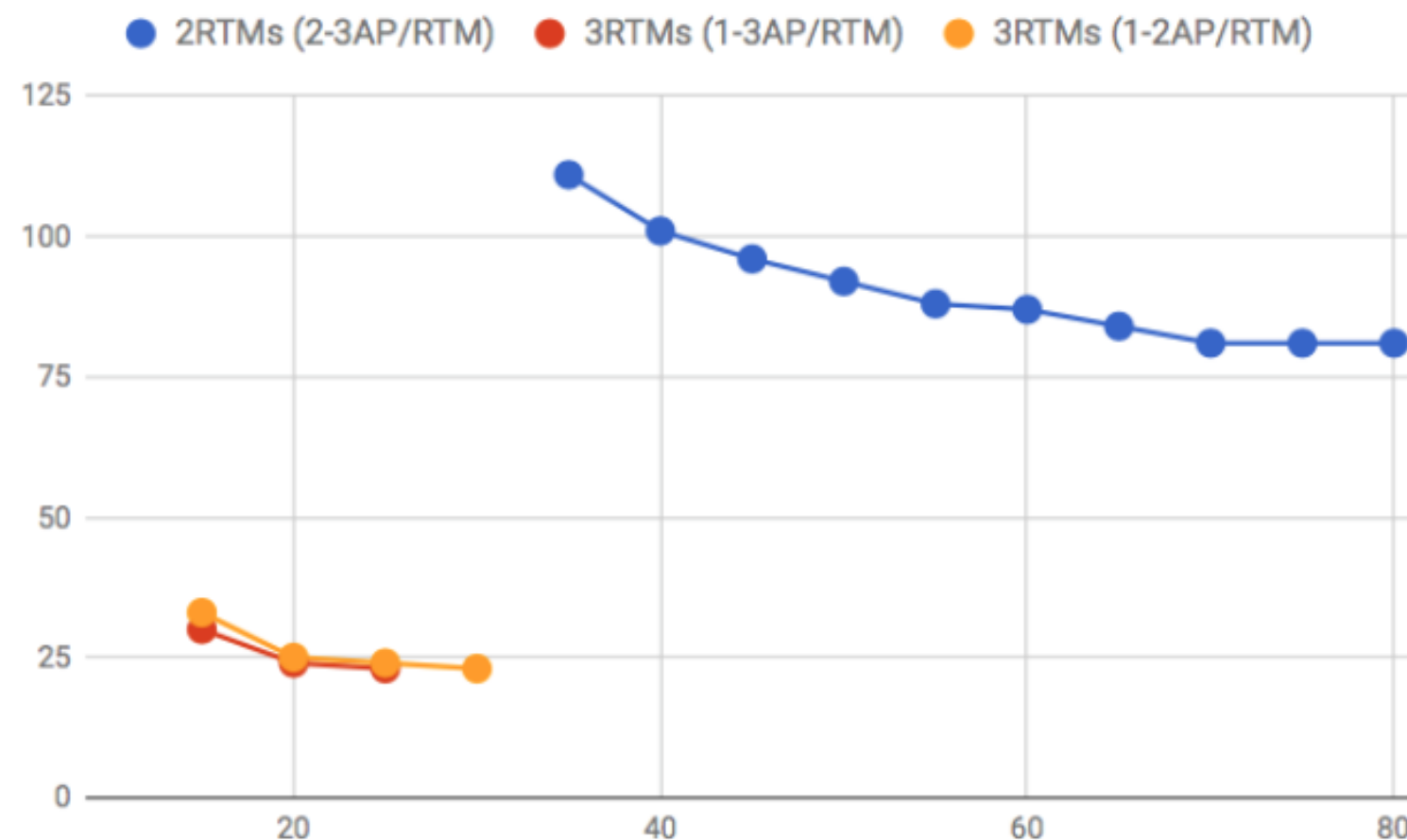
δ	# of modules	S	Δ	S' for 3RTMs (1-3AP/RTM)	S' for 3RTMs (1-2AP/RTM)
0	5	0	-	-	-
1	3	30	5	30	33
2	3	24	10	24	25
3	3	23	15	23	24
4	3	23	20	-	23
5	2	111	25	-	-
6	2	101	30	-	-
7	2	96	35	-	-
8	2	92	40	-	-
9	2	88	45	-	-
10	2	87	50	-	-
11	2	84	55	-	-
12	2	81	60	-	-
13	2	81	65	-	-
14	2	81	70	-	-
15	2	81	75	-	-
16	2	80	80	-	-



For MAP=2 we get the optimum of 3RTMs for $\delta=1$
33 shifts ↔ 7 shifts for original traffic

Same tradeoffs: more shifts — larger shifts (more minutes) — more APs/module

δ	# of modules	S	Δ	S for 3RTMs (1-3AP/RTM)	S for 3RTMs (1-2AP/RTM)
0	5	0	-	-	-
1	3	30	5	30	33
2	3	24	10	24	25
3	3	23	15	23	24
4	3	23	20	-	23
5	2	111	25	-	-
6	2	101	30	-	-
7	2	96	35	-	-
8	2	92	40	-	-
9	2	88	45	-	-
10	2	87	50	-	-
11	2	84	55	-	-
12	2	81	60	-	-
13	2	81	65	-	-
14	2	81	70	-	-
15	2	81	75	-	-
16	2	80	80	-	-



For MAP=2 we get the optimum of 3RTMs for $\delta=1$
33 shifts ↔ 7 shifts for original traffic

Conclusion/Future Work

Conclusion

Future Work

Conclusion

- Optimization problem for remote towers (FRAMA):

Future Work

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- Optimization problem for remote towers (FRAMA):
 - Shifts flights to other, nearby, slots

Future Work

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 - To minimize the total number of modules in the RTC

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 - To minimize the total number of modules in the RTC
- Discussed computational complexity

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- Optimization problem for remote towers (FRAMA):
 - Shifts flights to other, nearby, slots
 - To minimize the total number of modules in the RTC
- Discussed computational complexity
- Presented different solution approaches
- Experiments for IP for five Swedish airports

Future Work

Conclusion

- Optimization problem for remote towers (FRAMA):
 - Shifts flights to other, nearby, slots
 - To minimize the total number of modules in the RTC
- Discussed computational complexity
- Presented different solution approaches
- Experiments for IP for five Swedish airports
- ➡ Show applicability of our approach

Future Work

Conclusion

- Optimization problem for remote towers (FRAMA):
 - Shifts flights to other, nearby, slots
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- ➔ Show applicability of our approach
- ➔ Tradeoffs: more shifts — larger shifts (more minutes) — more APs/module

Future Work

Conclusion

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- Discussed computational complexity
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- Experiments for IP for five Swedish airports
- ➔ Show applicability of our approach
- ➔ Tradeoffs: more shifts — larger shifts (more minutes) — more APs/module
- ➔ Minor shifts (few minutes) can significantly reduce necessary number of modules

Future Work

Conclusion

- Optimization problem for remote towers (FRAMA):
 - Shifts flights to other, nearby, slots
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- Discussed computational complexity
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- ➔ Show applicability of our approach
- ➔ Tradeoffs: more shifts — larger shifts (more minutes) — more APs/module
- ➔ Minor shifts (few minutes) can significantly reduce necessary number of modules
- ➔ Cooperation between airlines, airport owners and ANSPs may help in reduction of RTC operation costs

Future Work

Conclusion

- Optimization problem for remote towers (FRAMA):
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Future Work

- Our conflict definition may be too conservative/precautionary

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Future Work

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- They cannot be discarded, and will influence staff planning

Conclusion

- Optimization problem for remote towers (FRAMA):
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- ➔ Continues discussion with operations

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- Discussed computational complexity
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- Experiments for IP for five Swedish airports
- ➔ Show applicability of our approach
- ➔ Tradeoffs: more shifts — larger shifts (more minutes) — more APs/module
- ➔ Minor shifts (few minutes) can significantly reduce necessary number of modules
- ➔ Cooperation between airlines, airport owners and ANSPs may help in reduction of RTC operation costs

Future Work

- Our conflict definition may be too conservative/precautionary
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- ➔ Continues discussion with operations
- ➔ Possibly: distinguish arrival/departures

Conclusion

- Optimization problem for remote towers (FRAMA):
 - Shifts flights to other, nearby, slots
 - To minimize the total number of modules in the RTC
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- Presented different solution approaches
- Experiments for IP for five Swedish airports
- ➔ Show applicability of our approach
- ➔ Tradeoffs: more shifts — larger shifts (more minutes) — more APs/module
- ➔ Minor shifts (few minutes) can significantly reduce necessary number of modules
- ➔ Cooperation between airlines, airport owners and ANSPs may help in reduction of RTC operation costs

Future Work

- Our conflict definition may be too conservative/precautionary
- They cannot be discarded, and will influence staff planning
- ➔ Continues discussion with operations
- ➔ Possibly: distinguish arrival/departures
- ➔ Possibly: consider uncertainty

Conclusion

- Optimization problem for remote towers (FRAMA):
 - Shifts flights to other, nearby, slots
 - To minimize the total number of modules in the RTC
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