First Results of the Project
Capacity Modeling and Shift Optimization for Train Dispatchers
CAPMO-Train

Christiane Schmidt
Rabii Zahir

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Image source: http://www.diplomacyandcommerce.rs/serbian-trains-will-be-even-safer-and-faster-thanks-to-russian-technology/

Agenda

- Train Dispatchers—Connection to Our Work on ATCOs
- Motivation for our Project
- Who Are We?
- Project Goals
- First Results for Daily Shift Planning for Train Dispatchers

Train Dispatchers

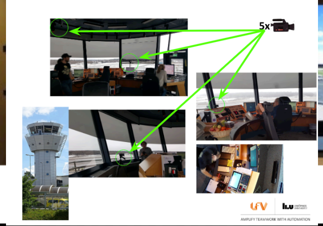
- Several train dispatchers direct and facilitate train movements
- Each train dispatcher is responsible for one or several (adjacent) geographical areas

https://www.youtube.com/watch?v=4bYtymMdg30

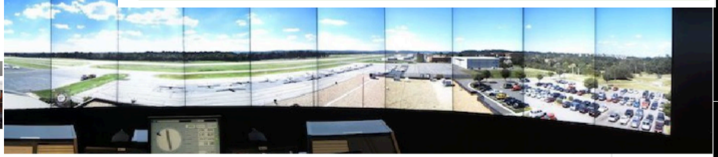
Research questions

- ✔ How are human resources (HR) **organized** at RTC?
- ✔ How is the **total taskload** from a number of airports **distributed** over several controller working positions? (**KODIC I, II projects 2016-2017**)
- ✔ How does the **workload** at the Remote Tower environment **differ** from the one at the conventional tower? (**CAPMOD project 2018-2021**)

Bromma Airport: Field Study



After optimization, RTC provides 42–55% savings



AMPLIFY TEAMWORK WITH AUTOMATION

Train dispatchers vs. ATCOs in an RTC: same same, but different

Motivation

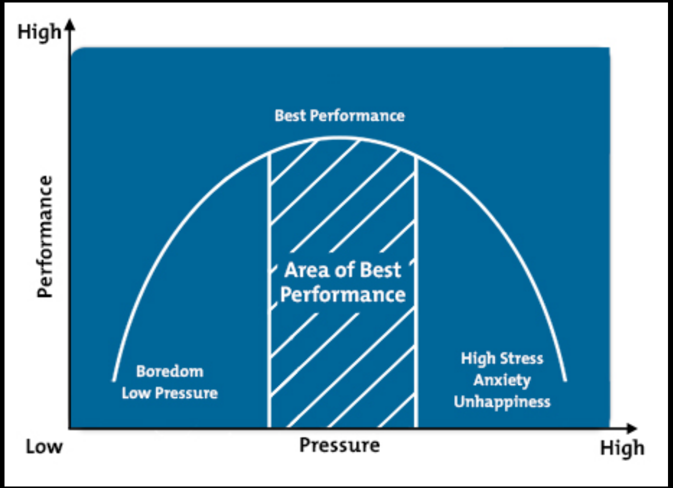


Image source: https://www.mindtools.com/pages/article/inverted-u.htm

- Several train dispatchers direct and facilitate train movements
- Work of a train dispatcher results in workload
- During a train dispatcher shift the workload should be neither too high or too low

➡ Workload within "sweet spot"

- Unforeseen events increase workload
- Shift work yields risk of fatigue

➡ Shift of train dispatchers should be planned such that workload does not exceed upper and lower thresholds, train dispatcher maintains situational awareness, fatigue is avoided, operational and legal regulations are taken into account

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Christiane Schmidt

Algorithms (PhD) and optimization,
Experience with similar combination from work with ATCOs

Tomas Lidén

PhD: optimization train traffic and maintenance,
Long experience in railway

Rabii Zahir, LiU

PhD student

Jan Andersson

Professor in HMI

Gunilla Björklund

PhD in psychology,
HMI in railway

Focus on optimization methods and shift planning (tactical and ad-hoc replanning)

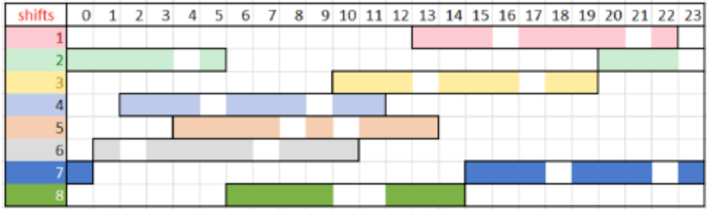
Focus on working environment of train dispatchers
Observations within other projects (BelOpt, X2R)
Usage of data in CAPMO-Train

Plan:

- Study upper and lower bounds for safe workload
- Study influence of unforeseen events on workload
- Study operational requirements on train dispatcher shifts
- Discuss objectives of any scheduling of train dispatchers from Trafikverket
- Design optimization framework for the optimal planning of train dispatcher shifts
- Computation and analysis of train dispatcher shifts for Malmö dispatching center
- Highlight trade-off between different objectives
- Highlight inefficiencies in current shift planning
- Extend optimization framework for ad-hoc replanning off train dispatcher shifts in case of unforeseen events
- Computation and analysis of train dispatcher shifts for Malmö dispatching center
- Automated shift planning incl. workload

19-Oct-16	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	2	0	0	2	1	0	0	2	0	0	0	0	0	0	0	0	1	0	0	0
AP2	1	1	2	3	4	9	10	7	5	3	2	5	7	4	5	10	8	7	6	8	8	2	0	2
AP3	1	0	2	1	6	5	2	6	4	3	5	4	2	5	6	4	6	8	6	4	3	1	2	2
AP4	0	0	0	0	2	3	3	3	2	1	2	3	2	2	2	4	3	3	0	2	0	0	0	0
AP5	0	0	0	0	3	2	0	4	3	1	2	1	0	2	4	3	2	2	1	2	0	1	0	0

Fig. 7. Controllers-to-airports assignment for the minimum total number of controllers (objective 1) during the day with highest traffic (Schema 2).The table entries give the number of movements per airport. Different colors represent different controllers.



Total #. of ATCOs	Av. # of ATCOs per airport	Av. # endorsements per ATCO	Av. time in position	Av. time at work	COP
8	7.2	4.5	7.88	9.88	0.8

Fig. 8. Top: Controller shifts (for Schema 2) for each of the eight controllers assigned to work at the RTC during the highest traffic day. The rectangular boundaries indicate the complete shift, while the colored cells indicate the hours “in position” for each controller. Bottom: Statistics for Schema 2.

Experience in shift planning and workload considerations for air traffic controllers in remote tower centers (KODIC+CAPMOD)

Initial Results CAPMO-Train (to appear in RailBelgrade 2023)

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Problem Background

A set of geographical areas to cover for one day

A set of dispatchers

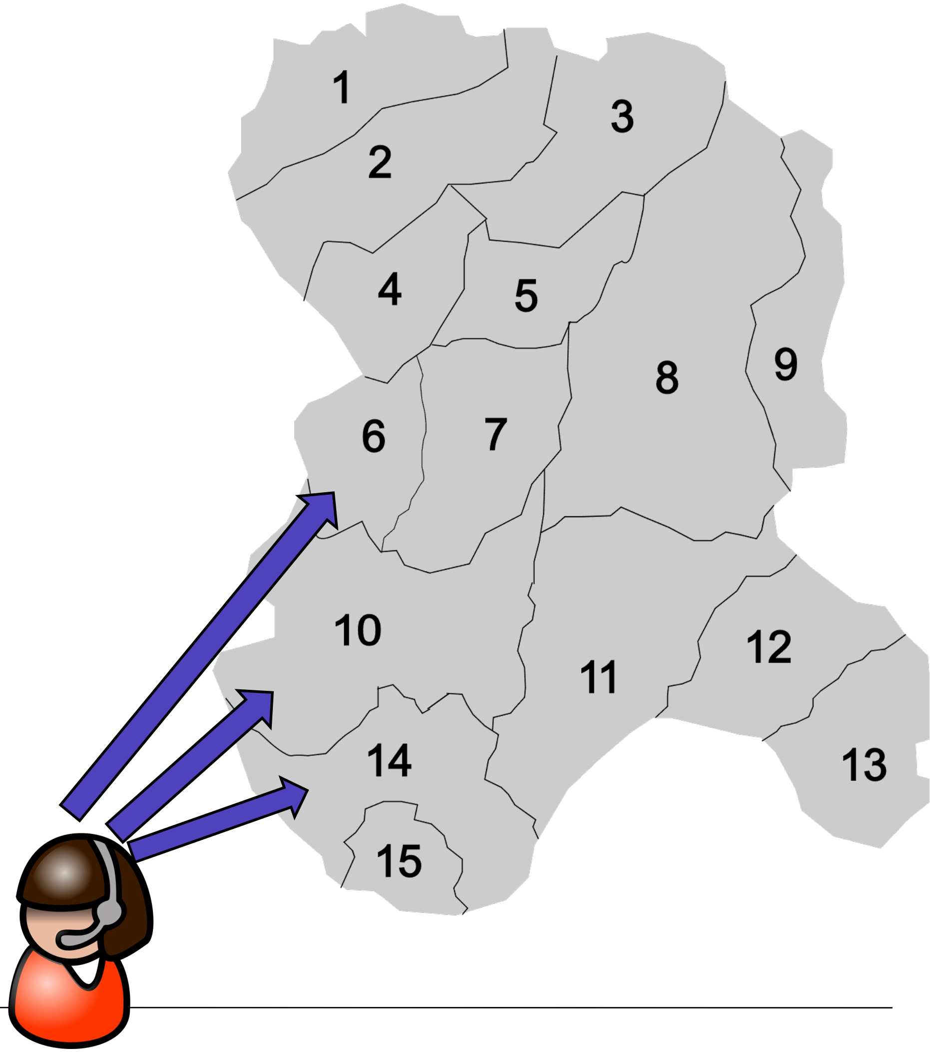
Allowed shift length

Minimum resting time between shifts

Task load per area and time period

(we use task load (train movements) to approximate workload)

The objective: produce a schedule using as less dispatchers as possible



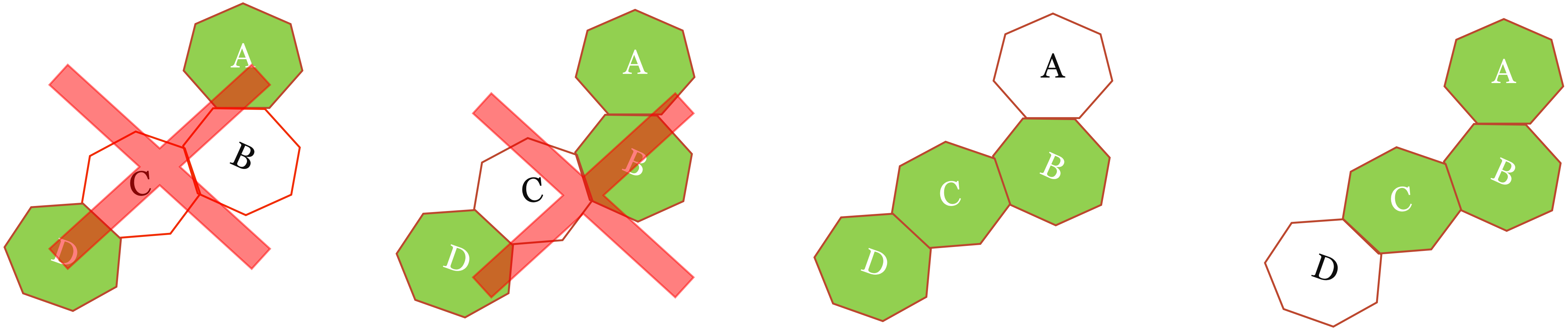
Methodology

- Literature review and interviews: Legal and operational constraints
- MILP model based on Josefsson et al.*

*Billy Josefsson, Tatiana Polishchuk, Valentin Polishchuk, and Christiane Schmidt. Scheduling air traffic controllers at the remote tower center. In 2017 IEEE/AIAA 36th Digital Avionics Systems Conference (DASC), pages 1–10. IEEE, 2017

Area Combinations

- Areas could be combined if task load allows it
- Only adjacent areas could be assigned to a dispatcher



The Model's Constraints

- Limit max task load per dispatcher
- Assign area to dispatchers with corresponding endorsement
- Limit length of a shift
- Limit min rest between shifts
- Limit size of area combinations

$$\sum_{j \in A} x_{i,j,k} \cdot TL_{j,k} \leq TL^{\max} \qquad \forall i \in D, \forall k \in P \qquad (1)$$

$$x_{i,j,k} \leq e_{i,j} \qquad \forall i \in D, \forall j \in A, \forall k \in P \qquad (2)$$

$$v_{i,k} \geq y_{i,k} - y_{i,(k-1) \pmod p} \qquad \forall i \in D, \forall k \in P \qquad (3)$$

$$v_{i,k} \leq y_{i,k} \qquad \forall i \in D, \forall k \in P \qquad (4)$$

$$\sum_{\mu = k+1-T^{\min}}^{k} v_{i,\mu \pmod p} \leq y_{i,k} \qquad \forall i \in D, \forall k \in P \qquad (5)$$

$$\sum_{\mu = k+1-T^{\max}}^{k} v_{i,\mu \pmod p} \geq y_{i,k} \qquad \forall i \in D, \forall k \in P \qquad (6)$$

$$v_{i,k} \leq q_i \qquad \forall i \in D, \forall k \in P \qquad (7)$$

$$\sum_{k \in P} v_{i,k} \geq q_i \qquad \forall i \in D \qquad (8)$$

$$y_{i,k} \leq \sum_{j \in A} x_{i,j,k} \qquad \forall i \in D, \forall k \in P \qquad (9)$$

$$y_{i,k} \geq x_{i,j,k} \qquad \forall i \in D, \forall j \in A, \forall k \in P \qquad (10)$$

$$\sum_{\mu = k+1}^{k+R^{\min}} v_{i,\mu \pmod p} \leq q_i - y_{i,k} \qquad \forall i \in D, \forall k \in P \qquad (11)$$

$$\sum_{i \in D} x_{i,j,k} = 1 \qquad \forall j \in A, k \in P \qquad (12)$$

$$x_{i,j,k} \geq c_{i,\ell,k} \qquad \forall i \in D, \forall k \in P, \forall \ell \in C, \forall j \in \ell \qquad (13)$$

$$\sum_{\ell \in C} c_{i,\ell,k} = y_{i,k} \qquad \forall i \in D, \forall k \in P \qquad (14)$$

$$x_{i,j,k} \leq 1 - c_{i,\ell,k} \qquad \forall i \in D, \forall \ell \in C, \forall j \in A \setminus \{\ell\}, \forall k \in P \qquad (15)$$

Decision Variables

- The assignment of each area during each time period for which dispatcher
- Whenever a dispatcher has been used

Variables	Description
$x_{i,j,k} \in \{0,1\}$	=1 if dispatcher i is assigned area j during period k
$c_{i,\ell,k} \in \{0,1\}$	=1 if dispatcher i is assigned area combination ℓ during period k
$y_{i,k} \in \{0,1\}$	=1 if dispatcher i is at work during period k
$v_{i,k} \in \{0,1\}$	=1 if dispatcher i starts a shift during period k
$q_i \in \{0,1\}$	=1 if dispatcher i is used during some period

The objective: Minimize the number of used dispatchers

$$\min . \quad \sum_{i \in D} q_i$$

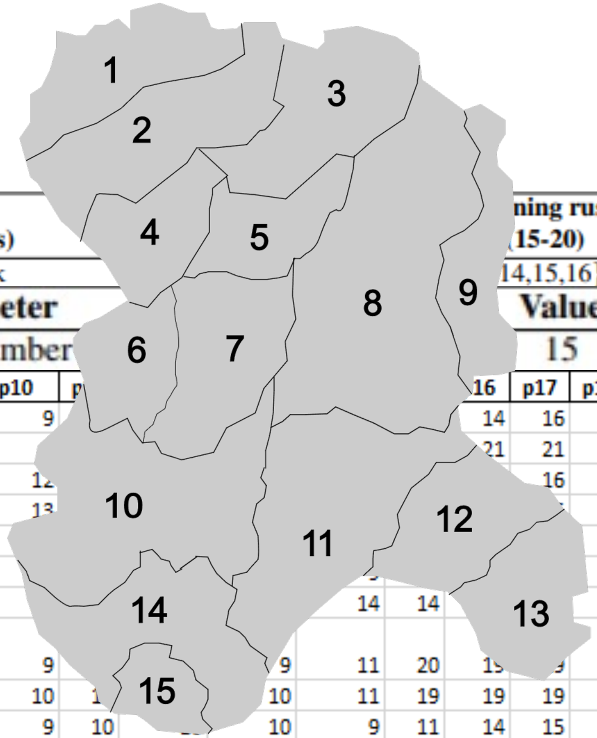
Experimental Study

Base scenario:

- Artificial data based on info from TrV
- Task load based on train movements
- 22 dispatchers to cover 15 areas
- Min and max shift length: [4h-11h]
- Min rest between shif
- Max task load: 30 mo
- Max size of area comb
- Endorsement ration:

Type and (list of areas)	ning rush (15-20)	Day time (9-15 & 20-24)
Single-track	{14,15,16}	{9,10,11}

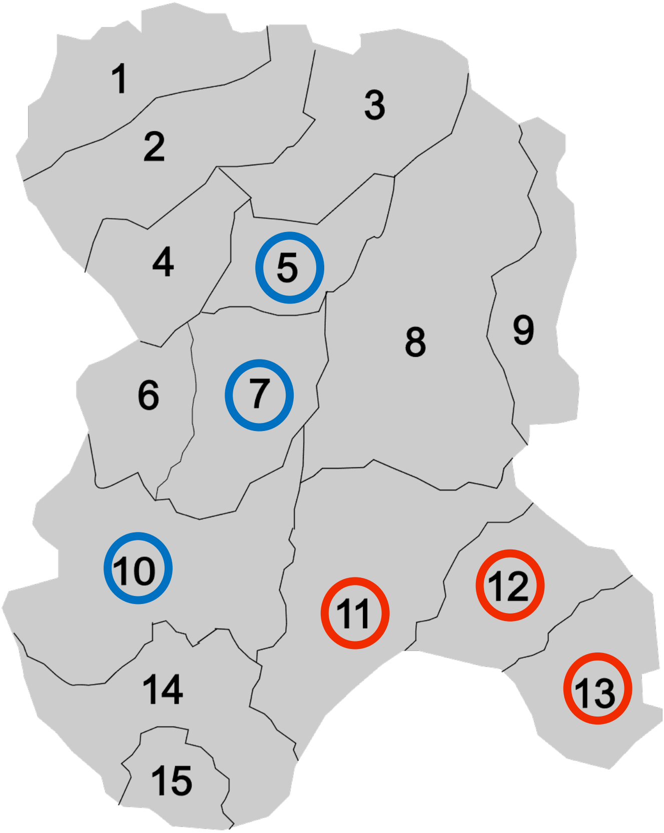
Parameter	Value
|A| (number	15



	p0	p1	p2	p3	p4	p5	p6	p7	p8	p9	p10	p11	p12	p13	p14	p15	p16	p17	p18	p19	p20	p21	p22	p23
ar.1	2	3	3	2	3	3	15	15	16	9	9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	14	16	14	10	10	10	10	9
ar.2	11	11	10	11	10	9	11	11	9	11	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	21	21	19	20	11	11	9	9
ar.3	11	12	13	11	11	11	15	14	15	13	12	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	16	16	16	11	13	14	10	12
ar.4	11	13	13	13	10	11	13	16	14	13	13	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	15	13	10	12	13	10
ar.5	11	11	11	10	9	9	9	9	11	11	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	19	20	9	9	10	9
ar.6	9	9	10	10	11	10	9	9	10	11	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	20	19	9	10	11	10
ar.7	11	14	11	13	13	12	16	15	14	10	[illegible]	[illegible]	[illegible]	[illegible]	14	14	[illegible]	[illegible]	16	12	11	11	11	13
ar.8	9	11	11	10	10	10	11	9	9	10	9	[illegible]	[illegible]	9	11	20	19	[illegible]	20	21	11	11	10	10
ar.9	10	10	9	9	11	10	10	11	9	10	10	[illegible]	[illegible]	10	11	19	19	19	21	21	11	11	9	10
ar.10	3	2	3	2	3	3	16	14	16	11	9	10	[illegible]	10	9	11	14	15	15	9	11	11	9	11
ar.11	2	2	2	3	3	2	14	14	15	11	9	10	10	10	10	11	14	15	16	11	11	9	11	10
ar.12	2	3	2	2	3	2	16	14	14	9	11	9	11	10	10	10	14	14	14	9	10	10	10	9
ar.13	3	3	2	2	3	2	14	16	14	10	9	10	10	9	11	11	15	16	16	11	11	10	11	11
ar.14	9	11	11	9	10	10	9	9	9	11	10	11	10	11	9	21	20	20	20	20	11	9	10	10
ar.15	9	9	10	9	11	11	10	10	10	11	10	10	9	10	11	20	19	19	19	19	10	10	9	9

Results Base Scenario

	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
D1												5;8;9	6;1	11;12;13	2;3	1;2	12;13	9	15	3;4	6	11;12;13		
D2	15	10	4;6	3	11;14;15	5;8;9	6;7	6;7	11;12	11;12;13	8;9													
D3														4	4;5	8	14	4;7	9	12;13	12;13	3	3;5	13
D4		3;5	1;2;3	11;12;13	12;13	1;2;3	1;2	1;2	3;4	1;2	1;2;3													
D5				10;14;15	1;2;3	4;6	10;11	10;11	14;15	6	11;12;13	10;14	1;2	15										
D6	5	4														7	5	14	5	5	7;1	6	7	1;2;3
D7	3	1	9	5	5;8;9	7	12;13	3;4														10	6;8;10	12
D8						11;12;13	14;15	12;13	1;2	14;15	14	1;2	8;9	1	1									
D9						10;14	5;8;9	14;15	5;8;9	7;8;9	6;7	3;4	4;7	8;9	6;8;10	12;13								
D10									6	10	10	6;7	12;13	2;3	11;14;15	14	4;7	8	11					
D11	6;10;14	6;7	11;12;13	1;2;4															12;13	14	3;4	1;2	14;15	10
D12	12	14;15	5;7;10														3	10;11	6	15	11	4	13	8;11
D13																15	2	15	3	9	5;8	8	1;2	7
D14	1;2;4	2														5	6	1	10	8	9	7	11;12	4;5;6
D15									13	4;5	4;5	11;12;13	5	5	7	9	15	6	14					
D16	13															3;4	1	5	2	10	15	14;15	9	9
D17	7	11;12;13	8	6;7	4;6	15	3;4	5;8;9	7;1	3	15													
D18												15	11;14;15	7	12;13	10;11	8	3	8	1;2	14	9		
D19																	9	12;13	7	11				
D20													3	6;10;14	9	6	10;11	2	4	7				
D21	8;9;11	8;9	14;15	8;9	7;1														1	6	1;2	5	4	14;15



Results Base Scenario

- Used 21 dispatchers
- Min shift length: 4h
- Max shift length: 11h
- Avg. shift length: 10.23h
- Avg. nr. Assigned areas: 1.67
- Run time: 57s

	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
D1												5;8;9	6;1	11;12;13	2;3	1;2	12;13	9	15	3;4	6	11;12;13		
D2	15	10	4;6	3	11;14;15	5;8;9	6;7	6;7	11;12	11;12;13	8;9													
D3														4	4;5	8	14	4;7	9	12;13	12;13	3	3;5	13
D4		3;5	1;2;3	11;12;13	12;13	1;2;3	1;2	1;2	3;4	1;2	1;2;3													
D5				10;14;15	1;2;3	4;6	10;11	10;11	14;15	6	11;12;13	10;14	1;2	15										
D6	5	4														7	5	14	5	5	7;1	6	7	1;2;3
D7	3	1	9	5	5;8;9	7	12;13	3;4														10	6;8;10	12
D8						11;12;13	14;15	12;13	1;2	14;15	14	1;2	8;9	1	1									
D9						10;14	5;8;9	14;15	5;8;9	7;8;9	6;7	3;4	4;7	8;9	6;8;10	12;13								
D10									6	10	10	6;7	12;13	2;3	11;14;15	14	4;7	8	11					
D11	6;10;14	6;7	11;12;13	1;2;4															12;13	14	3;4	1;2	14;15	10
D12	12	14;15	5;7;10														3	10;11	6	15	11	4	13	8;11
D13																15	2	15	3	9	5;8	8	1;2	7
D14	1;2;4	2														5	6	1	10	8	9	7	11;12	4;5;6
D15									13	4;5	4;5	11;12;13	5	5	7	9	15	6	14					
D16	13															3;4	1	5	2	10	15	14;15	9	9
D17	7	11;12;13	8	6;7	4;6	15	3;4	5;8;9	7;1	3	15													
D18												15	11;14;15	7	12;13	10;11	8	3	8	1;2	14	9		
D19																	9	12;13	7	11				
D20													3	6;10;14	9	6	10;11	2	4	7				
D21	8;9;11	8;9	14;15	8;9	7;1														1	6	1;2	5	4	14;15

Changing Endorsement Ratio

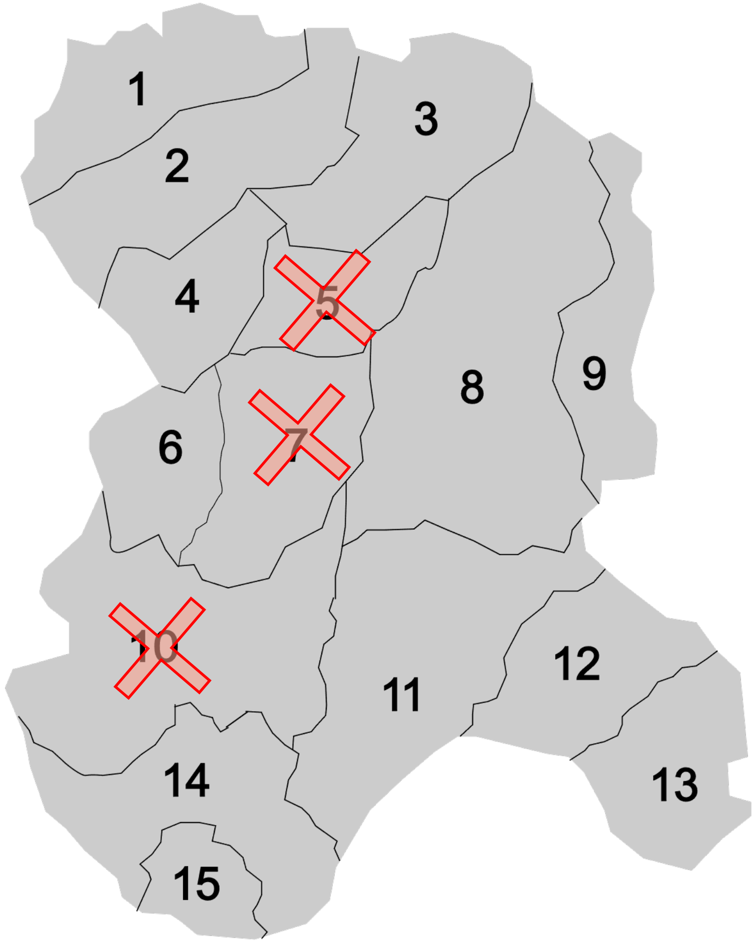
	Base scenario (100%)	$E_{1/2}$	$E_{1/3}$
nr dispatchers	21	21	22
min shift length	4h	9h	10h
max shift length	11h	11h	11h
avg. shift length	10.23h	10.86h	10.95h
avg. nr. assigned areas	1.67	1.67	1.49
run time	57s	20s	19s

Changing Allowed Size of Area Combinations

	Base scenario (3 areas)	M_4	M_2	M_1
nr dispatchers	21	21	22	33
min shift length	4h	5h	4h	10h
max shift length	11h	11h	11h	11h
avg. shift length	10.23h	10.09h	10.57h	10.91h
avg. nr. assigned areas	1.67	1.7	1.55	1
run time	57s	97s	39s	29s

Removing Areas with **High** Degree in the Adjacency Graph

	Base scenario (15 areas)	A_{10}	$A_{7,10}$	$A_{5,7,10}$
nr dispatchers	21	20	19	18
min shift length	4h	8h	10h	11h
max shift length	11h	11h	11h	11h
avg. shift length	10.23h	10.05h	10.95h	11h
avg. nr. assigned areas	1.67	1.6	1.5	1.45
run time	57s	39s	25s	21s



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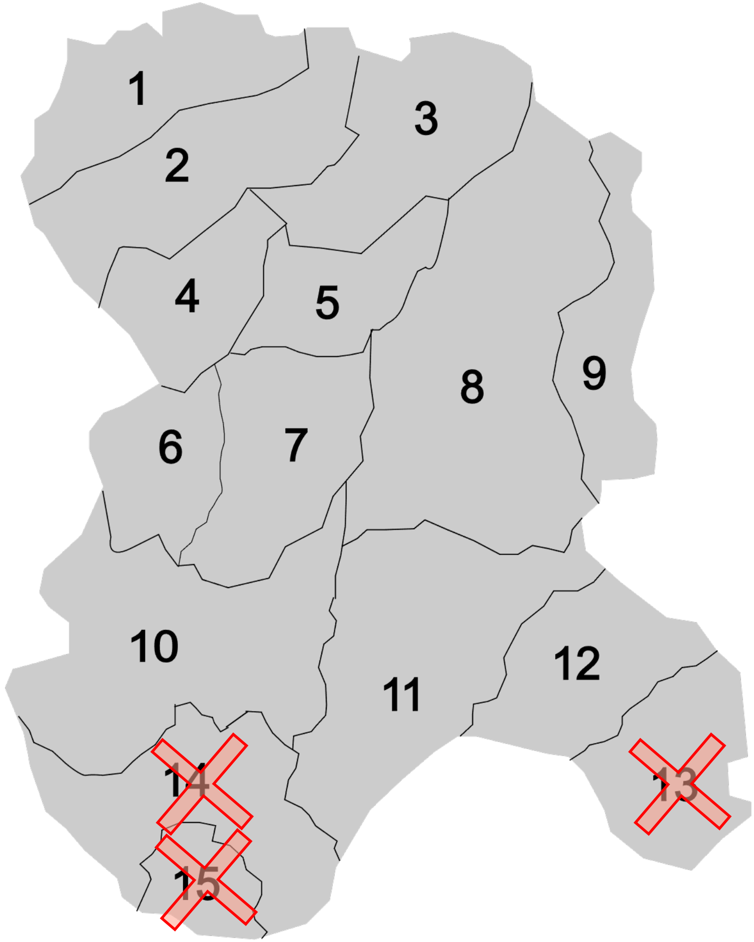
Removing Areas with **Low** Degree in the Adjacency Graph

	Base scenario (15 areas	A_{13}	$A_{13,15}$	$A_{13,14,15}$
nr dispatchers	21	20	18	17
min shift length	4h	8h	5h	5h
max shift length	11h	11h	11h	11h
avg. shift length	10.23h	10.55h	10.05h	10.58h
avg. nr. assigned areas	1.67	1.59	1.72	1.6
run time	57s	305s	245s	252s



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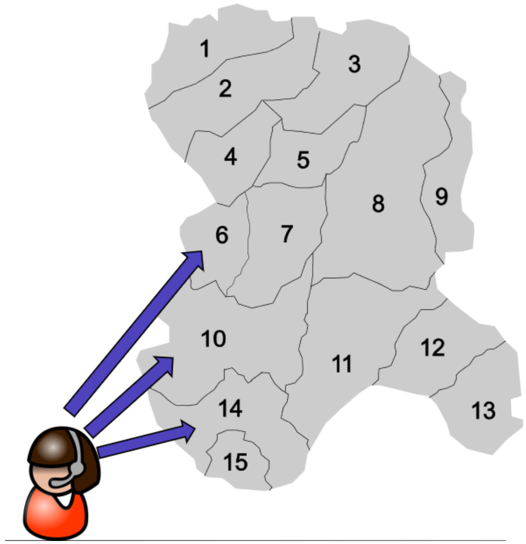
Conclusion and Future Work

- IP for automating shift scheduling
- Run time between 19 and 305s
- Surprisingly, the run time doesn’t necessary decrease with a lower nr of areas
- The avg and min shift length is independent of the different parameters (need to be controlled explicitly)
- Next: alternative objectives (min nr switches, min area assignments/disp), expanding time horizon, improve the model



Thank you for listening

$$\sum_{j\in A} x_{i,j,k}\cdot TL_{j,k} \le TL^{\max} \quad \forall i\in D, \forall k\in P \quad (1)$$

$$x_{i,j,k} \le e_{i,j} \quad \forall i\in D, \forall j\in A, \forall k\in P \quad (2)$$

$$v_{i,k} \ge y_{i,k} - y_{i,(k-1)(\text{mod } p)} \quad \forall i\in D, \forall k\in P \quad (3)$$

$$v_{i,k} \le y_{i,k} \quad \forall i\in D, \forall k\in P \quad (4)$$

$$\sum_{\mu=k+1-T^{\min}}^{k} v_{i,\mu(\text{mod } p)} \le y_{i,k} \quad \forall i\in D, \forall k\in P \quad (5)$$

$$\sum_{\mu=k+1-T^{\max}}^{k} v_{i,\mu(\text{mod } p)} \ge y_{i,k} \quad \forall i\in D, \forall k\in P \quad (6)$$

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$$\sum_{k\in P} v_{i,k} \ge q_i \quad \forall i\in D \quad (8)$$

$$y_{i,k} \le \sum_{j\in A} x_{i,j,k} \quad \forall i\in D, \forall k\in P \quad (9)$$

$$y_{i,k} \ge x_{i,j,k} \quad \forall i\in D, \forall j\in A, \forall k\in P \quad (10)$$

$$\sum_{\mu=k+1}^{k+R^{\min}} v_{i,\mu(\text{mod } p)} \le q_i - y_{i,k} \quad \forall i\in D, \forall k\in P \quad (11)$$

$$\sum_{i\in D} x_{i,j,k} = 1 \quad \forall j\in A, k\in P \quad (12)$$

$$x_{i,j,k} \ge c_{i,\ell,k} \quad \forall i\in D, \forall k\in P, \forall \ell\in C, \forall j\in \ell \quad (13)$$

$$\sum_{\ell\in C} c_{i,\ell,k} = y_{i,k} \quad \forall i\in D, \forall k\in P \quad (14)$$

$$x_{i,j,k} \le 1 - c_{i,\ell,k} \quad \forall i\in D, \forall \ell\in C, \forall j\in A\setminus\{\ell\}, \forall k\in P \quad (15)$$

	00	01	02	03	04	05	06	07	08	09	10	11
D1												5;8;9
D2	15	10	4;6	3	11;14;15	5;8;9	6;7	6;7	11;12	11;12;13	8;9	
D3												
D4		3;5	1;2;3	11;12;13	12;13	1;2;3	1;2	1;2	3;4	1;2	1;2;3	
D5				10;14;15	1;2;3	4;6	10;11	10;11	14;15	6	11;12;13	10;14
D6	5	4										
D7	3	1	9	5	5;8;9	7	12;13	3;4				
D8						11;12;13	14;15	12;13	1;2	14;15	14	1;2
D9						10;14	5;8;9	14;15	5;8;9	7;8;9	6;7	3;4
D10									6	10	10	6;7
D11	6;10;14	6;7	11;12;13	1;2;4								
D12	12	14;15	5;7;10									
D13												
D14	1;2;4	2										
D15									13	4;5	4;5	11;12;13
D16	13											
D17	7	11;12;13	8	6;7	4;6	15	3;4	5;8;9	7;1	3	15	
D18												15
D19												
D20												
D21	8;9;11	8;9	14;15	8;9	7;1							

	12	13	14	15	16	17	18	19	20	21	22	23
D1	6;1	11;12;13	2;3	1;2	12;13	9	15	3;4	6	11;12;13		
D2												
D3		4	4;5	8	14	4;7	9	12;13	12;13	3	3;5	13
D4												
D5	1;2	15										
D6				7	5	14	5	5	7;1	6	7	1;2;3
D7										10	6;8;10	12
D8	8;9	1	1									
D9	4;7	8;9	6;8;10	12;13								
D10	12;13	2;3	11;14;15	14	4;7	8	11					
D11							12;13	14	3;4	1;2	14;15	10
D12					3	10;11	6	15	11	4	13	8;11
D13				15	2	15	3	9	5;8	8	1;2	7
D14				5	6	1	10	8	9	7	11;12	4;5;6
D15	5	5	7	9	15	6	14					
D16				3;4	1	5	2	10	15	14;15	9	9
D17												
D18	11;14;15	7	12;13	10;11	8	3	8	1;2	14	9		
D19					9	12;13	7	11				
D20	3	6;10;14	9	6	10;11	2	4	7				
D21							1	6	1;2	5	4	14;15

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Project’s homepage: https://weber.itn.liu.se/~chrsc91/projects/CAPMO-Train/