Air Traffic and Air Transportation
Flygtrafik och flygtransporter

Planning for Remote Towers

Joint work with Billy Josefsson (LFV) and Tatiana and Valentin Polishchuk

Remote Tower Center (RTC)

- Provides ATS remotely to small airports
- Replaces local tower with cameras and sensors
- Increases efficiency: HR and ATS costs are split between several airports

- In Sweden: LFV + SAAB
- Within SESAR Joint Undertaking
- RTC in Sundsvall:

  Operates 2 airports remotely

  + 5 airports in development

How to distribute the total workload from several airports over several controller working positions?

Problem description

Given:

(1) Example schedules IFR traffic schedules for 1 day (movements = arrival + departure flights) for five Swedish airports
(2) Specifications of additional special traffic at these airports (military, school, hospital etc.)
(3) Airport opening hours

Goal:

Propose optimal assignment of the airports to RTC modules

Notation	Parameter		Notation	Variable
A	set of airports		$op_{j,k}$	= 1 if airport j is open during period k, = 0 otherwise
R	set of RTMs		M_k	number of modules in use during period k
P	set of time periods		$RTM_{i,k}$	= 1 if RTM i is used during period k, = 0 otherwise
p	number of time periods		$period_{i,j,k}$	= 1 if airport j is assigned to RTM i during period k, = 0 otherwise
$mMov$	max number of movements per RTM per period		$mov_{i,j,k}$	number of movements handled by RTM i at airport j during period k
mA	max number of airports per RTM		$switch_{i,j,k}$	= 0 if $period_{i,j,k} = period_{i,j,k+1}$, = 1 otherwise
$Amov_{j,k}$	number of movements at airport j during period k		$d_{l,m,k}$	difference between the workloads in modules l and m in period k

Constraints (MIP)

1. Number of airports assigned to one module ≤ mA
2. Total number of movements within a module ≤maxMov
3. One airport assigned to only one module
4. All scheduled traffic from 5 airports is handled
5. All opening hours at 5 airports are covered

$$\sum_{j \in A} period_{i,j,k} \leq RTM_{i,k} \cdot mA \qquad \forall i \in R, \forall k \in P$$

$$\sum_{j \in A} mov_{i,j,k} \leq mMov \qquad \forall i \in R, \forall k \in P$$

$$\sum_{i \in R} period_{i,j,k} \leq 1 \qquad \forall j \in A, \forall k \in P$$

$$mov_{i,j,k} \leq period_{i,j,k} \cdot mMov \qquad \forall i \in R, \forall j \in A, \forall k \in P$$

$$\sum_{i \in R} mov_{i,j,k} = Amov_{j,k} \qquad \forall j \in A, \forall k \in P$$

$$\sum_{i \in R} period_{i,j,k} \geq op_{j,k} \qquad \forall j \in A, \forall k \in P$$

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$Amov_{j,k}$	number of movements at airport j during period k		$d_{l,m,k}$	difference between the workloads in modules l and m in period k

Objectives

1. Minimize the number of remote tower modules in use
2. Balance workload between the modules
3. Minimize assignment switches

As much as possible!

$$\min \sum_{i \in R} \sum_{k \in P} RTM_{i,k}$$

$$d_{l,m,k} \geq \sum_{j \in A} mov_{l,j,k} - \sum_{j \in A} mov_{m,j,k} \quad \forall\, l,m \in R, \forall\, k \in P$$

$$d_{l,m,k} \geq \sum_{j \in A} mov_{m,j,k} - \sum_{j \in A} mov_{l,j,k} \quad \forall\, l,m \in R, \forall\, k \in P$$

$$\min \sum_{k \in P} d_{l,m,k} \qquad \forall\, l,m \in R : l \neq m$$

$$switch_{i,j,k} \geq s_{i,j,k} \forall\, i \in R, \forall\, j \in A, \forall\, k \in P$$

$$switch_{i,j,k} \geq -s_{i,j,k} \forall\, i \in R, \forall\, j \in A, \forall\, k \in P$$

$$s_{i,j,k} = period_{i,j,k+1} - period_{i,j,k}$$

$$\min \sum_{i \in R} \sum_{j \in A} \sum_{k=1}^{p-1} switch_{i,j,k}$$

Experimental evaluation

(1) Data analysis of:

- Example schedules and extra traffic specifications
- For two example weeks in 2016 for five Swedish airports

→ Extract 1-day data samples (the days with highest traffic)

(2) Solved MIP using AMPL CPLEX 12.6 solver

→ Solutions with different objectives

(3) Post-processing: avoid potential conflicts in schedules within one module

(4) Include special airport traffic

(5) Residual system capacity estimation

Initial assumptions (conservative)

(1) Max # airdromes/module = 2
(relaxed for the estimation of upper bound)

(2) Max movs per module / hour= 10

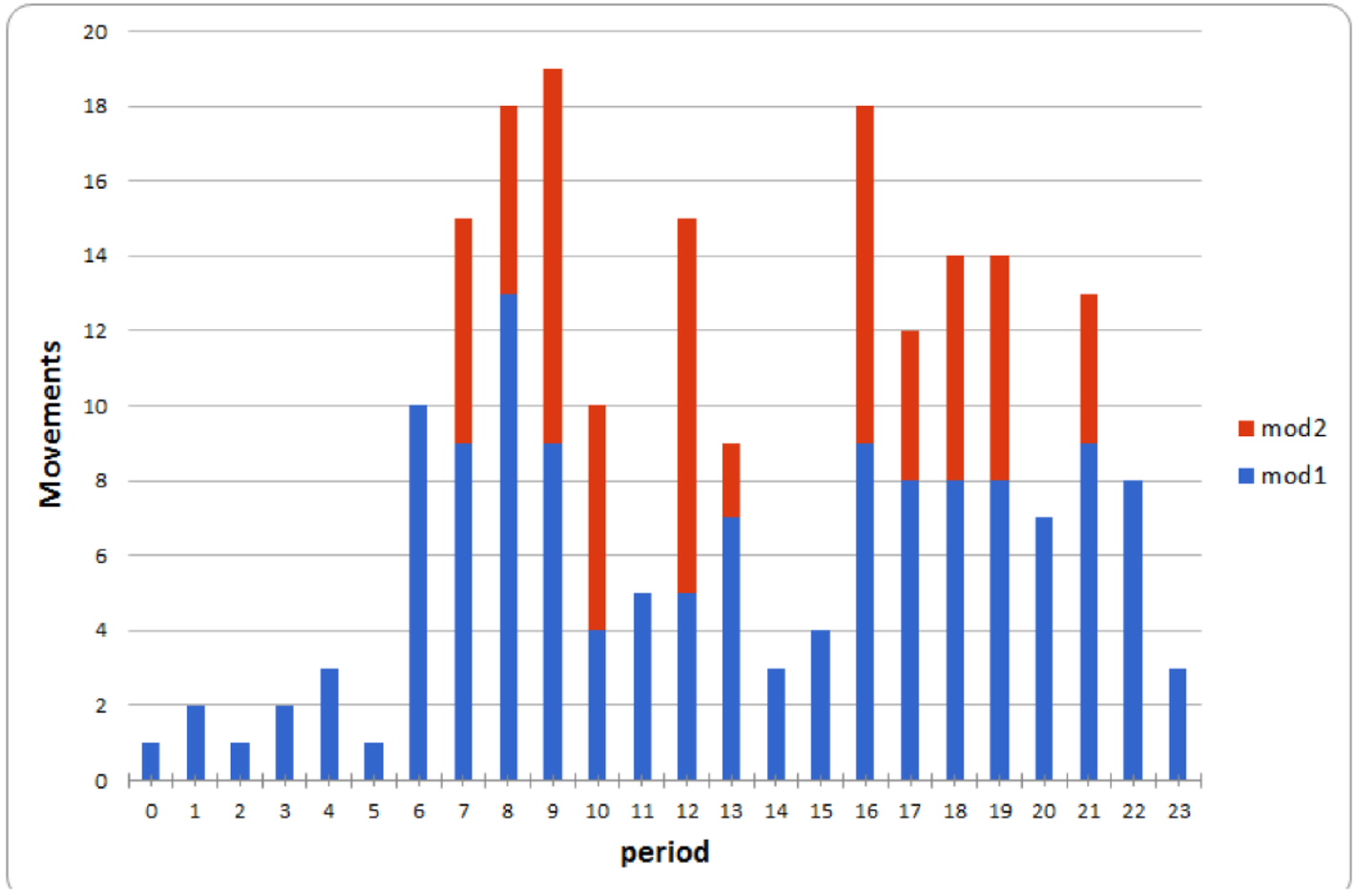
(if >10 movements are initially scheduled at some airport, reduce to 10 w.l.o.g. (→ will be scheduled in separate module)

Experimental Study

Minimize number of modules in use

Schema 1: Lower bound (>2 airports allowed per module)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
AP1	0	0	0	0	0	0	1	0	0	0	0	0	2	2	0	0	1	1	0	0	0	0	0	1
AP2	1	2	1	1	2	1	3	9	10	6	4	3	3	5	2	0	5	6	5	7	2	6	4	1
AP3	0	0	0	1	1	0	0	2	1	6	3	1	5	2	0	3	6	3	4	4	4	2	2	1
AP4	0	0	0	0	0	0	3	2	4	3	2	1	2	2	1	0	3	1	3	1	0	3	1	0
AP5	0	0	0	0	0	0	3	2	0	4	1	0	3	0	0	1	3	1	2	2	1	2	1	0



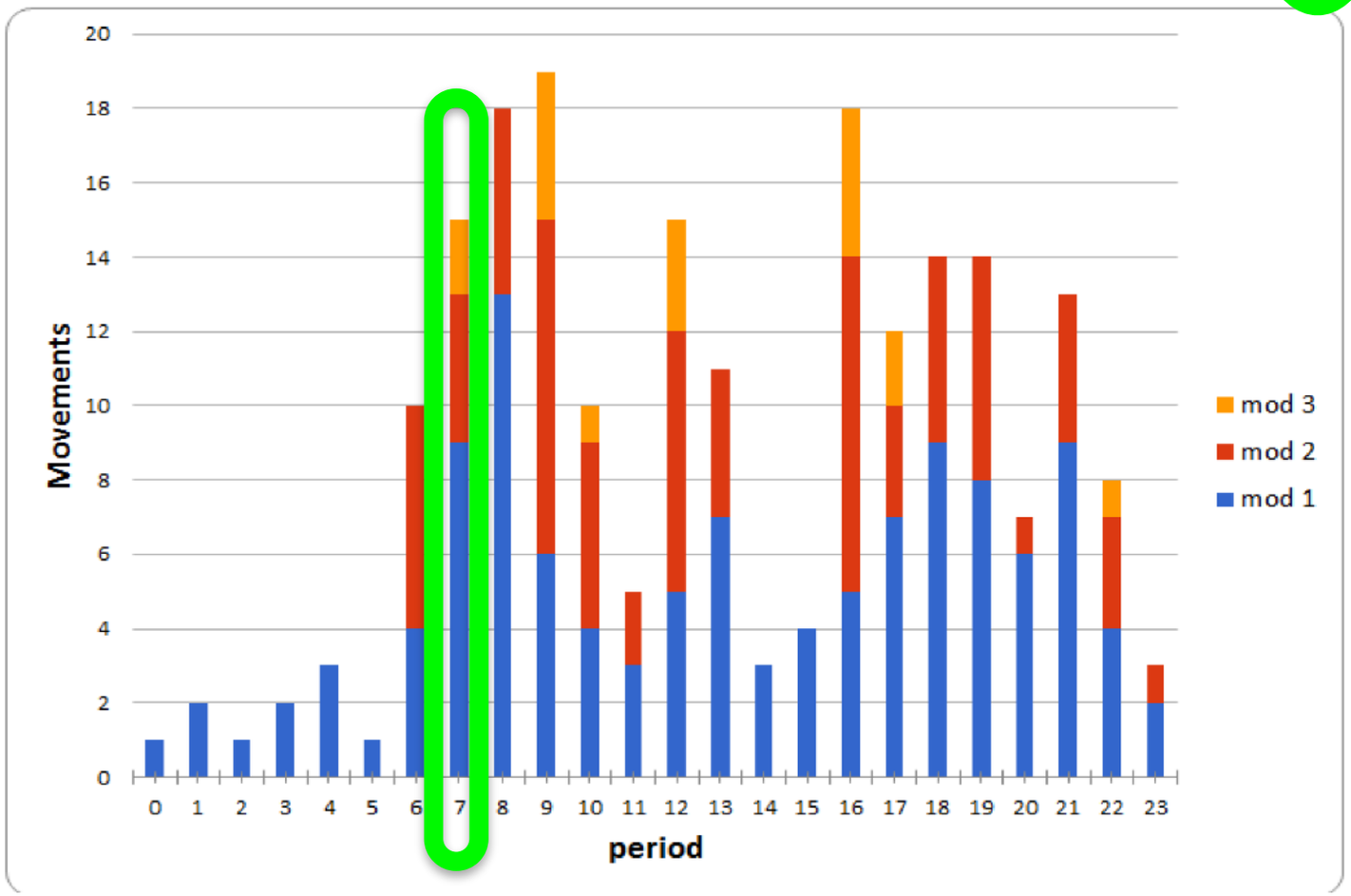
→ 2 modules suffice!

Minimize number of modules in use

Schema 2: ≤2 airports per module

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
AP1	0	0	0	0	0	0	1	0	0	0	0	0	2	2	0	0	1	1	0	0	0	0	0	1
AP2	1	2	1	1	2	1	3	9	10	6	4	3	3	5	2	0	5	6	5	7	2	6	4	1
AP3	0	0	0	1	1	0	0	2	1	6	3	1	5	2	0	3	6	3	4	4	4	2	2	1
AP4	0	0	0	0	0	0	3	2	4	3	2	1	2	2	1	0	3	1	3	1	0	3	1	0
AP5	0	0	0	0	0	0	3	2	0	4	1	0	3	0	0	1	3	1	2	2	1	2	1	0

not balanced in the number of movements per module

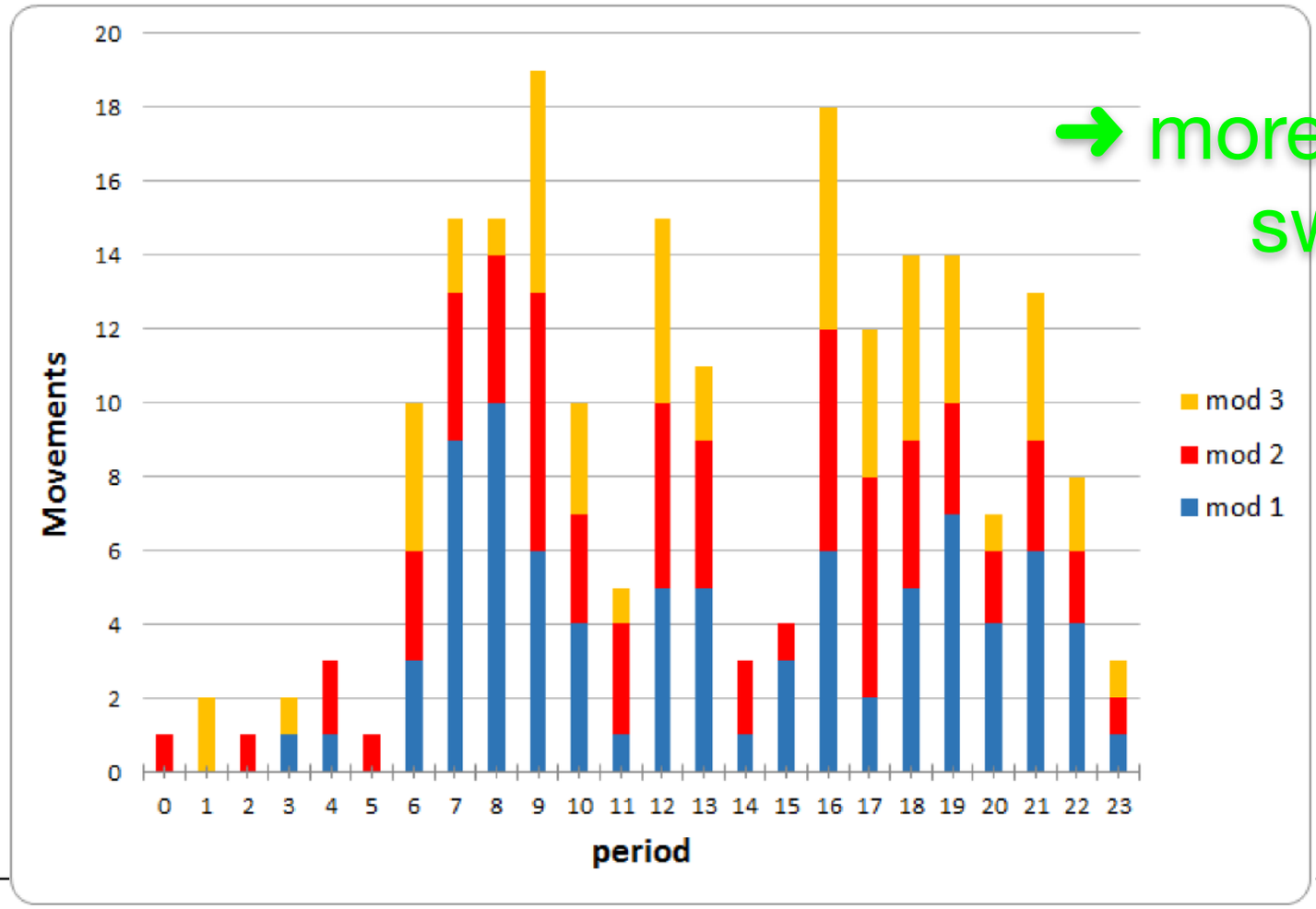


→ 3 modules are needed

Balancing the load

Schema 3: Better balanced

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
AP1	0	0	0	0	0	0	1	0	0	0	0	0	2	2	0	0	1	1	0	0	0	0	0	1
AP2	1	2	1	1	2	1	3	0	10	6	4	3	3	5	3	0	5	6	5	7	2	6	4	1
AP3	0	0	0	1	1	0	0	2	1	6	3	1	5	2	0	3	6	3	4	4	4	2	2	1
AP4	0	0	0	0	0	0	3	2	4	3	2	1	2	2	1	0	3	1	3	1	0	3	1	0
AP5	0	0	0	0	0	0	3	2	0	4	1	0	3	0	0	1	3	1	2	2	1	2	1	0

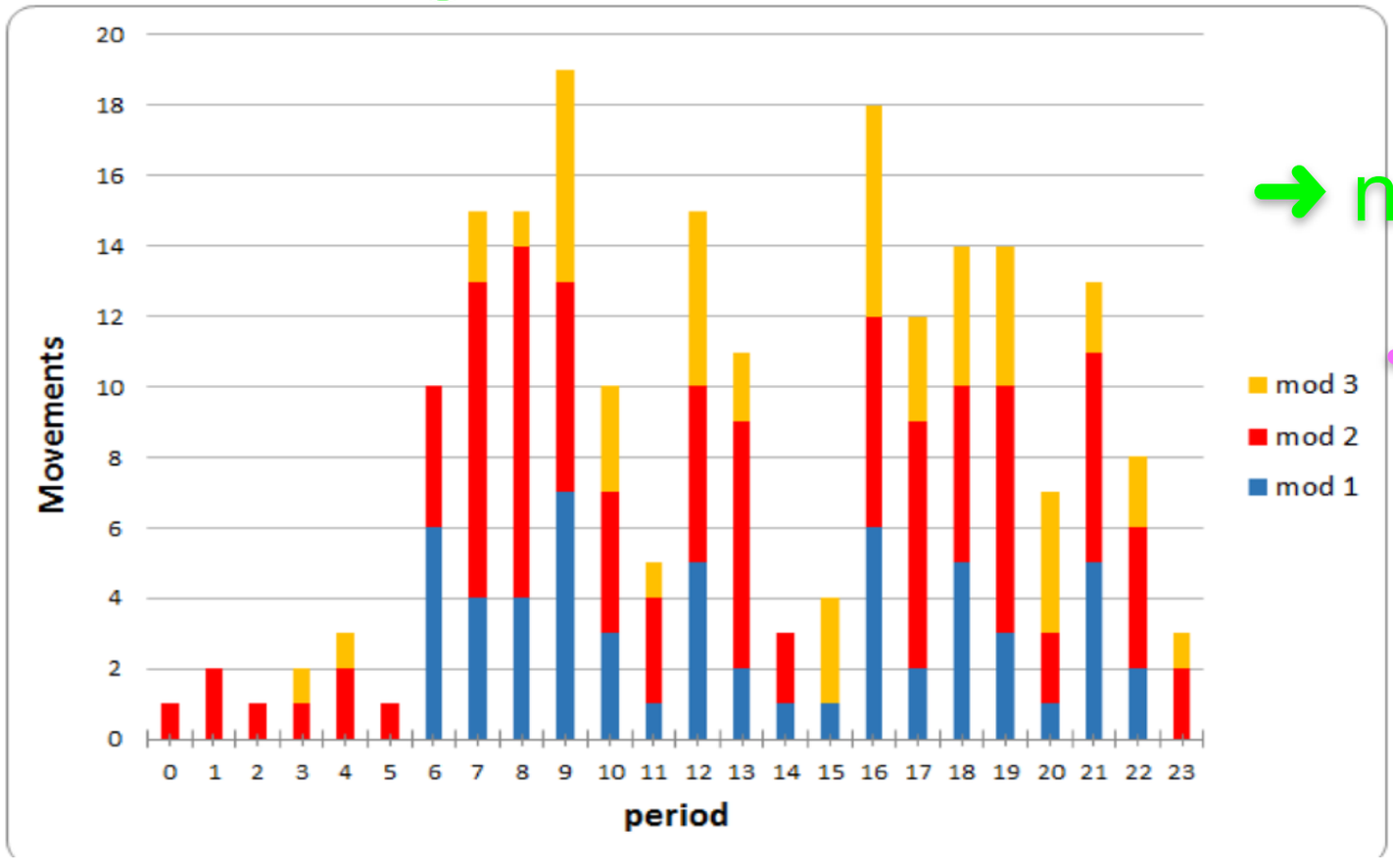


➜ more assignment switches

Minimize number of switches

Schema 4: Fewer assignment switches

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
AP1	0	0	0	0	0	0	1	0	0	0	0	0	2	2	0	0	1	1	0	0	0	0	0	1
AP2	1	2	1	1	2	1	3	9	10	6	4	3	3	5	2	0	5	6	5	7	2	6	4	1
AP3	0	0	0	1	1	0	0	2	1	6	3	1	5	2	0	3	6	3	4	4	4	2	2	1
AP4	0	0	0	0	0	0	3	2	4	3	2	1	2	2	1	0	3	1	3	1	0	3	1	0
AP5	0	0	0	0	0	0	3	2	0	4	1	0	3	0	0	1	3	1	2	2	1	2	1	0



➜ not balanced

➜ Trade-off

Observations

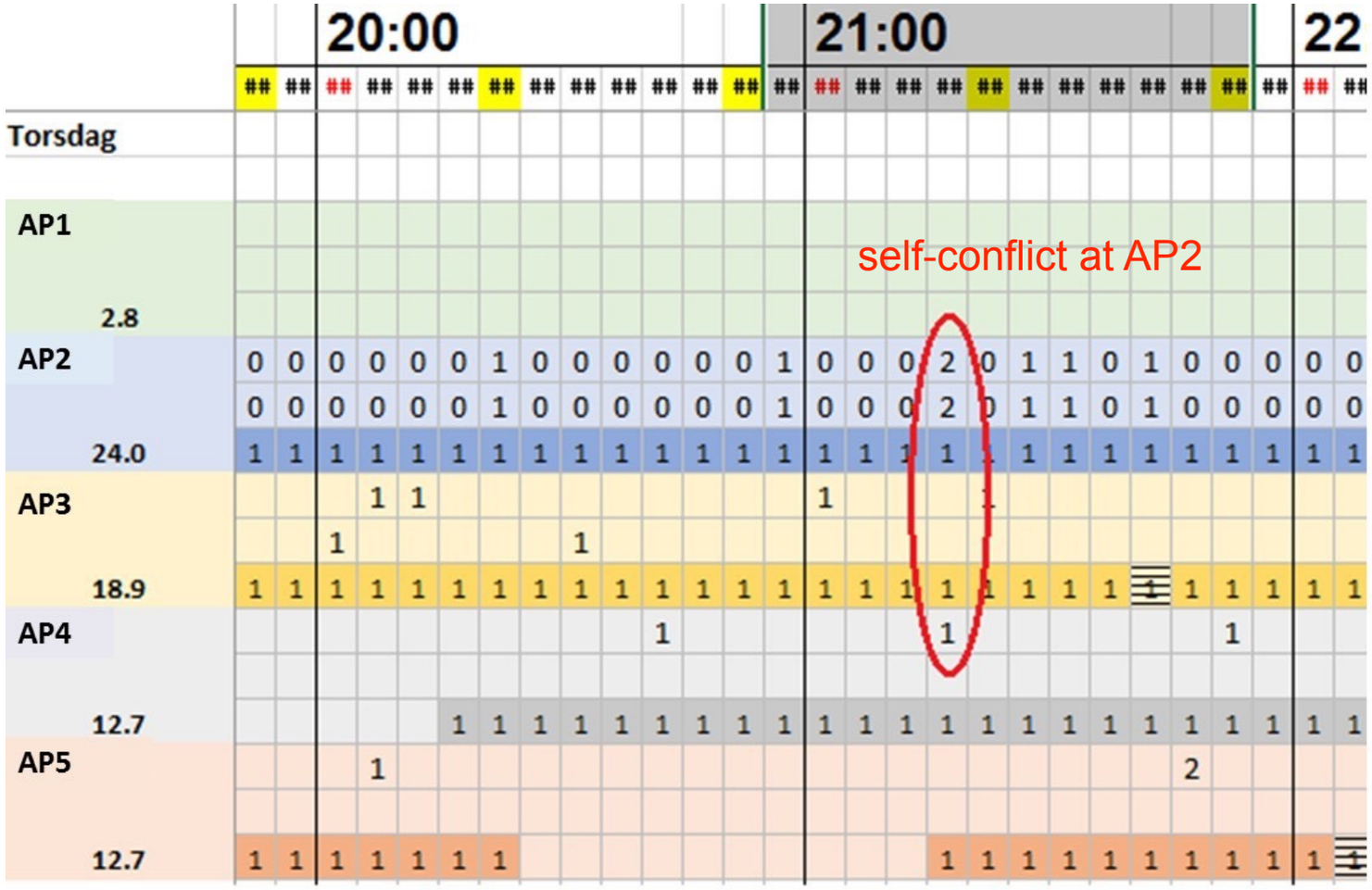
We observed clear **trade-offs** between the 3 objectives:

- Minimize the number of modules in use
- Improve balancing
- Minimize switches

What can we do?

- Prioritize according to current needs
  (e.g., balancing may have lower priority in the beginning)
- Combine solutions (e.g., first find the minimum number of modules, then apply the other 2 objectives)

Post-processing: avoid potential conflicts



Conflict:
≥3 movs / 5 min

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
AP2 self									8:10	9:20				13:30				17:20				21:15		
AP2_AP5										9:20														
AP2_AP3																	16:20							
AP2_AP4																						21:15		

Post-processing: avoid potential conflicts

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
AP2 self									8:1	9:20				13:30				17:20				21:15		
AP2_AP5										:20														
AP2_AP3																	16: 0							
AP2_AP4																						21:15		

assigned to separate model - ok ✔

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
AP1	0	0	0	0	0	0	1	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	1	0
AP2	0	6	2	0	4	2	1	0	8	4	2	2	2	10	0	4	2	8	6	2	4	10	4	0
AP3	0	3	0	2	2	0	3	5	1	7	3	1	6	1	0	3	5	3	4	5	4	2	1	1
AP4	0	0	0	0	0	0	1	2	4	2	1	1	3	3	2	0	4	1	4	2	1	2	0	0
AP5	0	0	0	0	0	0	3	1	2	4	1	0	4	0	0	2	4	3	2	2	1	2	1	0

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
AP1	0	0	0	0	0	0	1	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	1	0
AP2	0	6	2	0	4	2	1	0	8	4	2	2	2	10	0	4	2	8	6	2	4	10	4	0
AP3	0	3	0	2	2	0	3	5	1	7	3	1	6	1	0	3	5	3	4	5	4	2	1	1
AP4	0	0	0	0	0	0	1	2	4	2	1	1	3	3	2	0	4	1	4	2	1	2	0	0
AP5	0	0	0	0	0	0	3	1	2	4	1	0	4	0	0	2	4	3	2	2	1	2	1	0

Changes: re-assign AP2 to a separate module during periods 8, 9, and 17

Analysis of non-scheduled (VFR) traffic / day

		norm	worst case
kiruna	FM	3	10
	HKP	5	17
	Skol	1	3
	Special	2	5
	Övrigt	1	5
sturup	FM	1	3
	HKP	1	4
	Skol	5	20
	Special	14	60
	Övrigt	2	10
umeå	FM		
	HKP	4	12
	Skol	2	8
	Special	4	10
	Övrigt	4	4
visby	FM	6	125
	HKP	7	21
	Skol	4	10
	Special	2	10
	Övrigt		
Östersun	FM	8	20
	HKP	8	20
	Skol	3	8

3 types of model runs (modes)

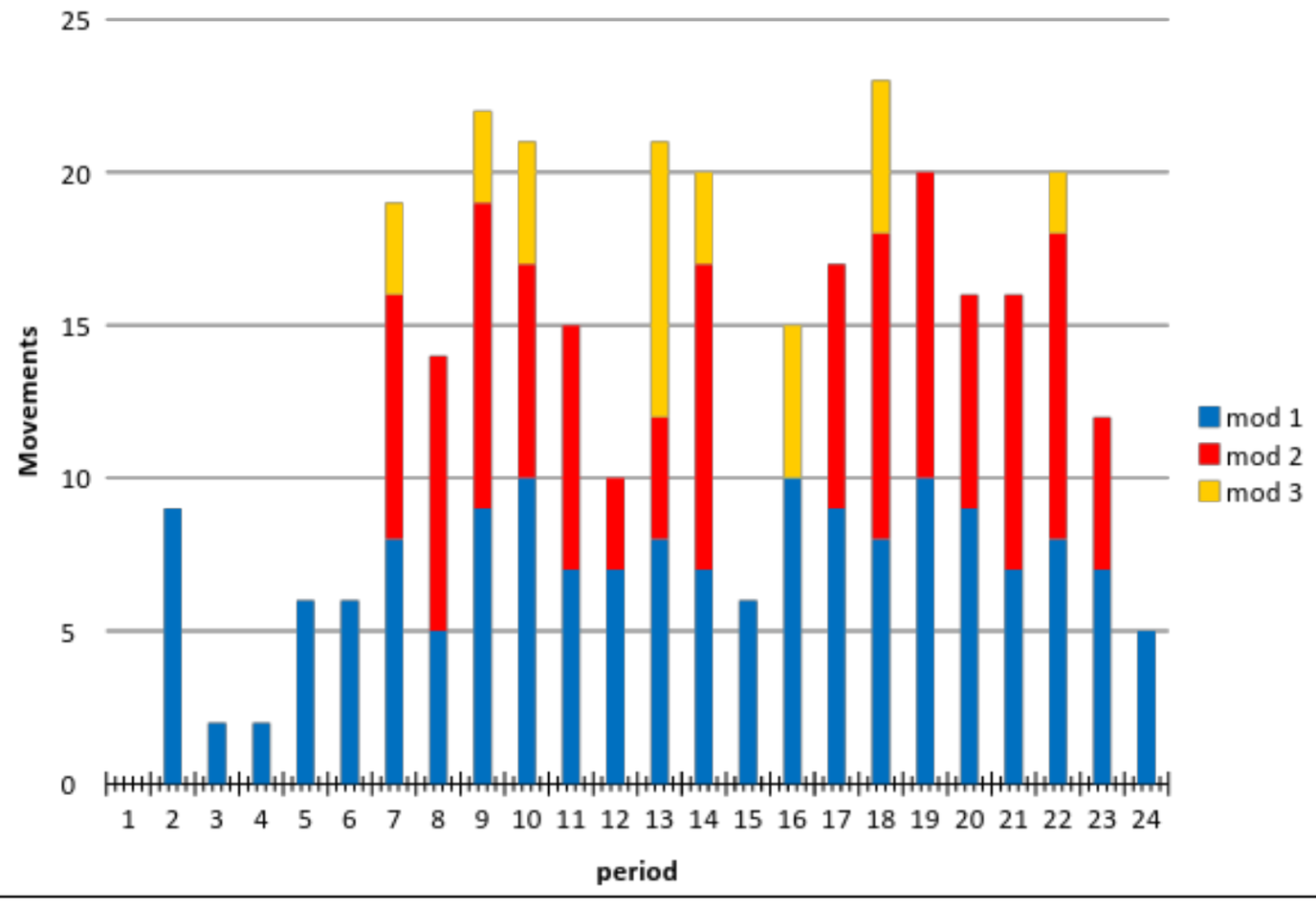
1. Only regular scheduled traffic (no extra traffic)
2. Add moderate amount of extra traffic (normal)
3. Worst-case scenario with MAXIMUM load

All schemas so far

Experimental Study

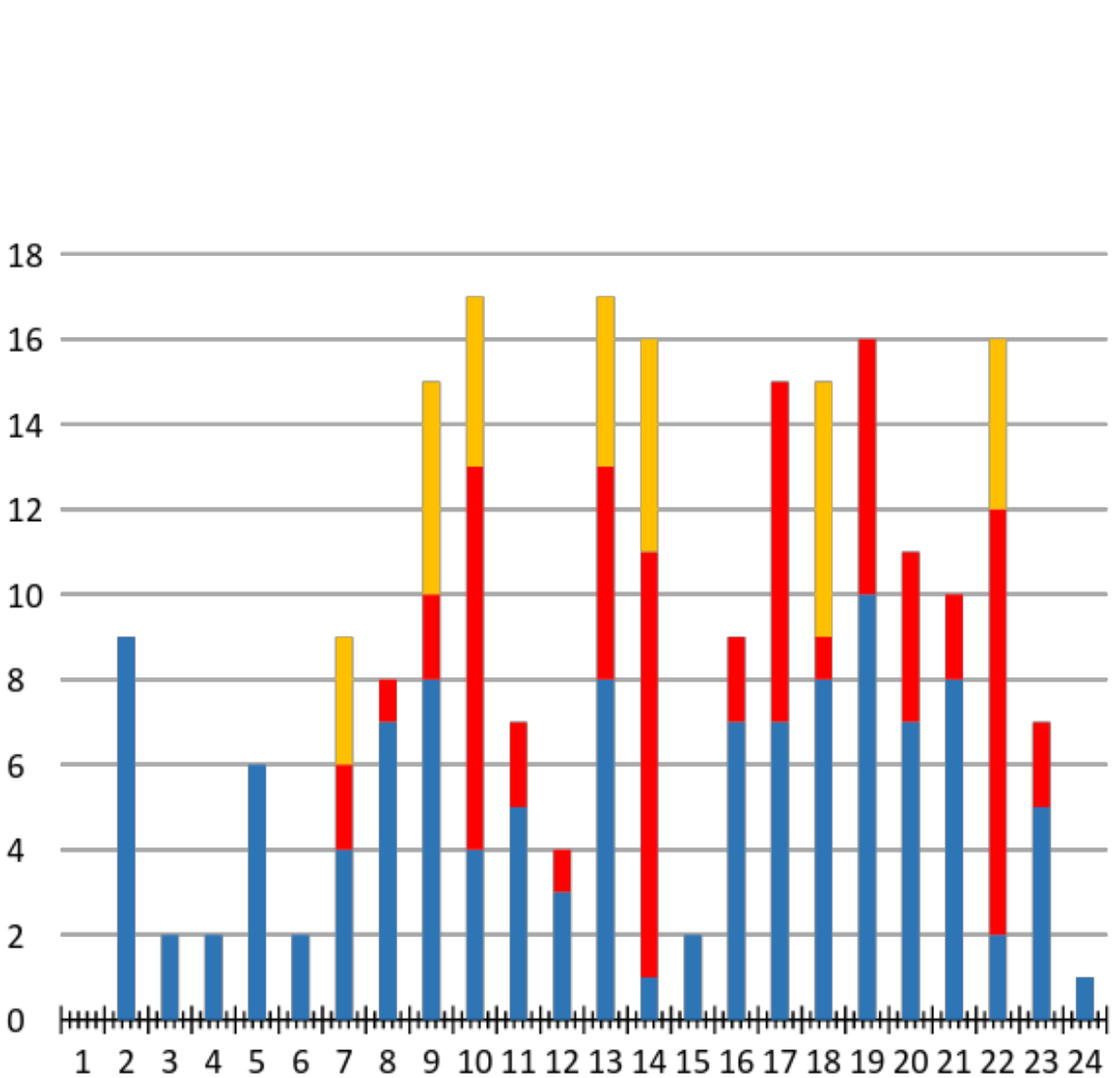
Mode 2: Extra traffic in normal operation (schema 5)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
AP1	0	0	0	0	0	2	3	0	0	0	0	0	4	4	0	0	0	0	0	0	0	0	3	2
AP2	0	6	2	0	4	4	3	2	10	6	4	4	2	10	2	6	4	10	6	3	4	10	4	0
AP3	0	3	0	2	2	0	5	5	3	7	5	3	6	3	0	5	5	5	6	5	6	4	3	3
AP4	0	0	0	0	0	0	3	4	5	4	3	3	3	3	4	0	4	3	4	4	3	2	0	0
AP5	0	0	0	0	0	0	5	3	4	4	3	0	6	0	0	4	4	5	4	4	3	4	2	0

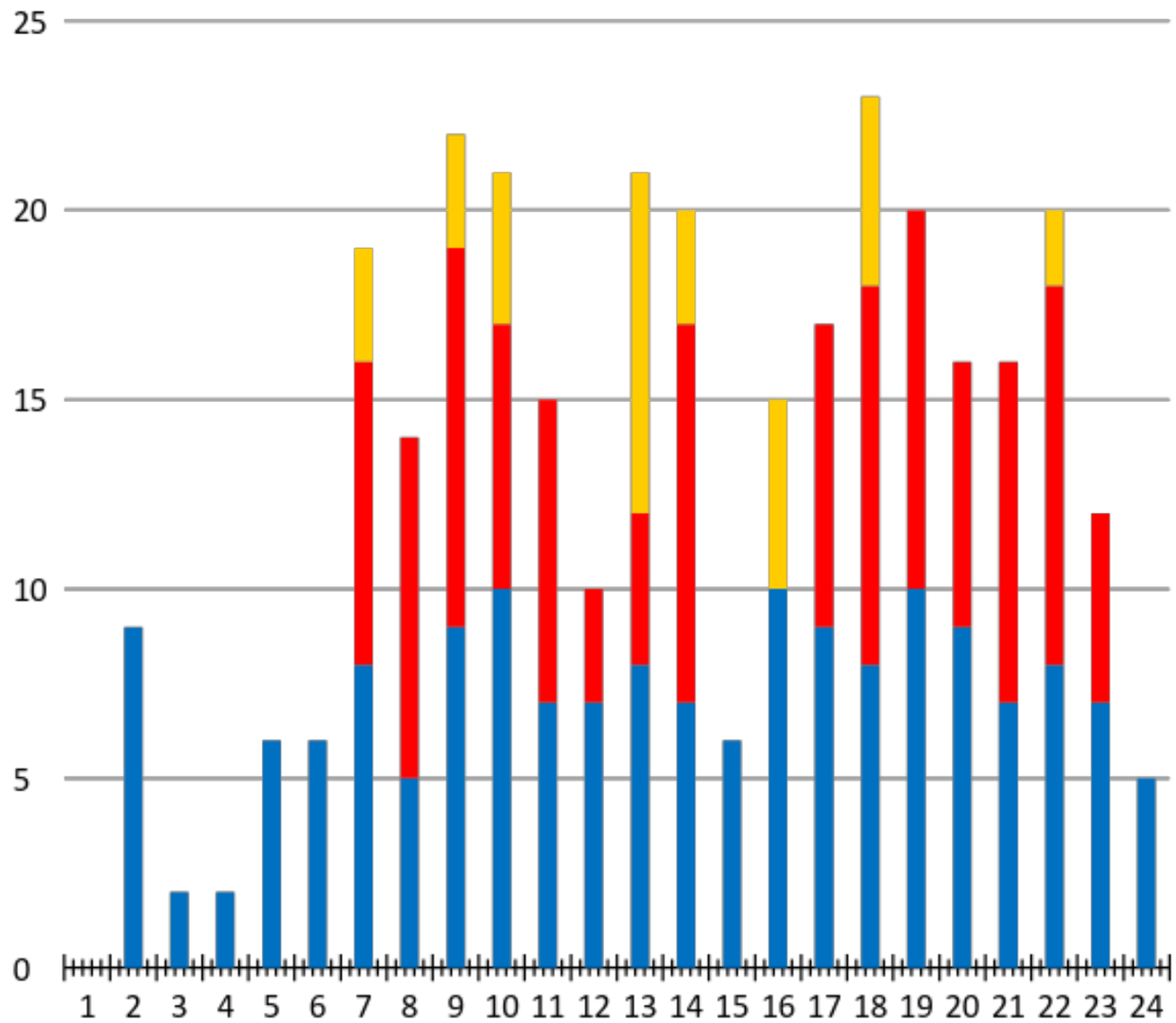


Experimental Study

Mode 2: Extra traffic in normal operation (schema 5)



Scheduled



Plus extra traffic (norm.)

Moderate amount of extra traffic added:

- Amount of traffic increases significantly
- 3 modules still suffice

Mode 3: Worst case: MAX load operation (schema 6)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
AP1	0	0	0	0	0	6	10	0	0	0	0	0	5	5	0	0	0	0	0	0	0	0	10	10
AP2	6	8	8	6	8	6	7	6	8	8	8	8	8	10	6	9	7	8	9	6	6	10	8	6
AP3	0	4	0	4	2	0	3	5	5	7	6	5	6	6	0	6	5	6	6	5	6	3	3	3
AP4	0	0	0	0	0	0	10	10	10	10	10	10	10	10	10	0	10	10	10	10	10	10	0	0
AP5	0	0	0	0	0	0	7	5	6	8	6	0	8	0	0	6	7	7	6	6	7	7	6	0

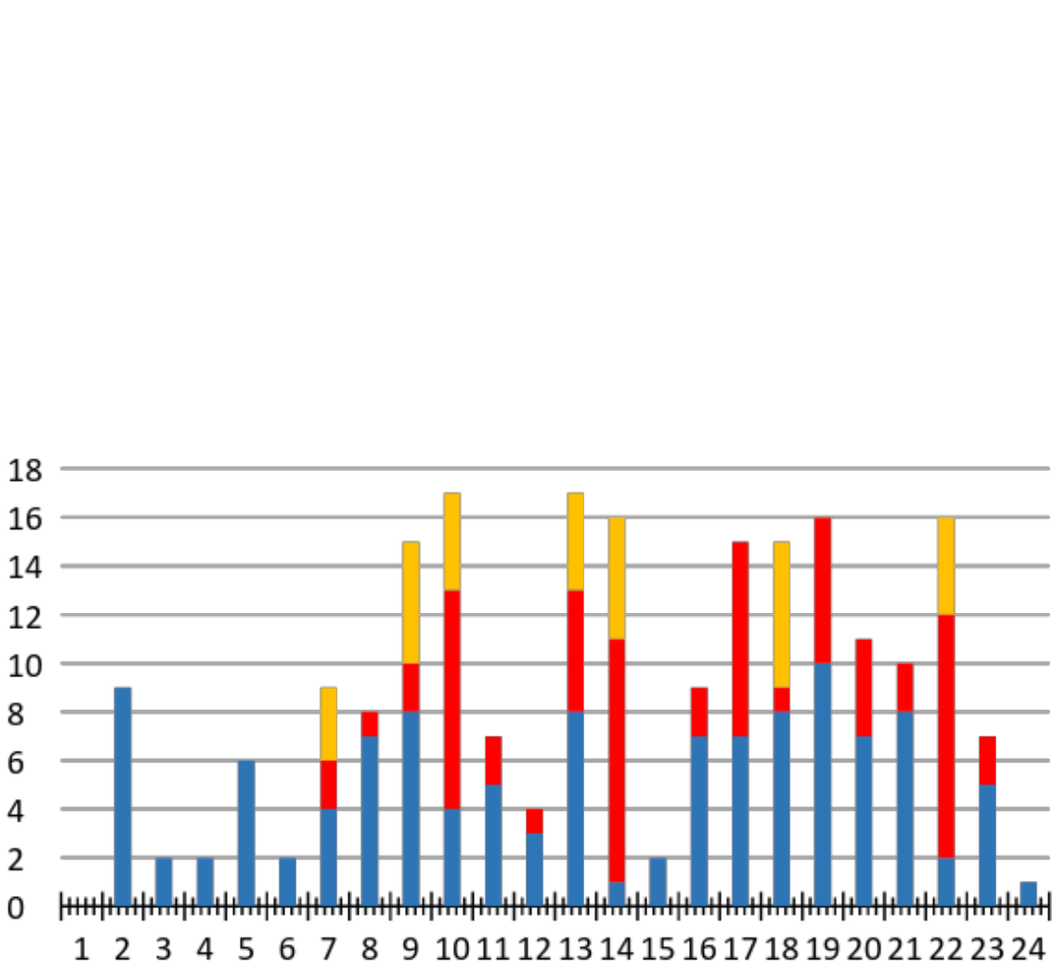
Problem: max extra traffic may not fit into the schedule

Possible solutions:

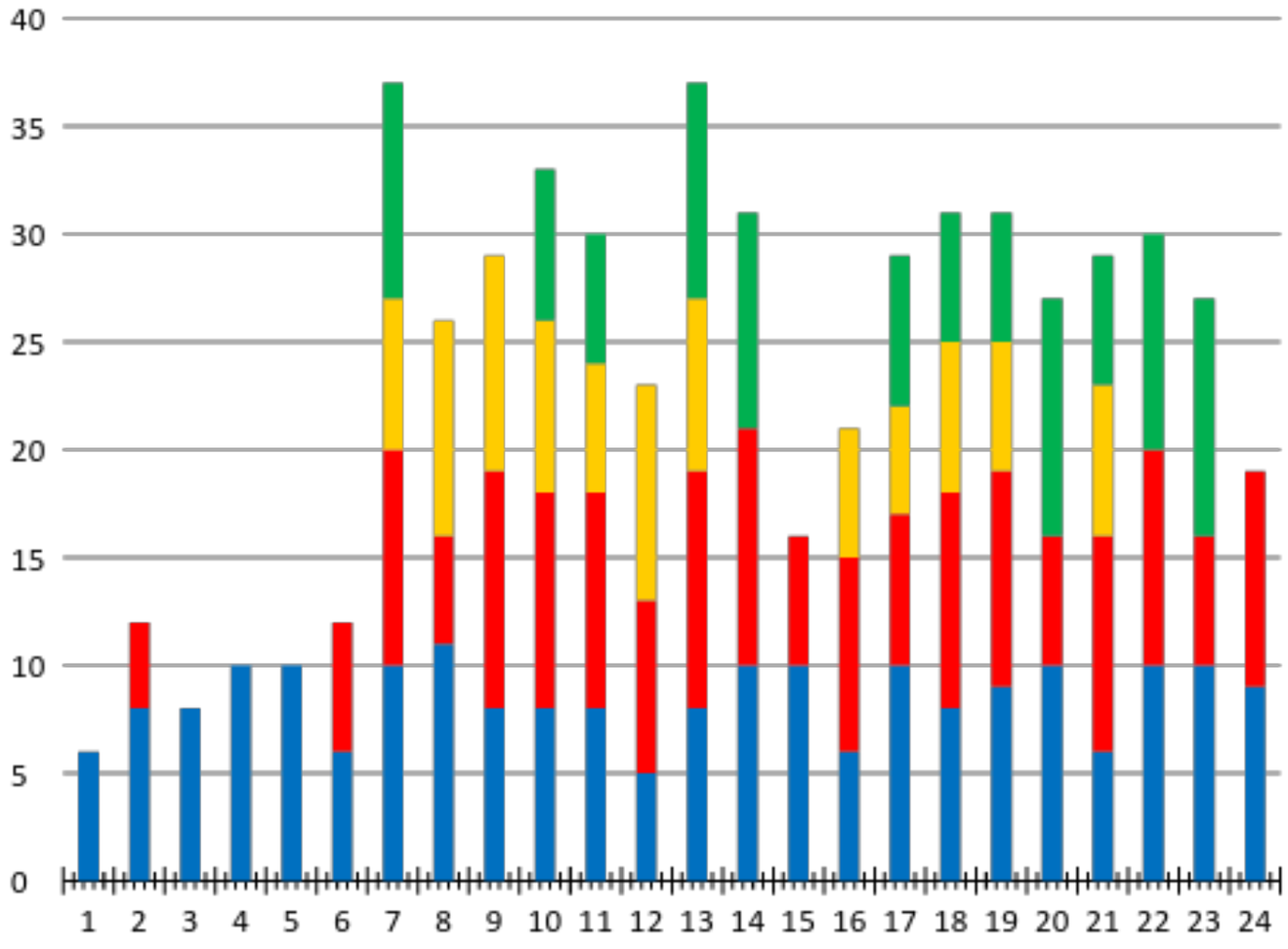
(1) Extend open hours in some special situations (e.g. max military traffic at AP4)
(2) Relax our conservative assumptions: Max mov/hour/module > 11? > 12?

Experimental Study

Mode 3: Worst case: MAX load operation (schema 6)



Scheduled



MAX extra traffic

➜ 4 modules needed:

- Workload significantly higher
- Modules at full capacity most of the time

Experimental Study

Residual capacity of RTC with 3 modules

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	*sum*
AP1						10	9						8	8									9	10	54
AP2	10	4	8	10	6	8	9		2	6	8	8	8	0		6	8	2	4	8	6	0	6	10	137
AP3	10	7		8	8		7	5	9	3	7	9	4	9		7	5	7	6	5	6	8	9	9	148
AP4							9	8	6	8	9	9	7	7	8		6	9	6	8	9	8			117
AP5							7	9	8	6	9		6			8	6	7	8	8	9	8	9		108

Residual = maximum # of movementss(10) – scheduled # of movements

Airport	Residual	MODE 2 (normal)	MODE 3 (worst-case)
AP1	54	12	40
AP2	137	23	97
AP3	148	24	34
AP4	117	19	166
AP5	108	23	60

Problem at AP4: max extra traffic exceeds the residual capacity

Conclusions

- ✓ Optimization framework for future staff planning at RTC is created
- ✓ Example solutions (schemas) proposed
- ✓ Provided new evidence of RTC efficiency
- ✓ Subject to reality checks and discussions

Future work

- ✓ Deeper EUROCONTROL data analysis for the year 2016
- ✓ Refine the model to reflect seasonal changes
- ✓ Shift focus towards actual ATCO shifts
- ✓ Include ground traffic into consideration
- ✓ Re-consider the workload definition: another bound than 10 movements per hour

Thank you.

Questions?