Shift Scheduling for Air Traffic Controllers in Remote Tower Centers and for Train Dispatchers

Christiane Schmidt, LiU

Based on joint work with Tobias Andersson Granberg, Eulalia Hernández-Romero, Jörn Jakobi, Billy Josefsson, Anastasia Lemetti, Tomas Lidén, Lothar Meyer, Anne Papenfuss, Maximilian Peukert, Tatiana Polishchuk, Valentin Polishchuk, Leonid Sedov, Rabii Zahir

MAI Optimization Seminar, March 4, 2024

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- ATCO work
  - Remote Tower Centers (RTCs)
  - Assigning Airports to Remote-Tower Modules
  - ATCO Rostering at an RTC
  - ATCO Workload Investigation
  - Weather Impact on ATCO Work
- Shift Scheduling for Train Dispatchers
  - Problem Formulation
  - First Model
  - Improved Model + Handling of Handovers
- Outlook: Current and Future Work

Remote Tower Center (RTC)

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- Provides air traffic services to small airports

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- Replaces local tower with cameras and sensors
- Increases efficiency: HR and ATS costs are split between several airports
- First RTC: Sundsvall RTC
- New RTC build in Stockholm

Remote Tower Center

- How to **distribute** the **total taskload** from several airports over several air traffic controller (ATCO) working positions?

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- How to assign a qualified **ATCO** to each position, respecting the constraints on the duration of controllers shifts, breaks and the necessity of maintaining ratings?

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➡ Development of general optimization framework designed as a flexible tool for **staff planning/shift scheduling**

Remote Tower Center (RTC)

- Which factors contribute to **ATCO's workload**?

CAPMOD: **Capacity Modeling for Controller Workload Evaluation at RTC Arlanda, 2018-2021**

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- **Difference** in workload at **RTC vs. conventional towers**?

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➡ Study of ATCO workload in RTCs

Remote Tower Center (RTC)

- Which factors contribute to **ATCO's workload**?
- **Difference** in workload at **RTC vs. conventional towers**?
- How do we factor in **unscheduled events: weather**?

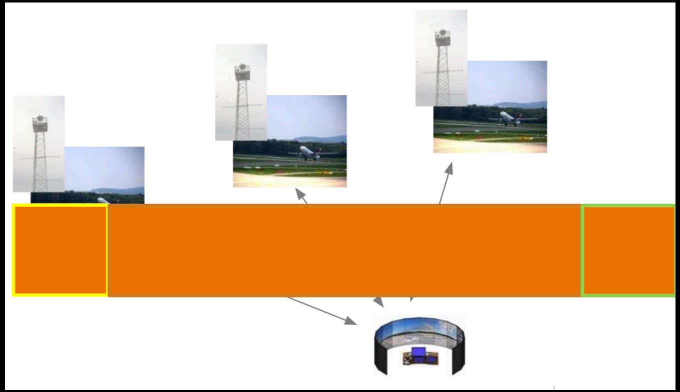
➡ Study of ATCO workload in RTCs

➡ Integration of probabilistic modeling for increased predictability of the extra workload due to unscheduled events (extreme weather conditions) into optimization framework

Assigning Airports to Remote-Tower Modules

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
(4) Number of airports assigned to one module bounded (1, 2, 3, ?)
(5) Total number of moves within a module is bounded



Goal: Propose optimal assignment of the airports to RTC modules

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T. Andersson, P. Axelsson, J. Petersson, T. Polishchuk, V. Polishchuk, C. Schmidt. *Configuration and Planning of the Remote Tower Modules in a Remote Tower Center.* In *ICRAT'16.* Philadelphia, USA.

B. Joseffson, T. Polishchuk, V. Polishchuk, C. Schmidt. *A Step Towards Remote Tower Center Deployment: Optimizing Staff Scheduling.* In *ATM Seminar 2017.* Seattle, USA.

ATCO Rostering at an RTC

B. Josefsson, T. Polishchuk, V. Polishchuk, C.Schmidt: Scheduling Air Traffic Controllers at the Remote Tower Center, In 36th IEEE/AIAA Digital Avionics Systems Conference (DASC), 2017.

ATCO Rostering at an RTC

- Workload from several airports (#movements per airport)

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- Workload from several airports (#movements per airport)
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ATCO Rostering at an RTC

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- Maximum time “in position”
- Scheduled breaks
- Endorsements and trainings
- 24/7 operation
- Automation needed

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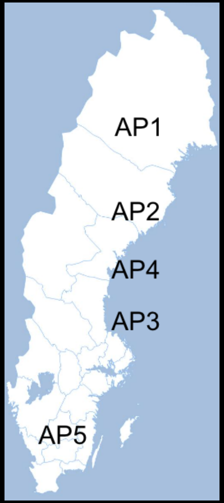
ATCO Rostering at an RTC–Objective: min #ATCOs

High traffic

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



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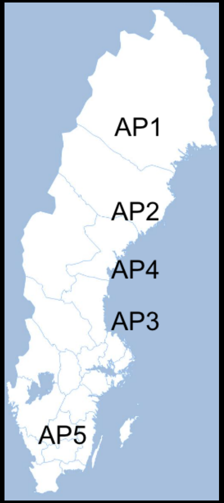
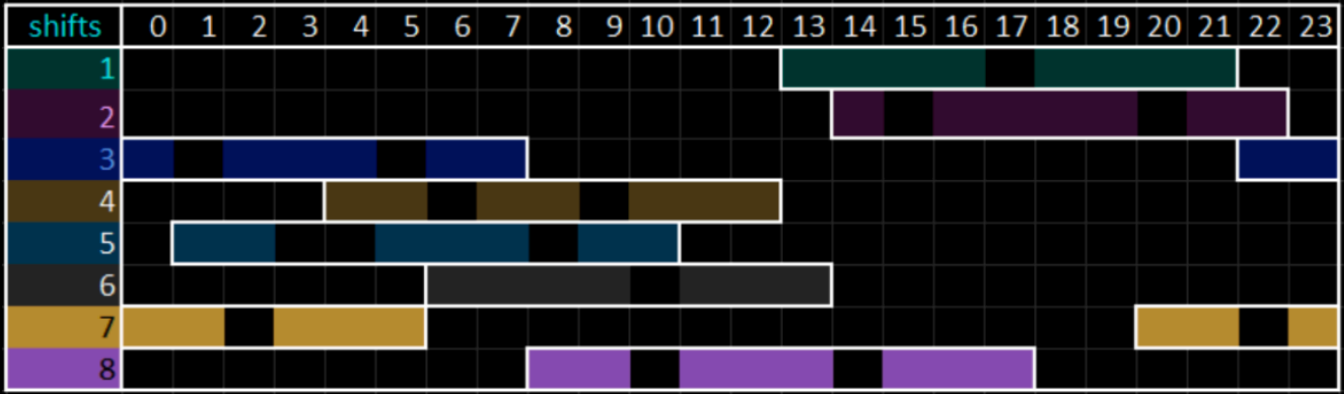


19-Oct-16	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
AP1	0	0	0	0	2	0	0	2	1	0	0	2	0	0	0	0	0	0	0	0	1	0	0	0
AP2	1	1	2	3	4	9	10	7	5	3	2	5	7	4	5	10	8	7	6	8	8	2	0	2
AP3	1	0	2	1	6	5	2	6	4	3	5	4	2	5	6	4	6	8	6	4	3	1	2	2
AP4	0	0	0	0	2	3	3	3	2	1	2	3	2	2	2	4	3	3	0	2	0	0	0	0
AP5	0	0	0	0	3	2	0	4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



Total #. of ATCOs	Av. # of ATCOs per airport	Av. # endorsements per ATCO	Av. time in position	Av. time at work	COP
8	3.4	2.13	7.5	9.38	0.8

Minimum 8 ATCOs needed to cover 5 airports

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ATCO Rostering at an RTC–Objective: min #ATCOs

ATCO	Mon 03.10	Tue 04.10	Wed 05.10	Thur 06.10	Fri 07.10	Sat 08.10	Sun 09.10
1	14:00 18:00	6:00 10:00		23:00 0:00	0:00-8:00 23:00-0:00	0:00-6:00 22:00-0:00	0:00-9:00 23:00-8:00
2		20:00 23:00	0:00-8:00 23:00-0:00	0:00-9:00 20:00-0:00	0:00-6:00 14:00-17:00		
3		8:00 12:00		9:00 17:00	15:00 23:00	16:00 22:00	6:00 16:00
4	19:00 0:00	0:00-2:00 22:00-0:00	0:00-6:00 19:00-0:00	0:00 6:00	19:00 0:00	11:00 16:00	
5		9:00 14:00	7:00 19:00	8:00 20:00	7:00 11:00		
6	0:00-8:00 16:00-21:00	6:00 12:00	13:00 21:00	8:00 17:00			
7	8:00 14:00	6:00 18:00		19:00 23:00	7:00 16:00		
8		15:00 22:00	8:00 12:00	16:00 23:00	9:00 14:00		11:00 23:00
9		20:00 0:00	0:00-7:00	14:00 18:00	10:00 14:00		
10	19:00 0:00	0:00 6:00			19:00 0:00	0:00-7:00 20:00-0:00	0:00-6:00 21:00-0:00
11	8:00 22:00	6:00 18:00	7:00 15:00		11:00 15:00		
12	0:00 9:00		10:00 21:00	6:00 10:00	6:00 18:00		
13	19:00 0:00	0:00 6:00		6:00 18:00			
14	11:00 18:00		20:00 0:00	0:00-8:00 20:00-0:00	17:00 21:00	6:00 15:00	
15	11:00 15:00	10:00 14:00	10:00 14:00			7:00 19:00	9:00 21:00
16			8:00 20:00	6:00 18:00			
17		9:00 20:00	17:00 0:00	0:00-1:00 9:00-13:00			

ATCO	Mon 10.10	Tue 11.10	Wed 12.10	Thur 13.10	Fri 14.10	Sat 15.10	Sun 16.10
1		22:00-0:00	0:00-10:00				
2	9:00 15:00	7:00 14:00		18:00 21:00	10:00 16:00	10:00 19:00	6:00 10:00
3			6:00 12:00				
4	20:00 0:00	0:00-7:00 18:00-0:00	0:00 6:00				
5	14:00 23:00		10:00 20:00		14:00 19:00	19:00 0:00	0:00 7:00
6	8:00 15:00		13:00 19:00	7:00 19:00	8:00 15:00		20:00 0:00
7	19:00 0:00	0:00-3:00 20:00-0:00	0:00-1:00 21:00-0:00	0:00-6:00 16:00-20:00	11:00 17:00		19:00 23:00
8	18:00 0:00	9:00 22:00					
9			8:00 14:00		17:00 22:00	6:00 18:00	6:00 18:00
10	0:00-9:00 18:00-22:00	6:00 12:00					
11		14:00 19:00	10:00 21:00	6:00 16:00		7:00 16:00	
12	19:00 0:00	0:00 6:00		11:00 16:00	17:00 22:00	18:00 0:00	0:00-6:00 21:00-0:00
13			19:00 0:00	0:00-7:00 23:00-0:00	0:00 11:00		8:00 20:00
14	14:00 18:00	6:00 18:00					
15	8:00 19:00	19:00 0:00	0:00 6:00				
16		8:00 20:00			8:00 20:00		
17	9:00 13:00	7:00 11:00		20:00 0:00	0:00-8:00 22:00-0:00	0:00 7:00	12:00 19:00

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ATCO Rostering at an RTC–Objective: min #ATCOs

ATCO	Mon 03.10		Tue 04.10		Wed 05.10		Thur 06.10		Fri 07.10		Sat 08.10		Sun 09.10	
1	14:00	18:00	6:00	10:00			23:00	0:00	0:00-8:00	23:00-0:00	0:00-6:00	22:00-0:00	0:00-9:00	23:00-8:00
2			20:00	23:00	0:00-8:00	23:00-0:00	0:00-9:00	20:00-0:00	0:00-6:00	14:00-17:00				
3			8:00	12:00			9:00	17:00	15:00	23:00	16:00	22:00	6:00	16:00
4	19:00	0:00	0:00-2:00	22:00-0:00	0:00-6:00	19:00-0:00	0:00	6:00	19:00	0:00	11:00	16:00		
5			9:00	14:00	7:00	19:00	8:00	20:00	7:00	11:00				
6	0:00-8:00	16:00-21:00	6:00	12:00	13:00	21:00	8:00	17:00						
7	8:00	14:00	6:00	18:00			19:00	23:00	7:00	16:00				
8			15:00	22:00	8:00	12:00	16:00	23:00	9:00	14:00			11:00	23:00
9			20:00	0:00	0:00-7:00		14:00	18:00	10:00	14:00				
10	19:00	0:00	0:00	6:00					19:00	0:00	0:00-7:00	20:00-0:00	0:00-6:00	21:00-0:00
11	8:00	22:00	6:00	18:00	7:00	15:00			11:00	15:00				
12	0:00	9:00			10:00	21:00	6:00	10:00	6:00	18:00				
13	19:00	0:00	0:00	6:00			6:00	18:00						
14	11:00	18:00			20:00	0:00	0:00-8:00	20:00-0:00	17:00	21:00	6:00	15:00		
15	11:00	15:00	10:00	14:00	10:00	14:00					7:00	19:00	9:00	21:00
16					8:00	20:00	6:00	18:00						
17			9:00	20:00	17:00	0:00	0:00-1:00	9:00-13:00						

ATCO	Mon 10.10		Tue 11.10		Wed 12.10		Thur 13.10		Fri 14.10		Sat 15.10		Sun 16.10	
1				22:00-0:00	0:00-10:00									
2	9:00	15:00	7:00	14:00			18:00	21:00	10:00	16:00	10:00	19:00	6:00	10:00
3					6:00	12:00								
4	20:00	0:00	0:00-7:00	18:00-0:00	0:00	6:00								
5	14:00	23:00			10:00	20:00			14:00	19:00	19:00	0:00	0:00	7:00
6	8:00	15:00			13:00	19:00	7:00	19:00	8:00	15:00			20:00	0:00
7	19:00	0:00	0:00-3:00	20:00-0:00	0:00-1:00	21:00-0:00	0:00-6:00	16:00-20:00	11:00	17:00			19:00	23:00
8	18:00	0:00	9:00	22:00										
9					8:00	14:00			17:00	22:00	6:00	18:00	6:00	18:00
10	0:00-9:00	18:00-22:00	6:00	12:00										
11			14:00	19:00	10:00	21:00	6:00	16:00			7:00	16:00		
12	19:00	0:00	0:00	6:00			11:00	16:00	17:00	22:00	18:00	0:00	0:00-6:00	21:00-0:00
13					19:00	0:00	0:00-7:00	23:00-0:00	0:00	11:00			8:00	20:00
14	14:00	18:00	6:00	18:00										
15	8:00	19:00	19:00	0:00	0:00	6:00								
16			8:00	20:00					8:00	20:00				
17	9:00	13:00	7:00	11:00			20:00	0:00	0:00-8:00	22:00-0:00	0:00	7:00	12:00	19:00

Minimum 17 ATCOs needed to cover 5 airports during 2 weeks

B. Josefsson, T. Polishchuk, V. Polishchuk, C.Schmidt: Scheduling Air Traffic Controllers at the Remote Tower Center, In 36th IEEE/AIAA Digital Avionics Systems Conference (DASC), 2017.

RTC Efficiency Evaluation

NUMBER OF CONTROLLERS	INDIVIDUAL 5 AIRPORTS	SAME 5 AIRPORTS AT RTC
Lower bound for the highest traffic day (October 19, 2016)	17	8
With the buffer of 33% – 45% for the highest traffic day (October 19, 2016)	26–34	12–15

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After optimization, the RTC provides savings of 42-55%

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ATCO Workload Investigation

- Within CAPMOD project:

Data analysis from Simulations

- DLR simulation data
- Sundsvall validation trials (May-June 2019)

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B. Josefsson, J. Jakobi, A. Papenfuss, T. Polishchuk, C. Schmidt, L. Sedov Identification of Complexity Factors for Remote Towers. In SESAR Innovation Days (SID 2018), December 3-5, Salzburg.

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L. Meyer, M. Peukert, T. Polishchuk, C.Schmidt: Investigating Ocular and Head-Yaw Measures as Indicators for Workload and Fatigue under Varying Taskload Conditions, In 10th International Conference on Research in Air Transportation (ICRAT '22)

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Observations and data collection in conventional towers (field study) + data analysis
- Field study at Bromma airport (March 2019) video-recording, audio, questionnaires

Statistical learning: Subjective vs. objective assessment (workload rating vs. quantitative measures derived from eye tracking and video analysis)

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  Statistical learning: Subjective vs. objective assessment (workload rating vs. quantitative measures derived from eye tracking and video analysis)
- Now running: OWL project (On WorkLoad Measures)

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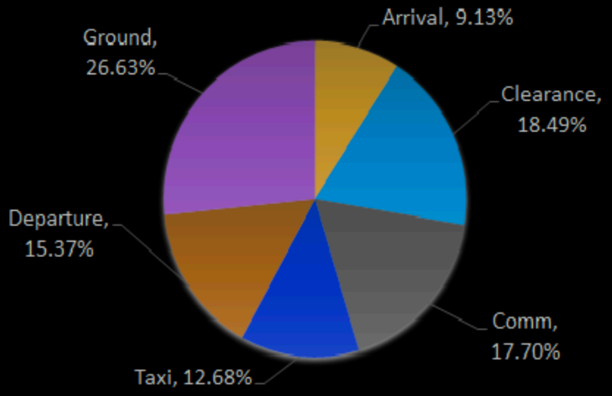
Bromma Field Study

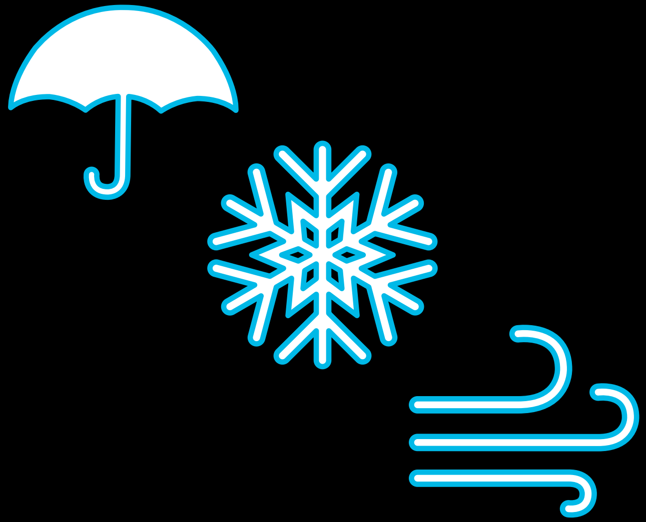
Weather Impact



Ground communication takes the largest share in total communication duration

Snow sweeping coordination is a major part in ground communication

Weather Impact on ATCO Work



- Increased communication with ground services and pilots
- More frequent out-of-window observations
- Changes in Arrival and Departure routes and procedures

B. Josefsson, A. Lemetti, T. Polishchuk, V. Polishchuk, C. Schmidt. Integrating Weather Impact in RTC Staff Scheduling. SESAR Innovation Days (SID) 2020.

E. Hérnandez-Romero, B. Josefsson, A. Lemetti, T. Polishchuk, C.Schmidt: Integrating Weather Impact in Air Traffic Controller Shift Scheduling in Remote and Conventional Towers, In EURO Journal on Transportation and Logistics

Weather Impact on ATCO Work

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- Conventional towers: staff adjustments are quite rare despite noticeable influence of weather
- Remote towers: weather impact to be integrated into automated rostering
- Multiple operation: ensure no controller is confronted unmanageable workload

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No good measures or classifications for weather impact on ATCOs exist

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Weather Impact on ATCO Work

- Increased communication with ground services and pilots
- More frequent out-of-window observations
- Changes in Arrival and Departure routes and procedures

- Conventional towers: staff adjustments are quite rare despite noticeable influence of weather
- Remote towers: weather impact to be integrated into automated rostering
- Multiple operation: ensure no controller is confronted unmanageable workload

No good measures or classifications for weather impact on ATCOs exist

Research questions:

How do different weather phenomena impact ATCO workload at different airports?

How to quantify the weather-induced capacity reductions?

How can we integrate this impact in RTC staff scheduling?

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Contributes to: safety assessment of multiple operation (required by unions and regulation bodies)

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Weather Impact on ATCO Work

To integrate weather impact into RTC staff scheduling we propose these steps:

1. Identify impactful weather phenomena for each considered airport
2. Define threshold values for these impactful weather phenomena
3. Obtain weather data in form of EPS
4. Obtain flight movements data for all airports for the chosen dates.
5. Calculate a distribution of the necessary number of ATCOs for RTC staffing

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Weather Impact on ATCO Work

ATCO interviews, identify additional tasks because of different weather phenomena

Prose formulation	Numerical value
no	0
rarely, not too much	0.25
sometimes, maybe, can happen, several times	0.5
often, increased, more likely, higher	0.75
yes	1
much more; yes, significantly	1.25

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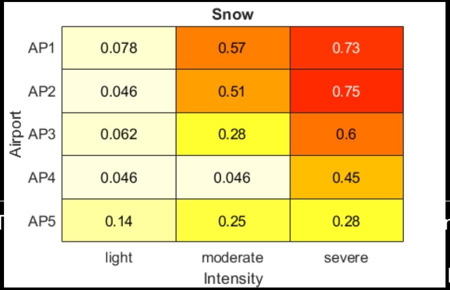
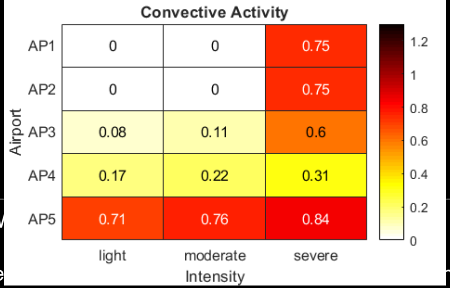
Snow
Precipitation
Low Visibility
Strong Winds
Convective Activity

We summed up the numerical values reflecting controller's answers and divided by the number of additional tasks





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Input: Flight movements at several RTC airports per hour **+ requirements for single operation**
Output: Optimal assignment of controllers to RTC airports per hour
Constraints: Operational + controller shift constraints (in multiple mode - max 2 a/p per ATCO)
+new constraint to force single operation

Formulated as MILP (mixed-integer linear program)

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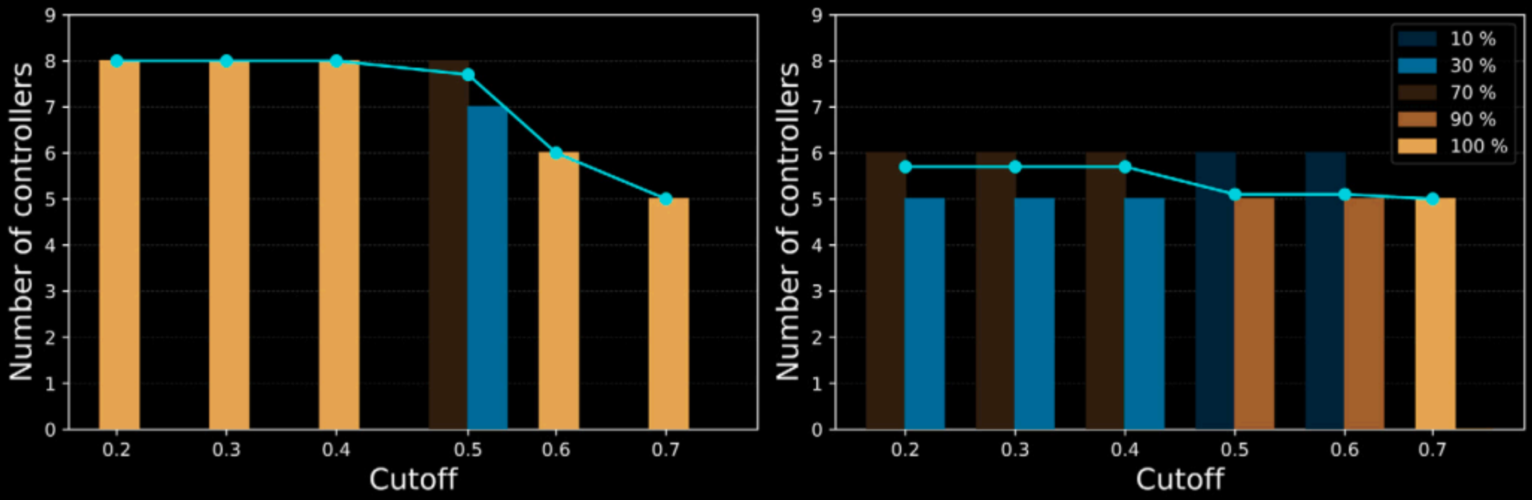
Weather Impact on ATCO Work

February 16, 2020 (6:00 - 14:00) winter weather **July 29, 2020 (14:00-22:00)** summer weather

No weather impact: **5** controllers needed



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Shift Scheduling for Train Dispatchers

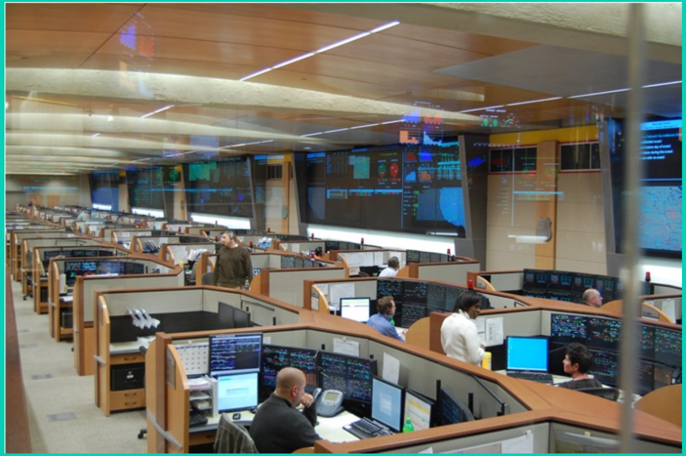

Image source: https://www.flickr.com/photos/americaspower/3418746613/

Now: Train Dispatchers

- The role of a train dispatcher:

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Now: Train Dispatchers

- The role of a train dispatcher:
  - Monitoring & controlling train traffic

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- The role of a train dispatcher:
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- The role of a train dispatcher:
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- The role of a train dispatcher:
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- High tempo: high workload (WL) level

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Shift scheduling today:

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CAPMO-Train: **Capacity Modeling and Shift Optimization for Train Dispatchers,** 2021-2024

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Shift scheduling today:

- Manual process

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- Very complex and time consuming

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Shift scheduling today:

- Manual process
- Very complex and time consuming
- Should fulfill many legal and operational constraints
- May result in over/understaffed shifts: cost vs safety

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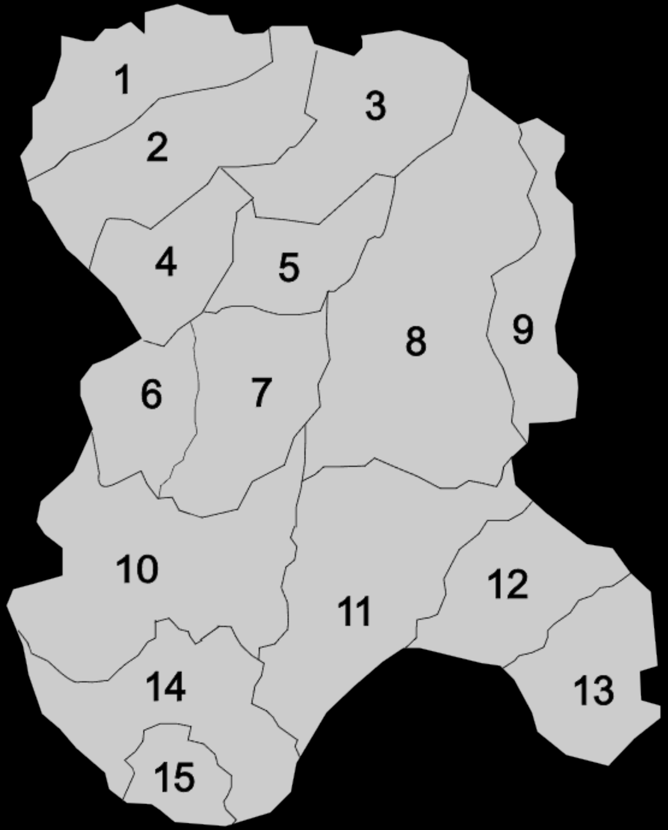
Problem

- A set of geographical areas to cover (for one day)



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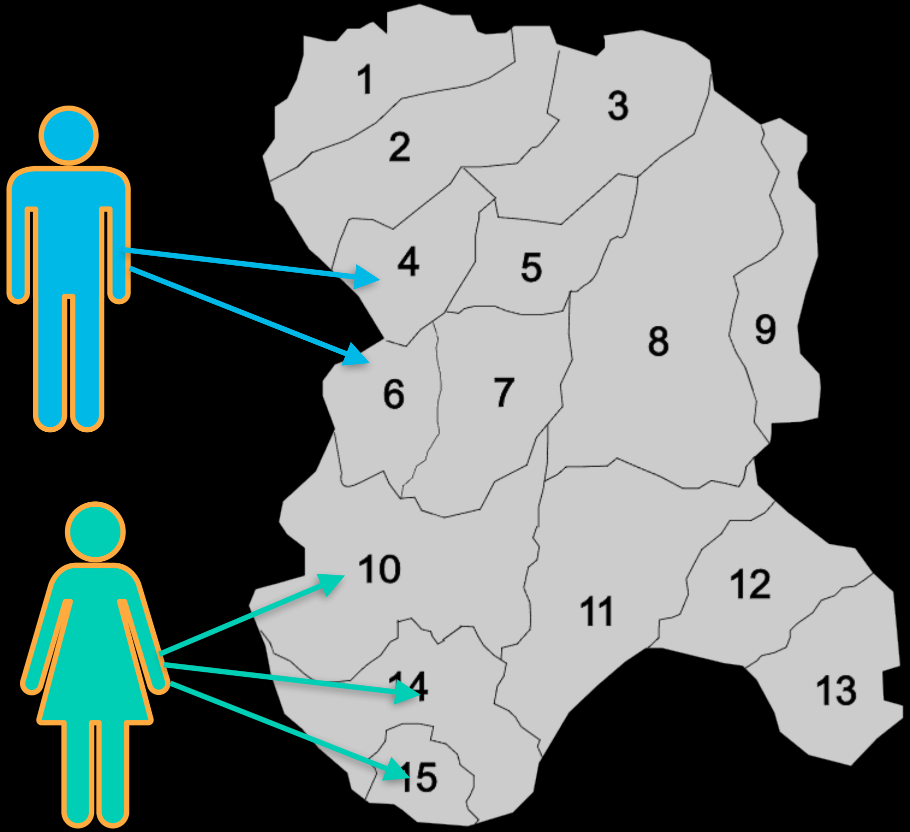
Problem

- A set of geographical areas to cover (for one day)
- A set of dispatchers to be assigned to the areas



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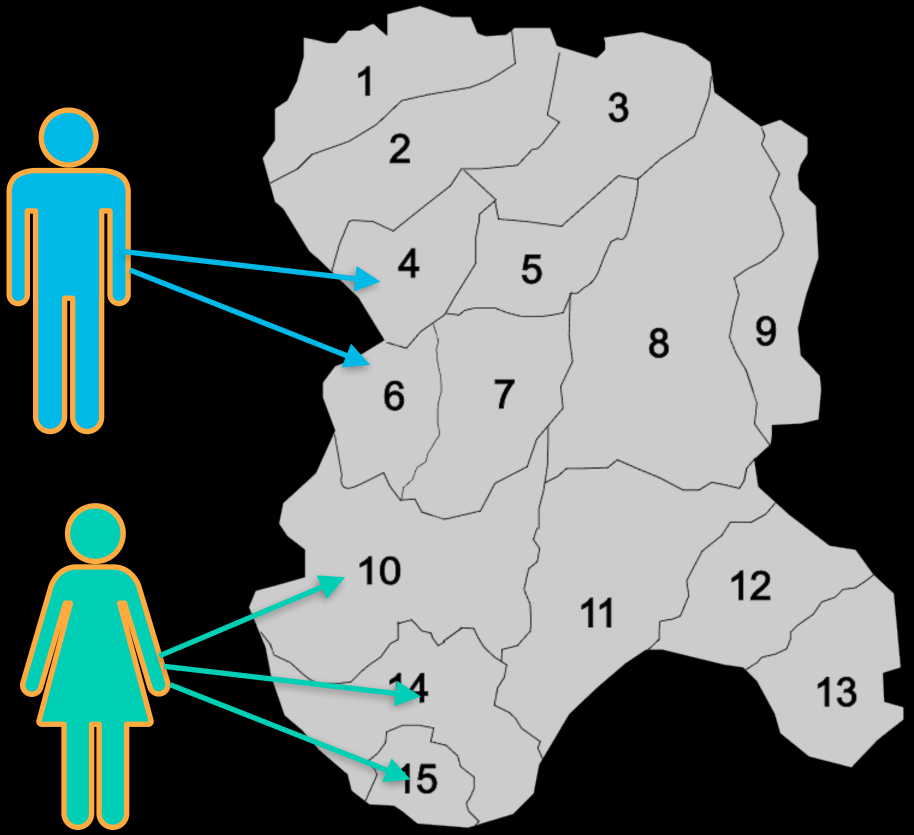
Problem

- A set of geographical areas to cover (for one day)
- A set of dispatchers to be assigned to the areas
- Allowed shift length



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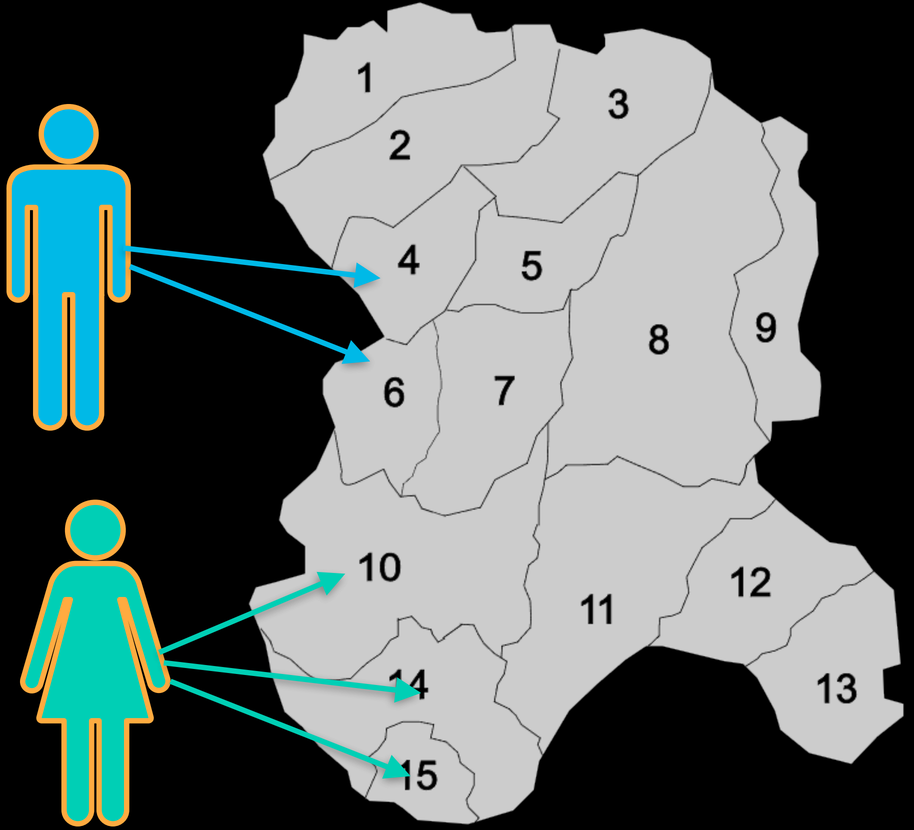
Problem

- A set of geographical areas to cover (for one day)
- A set of dispatchers to be assigned to the areas
- Allowed shift length
- Minimum resting time between shifts



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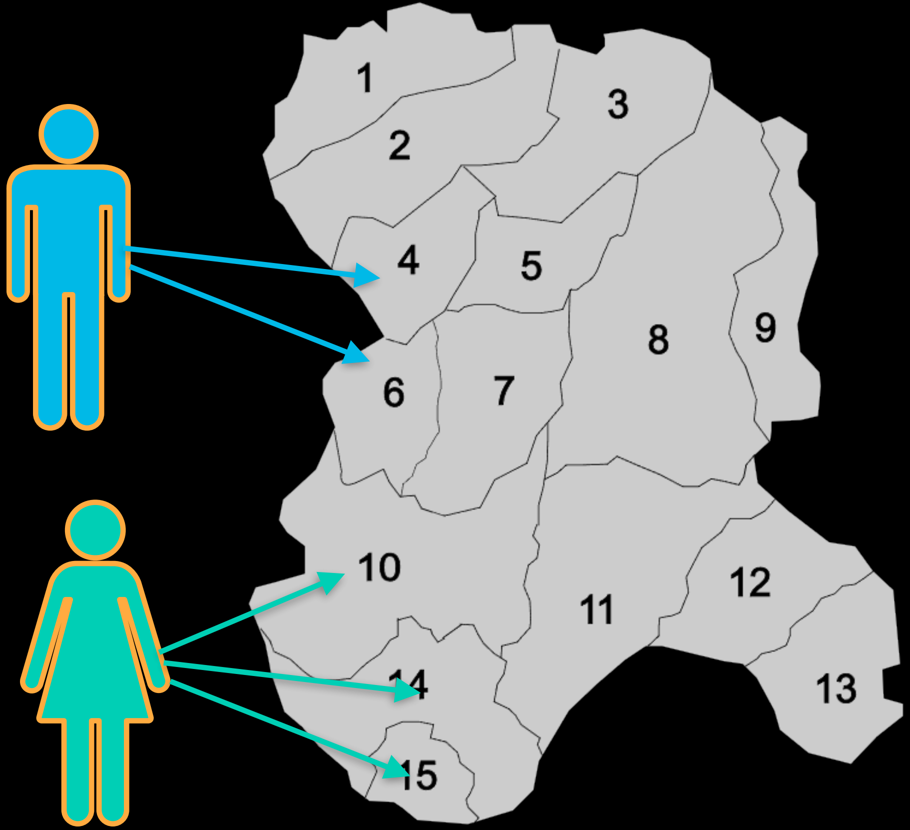

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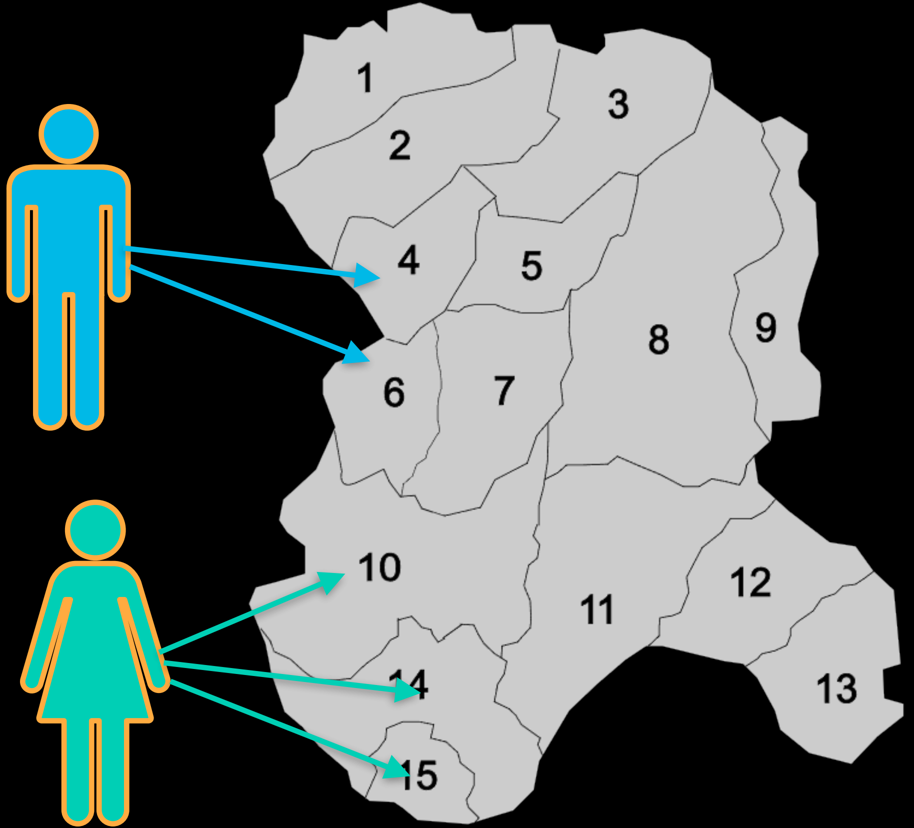

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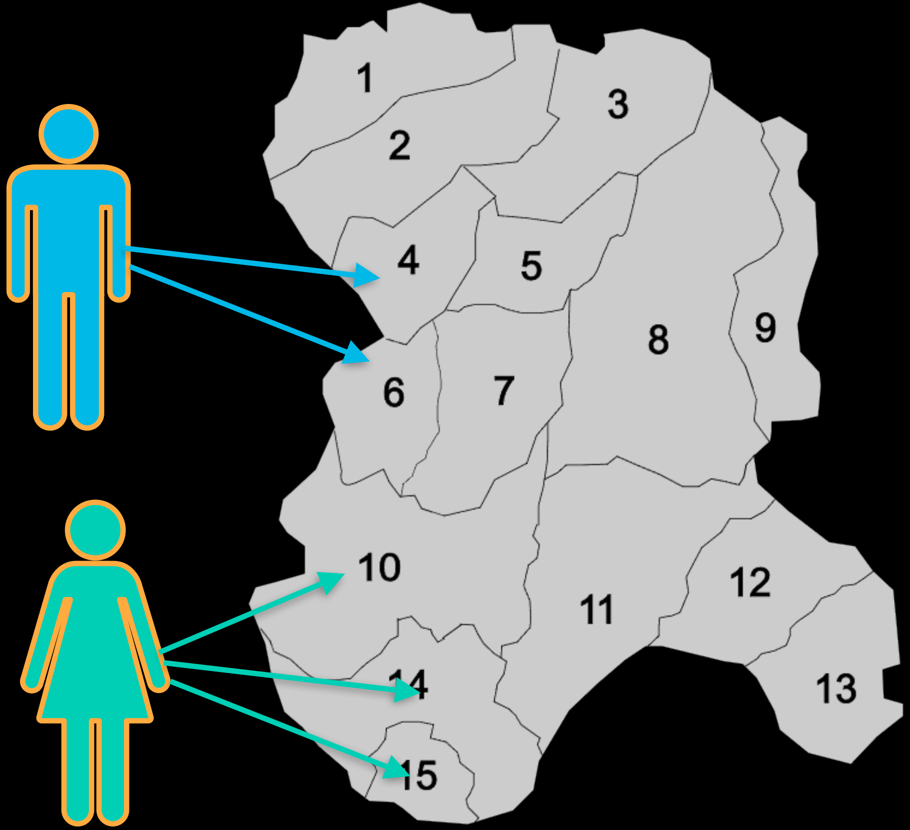
- Areas can be combined if



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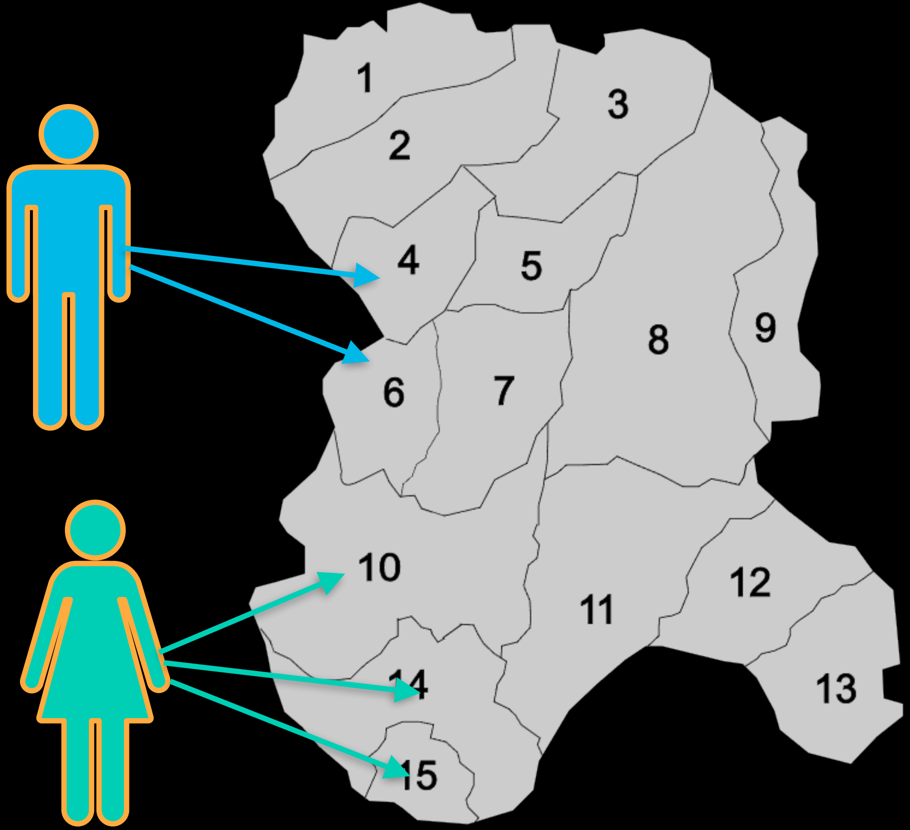

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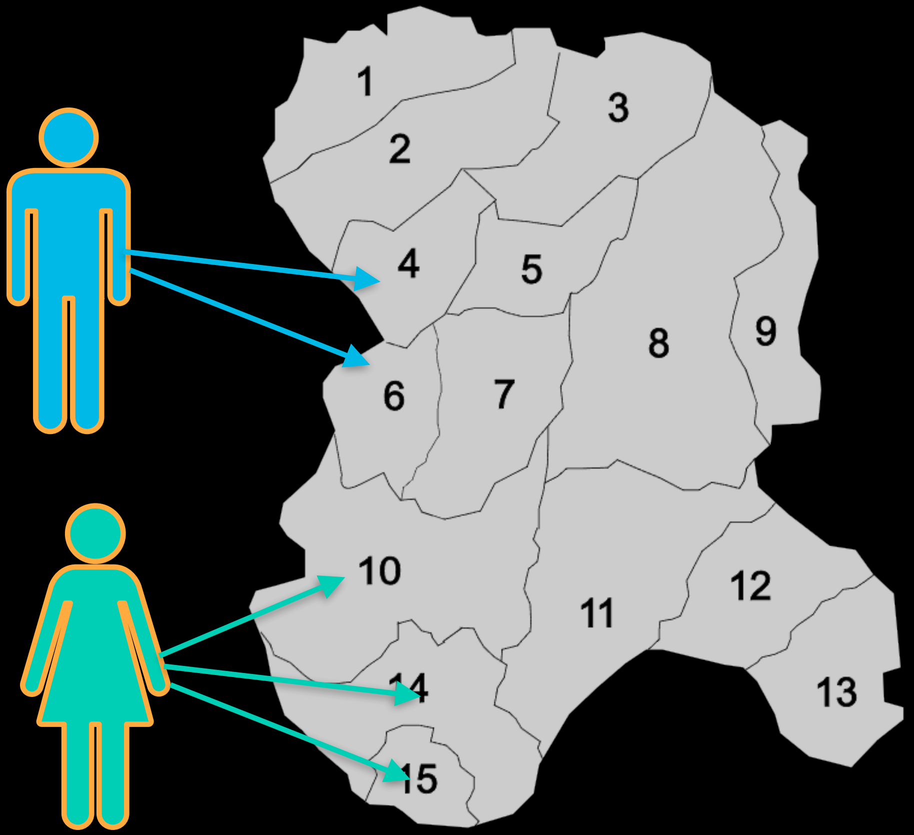
  - Assigned areas are adjacent



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Train Dispatchers: First Model

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

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Train Dispatchers: First Model

$$
\begin{aligned}
\sum_{j\in A} x_{i,j,k}\cdot TL_{j,k} &\leq TL^{\max} && \forall i\in D,\forall k\in P && (1)\\
x_{i,j,k} &\leq e_{i,j} && \forall i\in D,\forall j\in A,\forall k\in P && (2)\\
v_{i,k} &\geq y_{i,k} - y_{i,(k-1)\pmod p} && \forall i\in D,\forall k\in P && (3)\\
v_{i,k} &\leq y_{i,k} && \forall i\in D,\forall k\in P && (4)\\
\sum_{\mu=k+1-T^{\min}}^{k} v_{i,\mu\pmod p} &\leq y_{i,k} && \forall i\in D,\forall k\in P && (5)\\
\sum_{\mu=k+1-T^{\max}}^{k} v_{i,\mu\pmod p} &\geq y_{i,k} && \forall i\in D,\forall k\in P && (6)\\
v_{i,k} &\leq q_i && \forall i\in D,\forall k\in P && (7)\\
\sum_{k\in P} v_{i,k} &\geq q_i && \forall i\in D && (8)\\
y_{i,k} &\leq \sum_{j\in A} x_{i,j,k} && \forall i\in D,\forall k\in P && (9)\\
y_{i,k} &\geq x_{i,j,k} && \forall i\in D,\forall j\in A,\forall k\in P && (10)\\
\sum_{\mu=k+1}^{k+R^{\min}} v_{i,\mu\pmod p} &\leq q_i - y_{i,k} && \forall i\in D,\forall k\in P && (11)\\
\sum_{i\in D} x_{i,j,k} &= 1 && \forall j\in A, k\in P && (12)\\
x_{i,j,k} &\geq c_{i,\ell,k} && \forall i\in D,\forall k\in P, \forall \ell\in C,\forall j\in \ell && (13)\\
\sum_{\ell\in C} c_{i,\ell,k} &= y_{i,k} && \forall i\in D,\forall k\in P && (14)\\
x_{i,j,k} &\leq 1 - c_{i,\ell,k} && \forall i\in D,\forall \ell\in C, \forall j\in A\setminus\{\ell\},\forall k\in P && (15)
\end{aligned}
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Train Dispatchers: First Model

- Taskload does not exceed the maximum

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

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

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

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

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

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Train Dispatchers: First Model

- Taskload does not exceed the maximum
- Only assigned if dispatcher is qualified for the area

$$
\begin{array}{llll}
\sum_{j\in A} x_{i,j,k}\cdot TL_{j,k} & \leq & TL^{\max} & \forall i\in D, \forall k\in P \quad (1)\\
x_{i,j,k} & \leq & e_{i,j} & \forall i\in D, \forall j\in A, \forall k\in P \quad (2)\\
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\end{array}
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- Taskload does not exceed the maximum
- Only assigned if dispatcher is qualified for the area
- Only start if at work, and was not at work before

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

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

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

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

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

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

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

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

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

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Train Dispatchers: First Model

- Taskload does not exceed the maximum
- Only assigned if dispatcher is qualified for the area
- Only start if at work, and was not at work before
- Minimum and maximum shift length

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

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

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$$
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\sum_{j\in A} x_{i,j,k} \cdot TL_{j,k} & \leq & TL^{\max} & \forall i \in D, \forall k \in P & (1)\\
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- Minimum rest between shifts

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\begin{aligned}
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$$
\begin{aligned}
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- Negative connection of x and c

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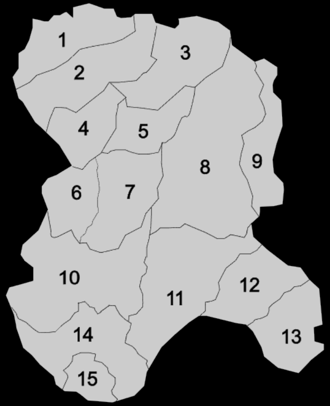
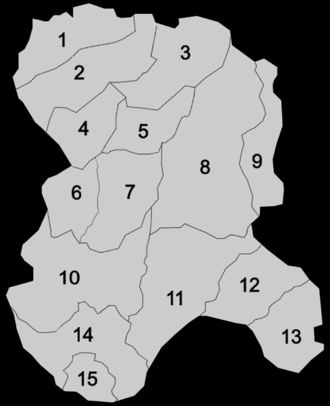
Experiments

Base scenario:



Lidén, T., Schmidt, C., & Zahir, R.(2023). Shift Scheduling for Train Dispatchers. In *10th International Conference on Railway Operations Modelling and Analysis (ICROMA), Belgrade, Serbia, April 25th–28th, 2023* (pp. 120-120).

Experiments



Base scenario:
- Artificial data based on info from Trafikverket

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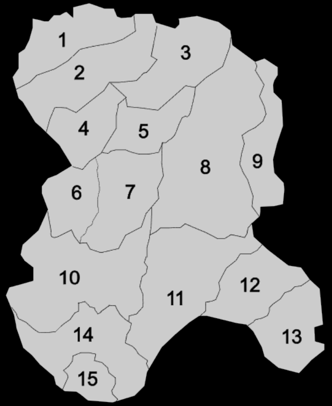
Experiments



Base scenario:

- Artificial data based on info from Trafikverket
- Task load based on train movements

Type and (list of areas)	Night time (0-6)	Morning rush (6-9)	Evening rush (15-20)	Day time (9-15 & 20-24)
Single-track (1,10,11,12,13)	{2,3}	{14,15,16}	{14,15,16}	{9,10,11}
Double-track (2,5,6,8,9,14,15)	{9,10,11}	{9,10,11}	{19,20,21}	{9,10,11}
Complex (3,4,7)	{10,11,12,13,14}	{13,14,15,16}	{14,15,16,17}	{10,11,12,13,14}

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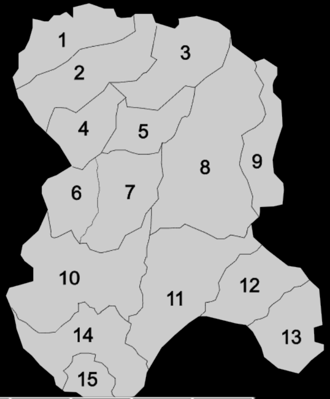
Experiments



Base scenario:

- Artificial data based on info from Trafikverket
- Task load based on train movements

	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	11	10	11	11	9	14	16	14	10	10	10	10	9
ar.2	11	11	10	11	10	9	11	11	9	11	9	9	11	9	11	21	21	21	19	20	11	11	9	9
ar.3	11	12	13	11	11	11	15	14	15	13	12	13	13	11	10	13	16	16	16	11	13	14	10	12
ar.4	11	13	13	13	10	11	13	16	14	13	13	13	14	11	13	12	16	15	15	13	10	12	13	10
ar.5	11	11	11	10	9	9	9	9	11	11	9	9	9	10	11	19	20	21	19	20	9	9	10	9
ar.6	9	9	10	10	11	10	9	9	10	11	10	10	10	9	9	21	20	20	20	19	9	10	11	10
ar.7	11	14	11	13	13	12	16	15	14	10	13	12	12	13	14	14	14	15	16	12	11	11	11	13
ar.8	9	11	11	10	10	10	11	9	9	10	9	11	11	9	11	20	19	19	20	21	11	11	10	10
ar.9	10	10	9	9	11	10	10	11	9	10	10	10	10	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	10	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

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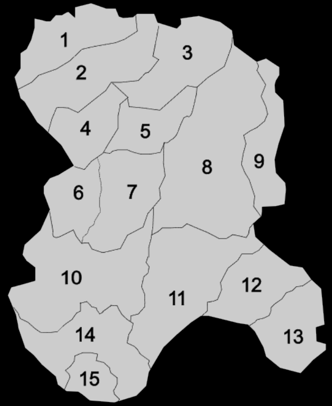
Experiments



Base scenario:

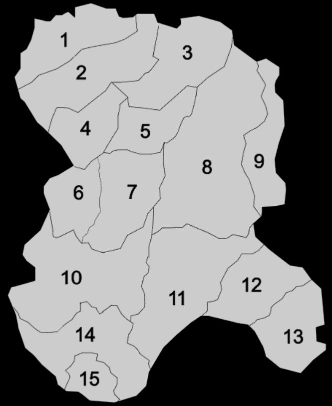
- Artificial data based on info from Trafikverket
- Task load based on train movements
- 22 dispatchers (available) to cover 15 areas

Lidén, T., Schmidt, C., & Zahir, R.(2023). Shift Scheduling for Train Dispatchers. In *10th International Conference on Railway Operations Modelling and Analysis (ICROMA), Belgrade, Serbia, April 25th–28th, 2023* (pp. 120-120).

Experiments

Base scenario:

- Artificial data based on info from Trafikverket
- Task load based on train movements
- 22 dispatchers (available) to cover 15 areas
- Min and max shift length: [4h-11h]



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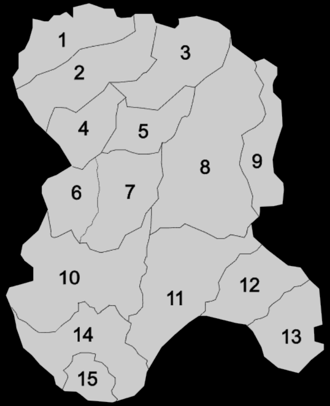
Experiments



Base scenario:

- Artificial data based on info from Trafikverket
- Task load based on train movements
- 22 dispatchers (available) to cover 15 areas
- Min and max shift length: [4h-11h]
- Min rest between shifts: 11h

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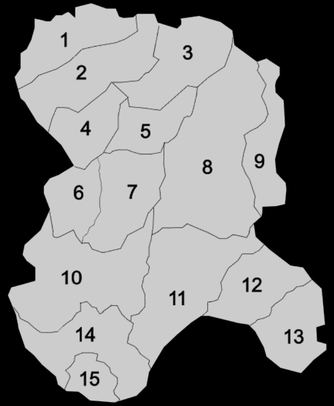
Experiments

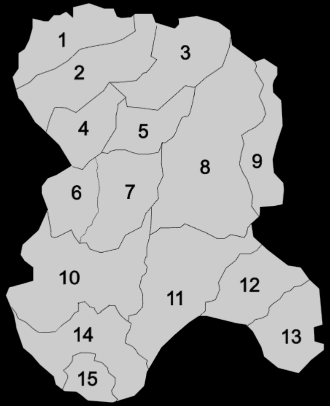


Base scenario:

- Artificial data based on info from Trafikverket
- Task load based on train movements
- 22 dispatchers (available) to cover 15 areas
- Min and max shift length: [4h-11h]
- Min rest between shifts: 11h
- Max task load: 30 movements

Lidén, T., Schmidt, C., & Zahir, R.(2023). Shift Scheduling for Train Dispatchers. In *10th International Conference on Railway Operations Modelling and Analysis (ICROMA), Belgrade, Serbia, April 25th–28th, 2023* (pp. 120-120).

Experiments



Base scenario:

- Artificial data based on info from Trafikverket
- Task load based on train movements
- 22 dispatchers (available) to cover 15 areas
- Min and max shift length: [4h-11h]
- Min rest between shifts: 11h
- Max task load: 30 movements
- Max size of area combinations: 3

LINKÖPING UNIVERSITY

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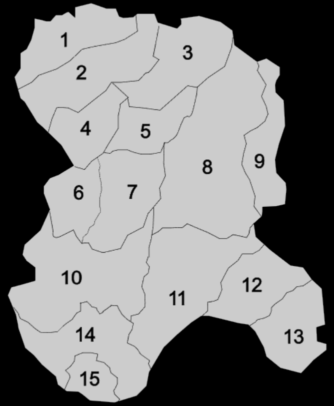
Experiments

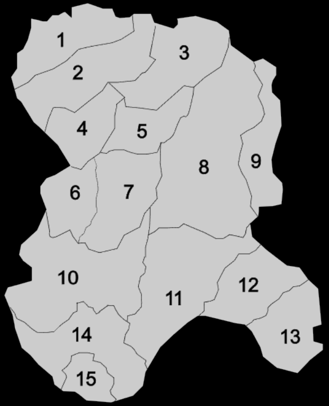


Base scenario:

- Artificial data based on info from Trafikverket
- Task load based on train movements
- 22 dispatchers (available) to cover 15 areas
- Min and max shift length: [4h-11h]
- Min rest between shifts: 11h
- Max task load: 30 movements
- Max size of area combinations: 3
- Endorsement ratio: 100%

Lidén, T., Schmidt, C., & Zahir, R.(2023). Shift Scheduling for Train Dispatchers. In *10th International Conference on Railway Operations Modelling and Analysis (ICROMA), Belgrade, Serbia, April 25th–28th, 2023* (pp. 120-120).

Result 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

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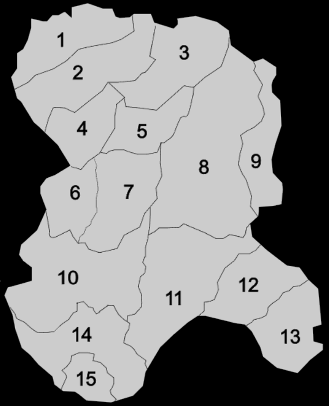
Result Base Scenario

- 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

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Changing the Ratio of Endorsements Hold

	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

Lidén, T., Schmidt, C., & Zahir, R.(2023). Shift Scheduling for Train Dispatchers. In *10th International Conference on Railway Operations Modelling and Analysis (ICROMA), Belgrade, Serbia, April 25th–28th, 2023* (pp. 120-120).

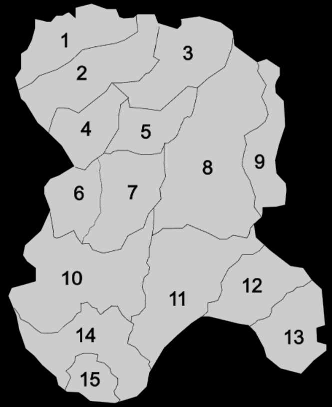
Different Maximum Cardinality of Connected Components

	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

Lidén, T., Schmidt, C., & Zahir, R.(2023). Shift Scheduling for Train Dispatchers. In *10th International Conference on Railway Operations Modelling and Analysis (ICROMA), Belgrade, Serbia, April 25th–28th, 2023* (pp. 120-120).

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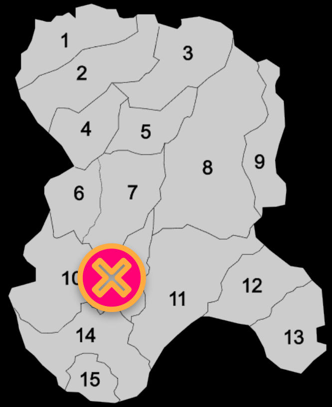
Removing Areas with High Degree in Adjacency Graph

	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 High Degree in 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
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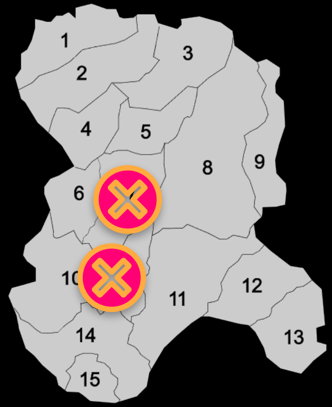

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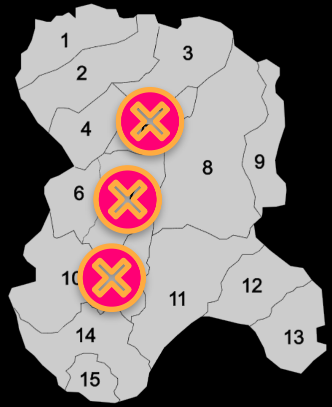
Removing Areas with High Degree in Adjacency Graph

	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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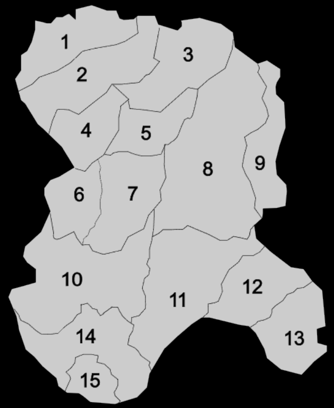
Removing Areas with Low Degree in Adjacency Graph

	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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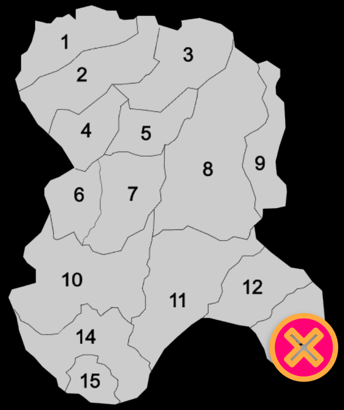
Removing Areas with Low Degree in Adjacency Graph

	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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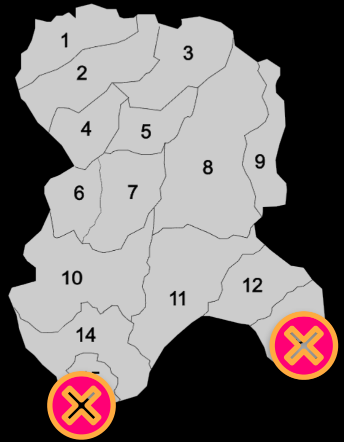
Removing Areas with Low Degree in Adjacency Graph

	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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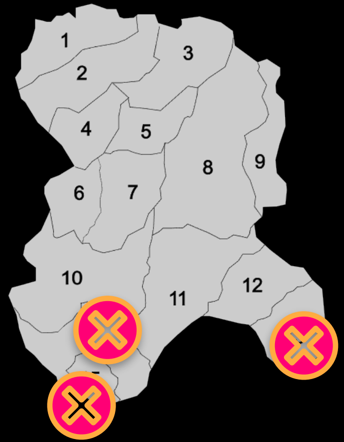
Lidén, T., Schmidt, C., & Zahir, R.(2023). Shift Scheduling for Train Dispatchers. In *10th International Conference on Railway Operations Modelling and Analysis (ICROMA), Belgrade, Serbia, April 25th–28th, 2023* (pp. 120-120).

Removing Areas with Low Degree in 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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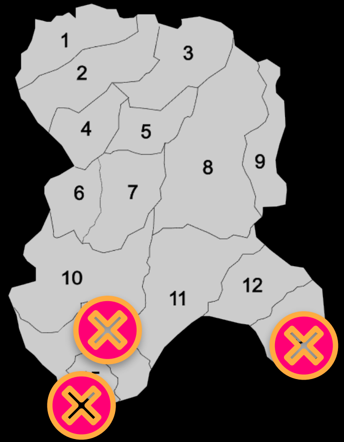

Runtime does not necessarily decrease with fewer areas

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What Should We Improve?

	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

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What Should We Improve?

- Runtime

	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

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What Should We Improve?

- Runtime
- Too short shifts

	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	[illegible]	[illegible]	[illegible]	[illegible]	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

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What Should We Improve?

- Runtime
- Too short shifts
- Undesirable starting times

	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	[illegible]	[illegible]	[illegible]	[illegible]	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

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What Should We Improve?

- Runtime
- Too short shifts
- Undesirable starting times
- Too many handovers

	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						[illegible]	[illegible]	[illegible]	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	[illegible]	[illegible]	[illegible]	[illegible]	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

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Runtime: Stronger Formulation

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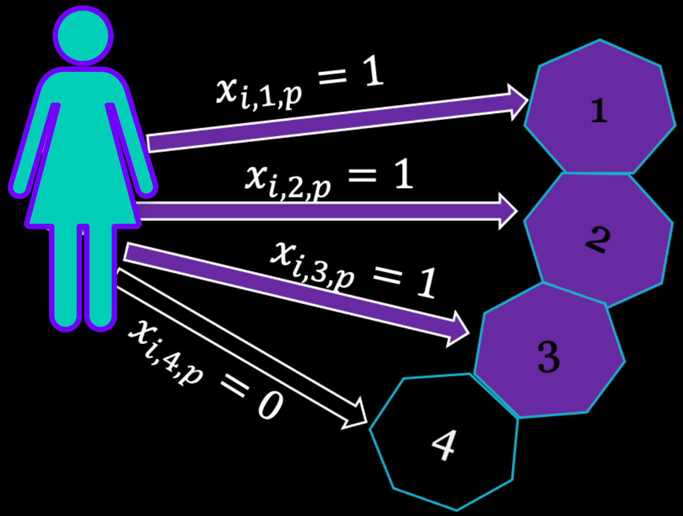
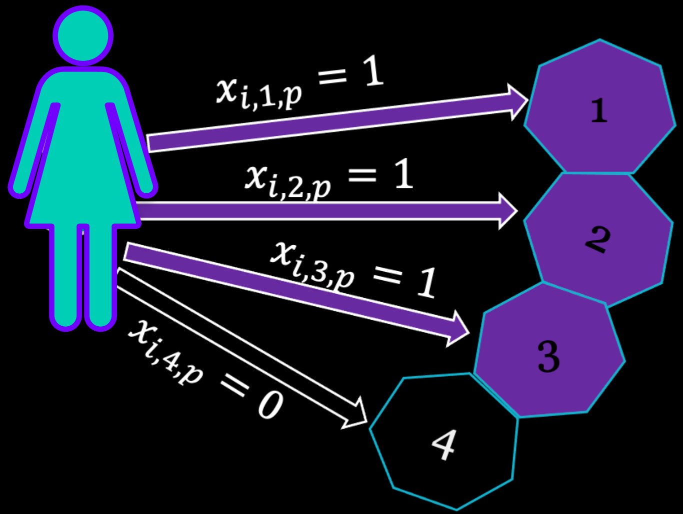
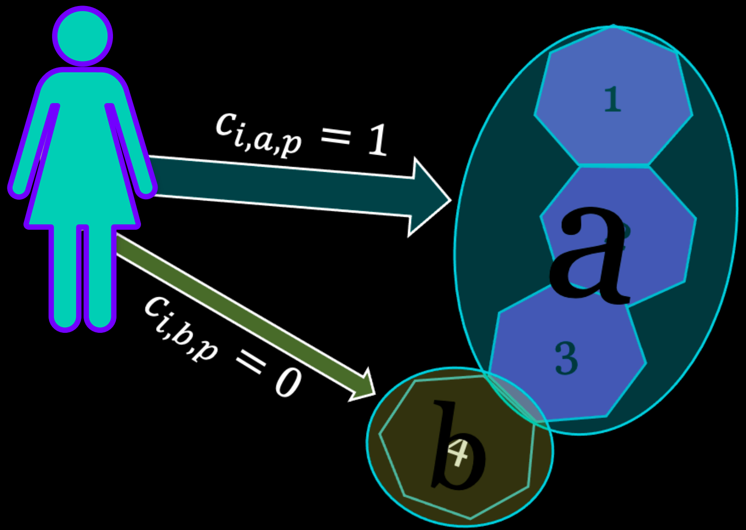
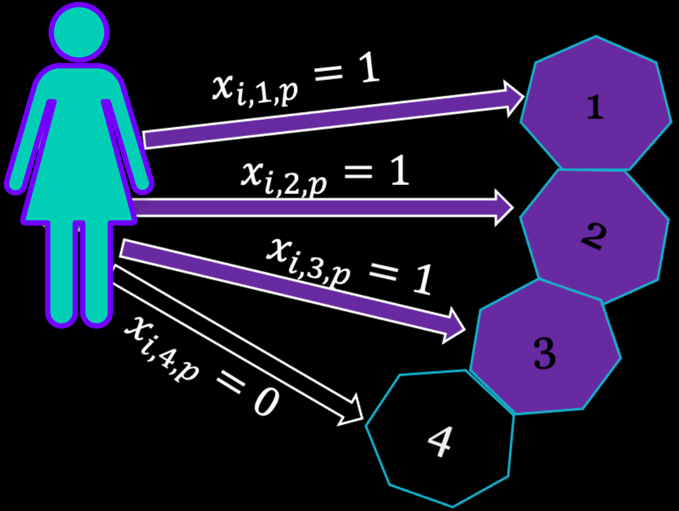


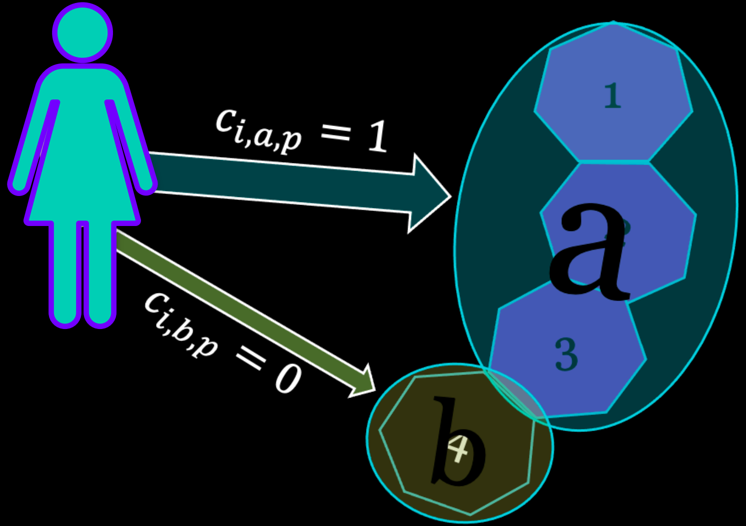
Runtime: Stronger Formulation





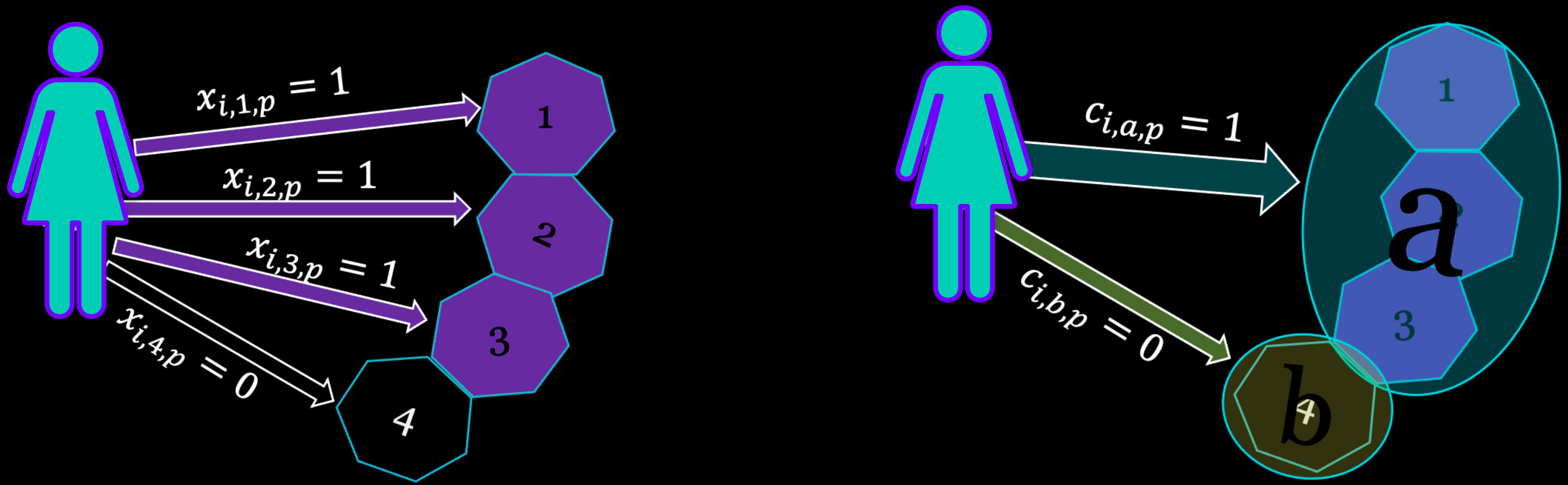
Runtime: Stronger Formulation





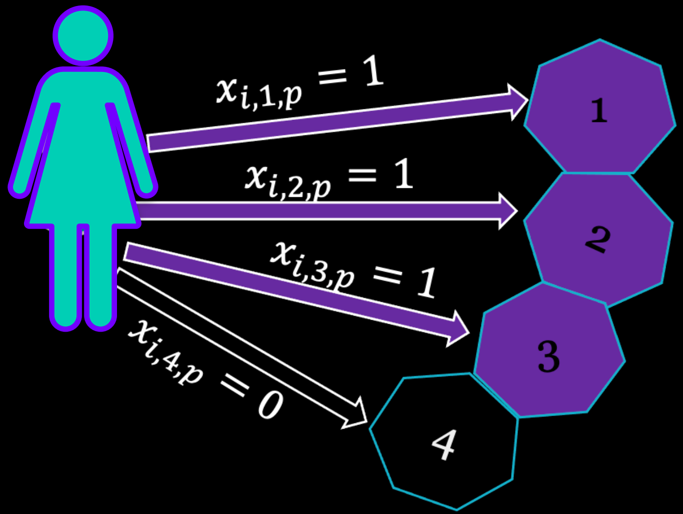
- Assignments steered by variables $c_{i,l,k}$ (CCs) instead of $x_{i,j,k}$

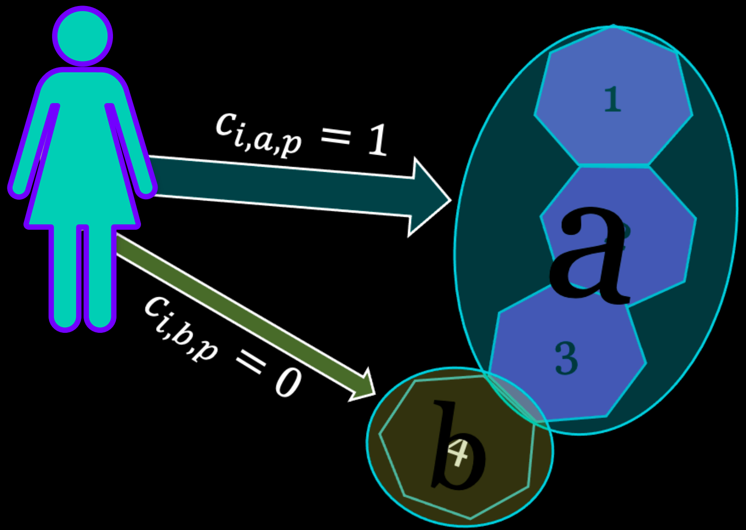
Runtime: Stronger Formulation



- Assignments steered by variables $c_{i,l,k}$ (CCs) instead of $x_{i,j,k}$
- Connect variables $x_{i,j,k}$ and $c_{i,l,k}$ to track area assignments

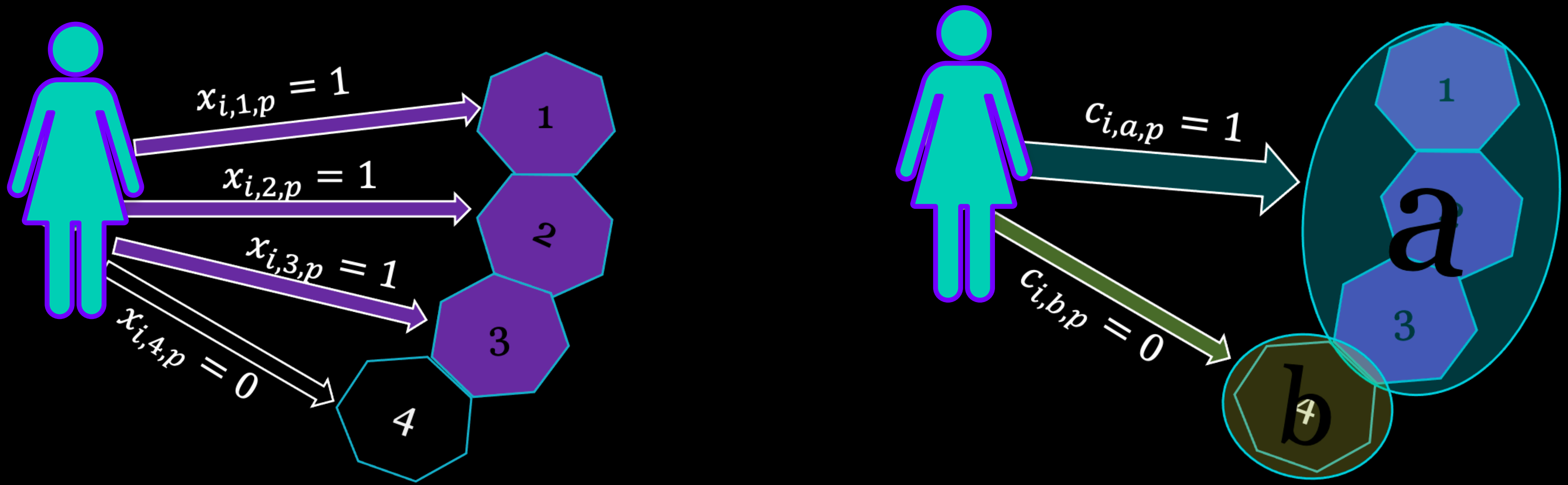
Runtime: Stronger Formulation





- Assignments steered by variables $c_{i,l,k}$ (CCs) instead of $x_{i,j,k}$
- Connect variables $x_{i,j,k}$ and $c_{i,l,k}$ to track area assignments
- Runtime reduced by about 90%

Runtime: Stronger Formulation



- Assignments steered by variables $c_{i,l,k}$ (CCs) instead of $x_{i,j,k}$
- Connect variables $x_{i,j,k}$ and $c_{i,l,k}$ to track area assignments
- Runtime reduced by about 90%

Old Model

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

New Model

- Taskload does not exceed the maximum
- Only assigned if dispatcher is qualified for the area
- Only start if at work, and was not at work before
- Minimum and maximum shift length
- If dispatcher starts, he works, and if he works, he must start
- If dispatcher i works during k, he must be assigned to some area j
- Minimum rest between shifts
- Each area must be assigned to exactly one dispatcher during each period
- If connected component ℓ is assigned to dispatcher i during k, so have to be all areas j in that CC
- If i works during k, they must be assigned to one CC
- Negative connection of x and c

Old Model

$$
\begin{array}{llll}
\sum_{j \in A} TL_{j}\, x_{i,j,k} & \le & TL^{\max} & \forall i \in D, \forall k \in P \quad (1) \\
x_{i,j,k} & \le & e_{i,j} & \forall i \in D, \forall j \in A, \forall k \in P \quad (2) \\
v_{i,k} & \ge & y_{i,k} - y_{i,(k-1)(\mathrm{mod}\ p)} & \forall i \in D, \forall k \in P \quad (3) \\
v_{i,k} & \le & y_{i,k} & \forall i \in D, \forall k \in P \quad (4) \\
\sum_{\mu=k+1-T^{\min}}^{k} v_{i,\mu(\mathrm{mod}\ p)} & \le & y_{i,k} & \forall i \in D, \forall k \in P \quad (5) \\
\sum_{\mu=k+1-T^{\max}}^{k} v_{i,\mu(\mathrm{mod}\ p)} & \ge & y_{i,k} & \forall i \in D, \forall k \in P \quad (6) \\
v_{i,k} & \le & q_i & \forall i \in D, \forall k \in P \quad (7) \\
\sum_{k \in P} v_{i,k} & \ge & q_i & \forall i \in D \quad (8) \\
y_{i,k} & \le & \sum_{j \in A} x_{i,j,k} & \forall i \in D, \forall k \in P \quad (9) \\
y_{i,k} & \ge & x_{i,j,k} & \forall i \in D, \forall j \in A, \forall k \in P \quad (10) \\
\sum_{\mu=k+1}^{k+R^{\min}} v_{i,\mu(\mathrm{mod}\ p)} & \le & q_i - y_{i,k} & \forall i \in D, \forall k \in P \quad (11) \\
\sum_{i \in D} x_{i,j,k} & = & 1 & \forall j \in A, k \in P \quad (12) \\
x_{i,j,k} & \ge & c_{i,\ell,k} & \forall i \in D, \forall k \in P, \forall \ell \in C, \forall j \in \ell \quad (13) \\
\sum_{\ell \in C} c_{i,\ell,k} & = & & \forall i \in D, \forall k \in P \quad (14) \\
x_{i,j,k} & \le & 1 - c_{i,\ell,k} & \forall i \in D, \forall \ell \in C, \forall j \in A \setminus \{\ell\}, \forall k \in P \quad (15)
\end{array}
$$

New Model

- Taskload does not exceed the maximum
- Only assigned if dispatcher is qualified for the area
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Old Model

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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- Negative connection of x and c

$a_{\ell,j}$ is equal to 1 whenever area j is an element of area combination ℓ.

Old Model

$$
\begin{array}{llll}
\sum_{j\in A} TL_{\ldots} & \le TL^{\max} & \forall i \in D, \forall k \in P & (1)\\
\ldots_{j,k} & \le e_{i,j} & \forall i \in D, \forall j \in A, \forall k \in P & (2)\\
v_{i,k} & \ge y_{i,k} - y_{i,(k-1)(\text{mod } p)} & \forall i \in D, \forall k \in P & (3)\\
v_{i,k} & \le y_{i,k} & \forall i \in D, \forall k \in P & (4)\\
\sum_{\mu=k+1-T^{\min}}^{k} v_{i,\mu(\text{mod } p)} & \le y_{i,k} & \forall i \in D, \forall k \in P & (5)\\
\sum_{\mu=k+1-T^{\max}}^{k} v_{i,\mu(\text{mod } p)} & \ge y_{i,k} & \forall i \in D, \forall k \in P & (6)\\
v_{i,k} & \le q_i & \forall i \in D, \forall k \in P & (7)\\
\sum_{k\in P} v_{i,k} & \ge q_i & \forall i \in D & (8)\\
y_{i,k} & \le \sum_{j\in A} x_{i,j,k} & \forall i \in D, \ldots & (9)\\
y_{i,k} & \ge x_{i,j,k} & \ldots \forall k \in P & (10)\\
\sum_{\mu=k+1}^{k+R^{\min}} v_{i,\mu(\text{mod } p)} & \le q_i - y_{i,k} & \forall i \in D, \forall k \in P & (11)\\
\sum_{i\in D} x_{i,j,k} & = 1 & \forall j \in A, k \in P & (12)\\
x_{i,j,k} & \ge c_{i,\ell,k} & \ldots \in D, \forall k \in P, \forall \ell \in C, \forall j \in \ell & (13)\\
\sum_{\ell\in C} c_{i,\ell,k} & = & \forall i \in D, \forall k \in P & (14)\\
x_{i,j,k} & \le 1 - c_{i,\ell,k} & \forall i \in D, \forall \ell \ldots, \forall j \in A \setminus \{\ell\}, \forall k \in P & (15)
\end{array}
$$

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$a_{\ell,j}$ is equal to 1 whenever area j is an element of area combination ℓ.

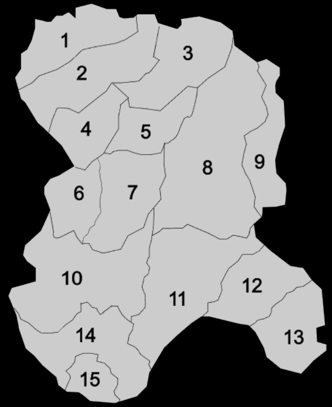
$$
\begin{array}{llll}
\sum_{j\in A}\sum_{\ell\in C} c_{i,\ell,k} \cdot a_{\ell,j} \cdot TL_{j,k} & \le TL^{\max} & \forall i \in D, \forall k \in P & (17)\\
c_{i,\ell,k} & \le e_{i,j} & \forall i \in D, \forall \ell \in C, \forall j \in \ell, \forall k \in P & (18)\\
\sum_{\ell\in C\setminus\{0\}} c_{i,\ell,k} & = y_{i,k} & \forall i \in D, \forall k \in P & (19)\\
c_{i,0,k} & = 1 - y_{i,k} & \forall i \in D, \forall k \in P & (20)\\
\sum_{\ell\in C\setminus\{0\}}\sum_{i\in D} a_{\ell,j} \cdot c_{i,\ell,k} & = 1 & \forall k \in P, \forall j \in A & (21)
\end{array}
$$

Experiments: Stronger Formulation

I_{a,b,A_r}

- *a* is the endorsement ratio
- *b* is the maximum size of area combinations
- Set A_r contains the areas that have been removed from the 15 areas in the basic scenario

		Basic model		Strong model		
In.	d	row; col	R(s)	row; col	R(s)	%dif
$I_{1,3,\emptyset}$	21	18221; 34120	58	3019; 27058	8.3	-86
$I_{1/2,3,\emptyset}$	21	9152; 10192	23.1	3015; 7605	8.4	-64
$I_{1/3,3,\emptyset}$	22	6038; 6127	21.6	3009; 4923	8.7	-60
$I_{1,4,\emptyset}$	21	37926; 38058	97	3019; 30622	18.4	-81
$I_{1,2,\emptyset}$	22	18221; 26662	39	3019; 19600	4.98	-87
$I_{1,1,\emptyset}$	33	4627; 14313	30.5	4592; 14313	69	+126
$I_{1,3,\{13\}}$	20	47985; 32272	305	2995; 25738	10.3	-97
$I_{1,3,\{13,15\}}$	18	45573; 31070	245	2971; 24264	9.36	-96
$I_{1,3,\{13,14,15\}}$	17	35155; 27190	244	2947; 21514	9.45	-96
$I_{1,3,\{10\}}$	20	17053; 27014	39	2995; 20524	7.9	-80
$I_{1,3,\{7,10\}}$	19	15929; 23890	25	2971; 17950	5.2	-79
$I_{1,3,\{5,7,10\}}$	18	15069; 20546	21	2947; 15024	4.64	-78



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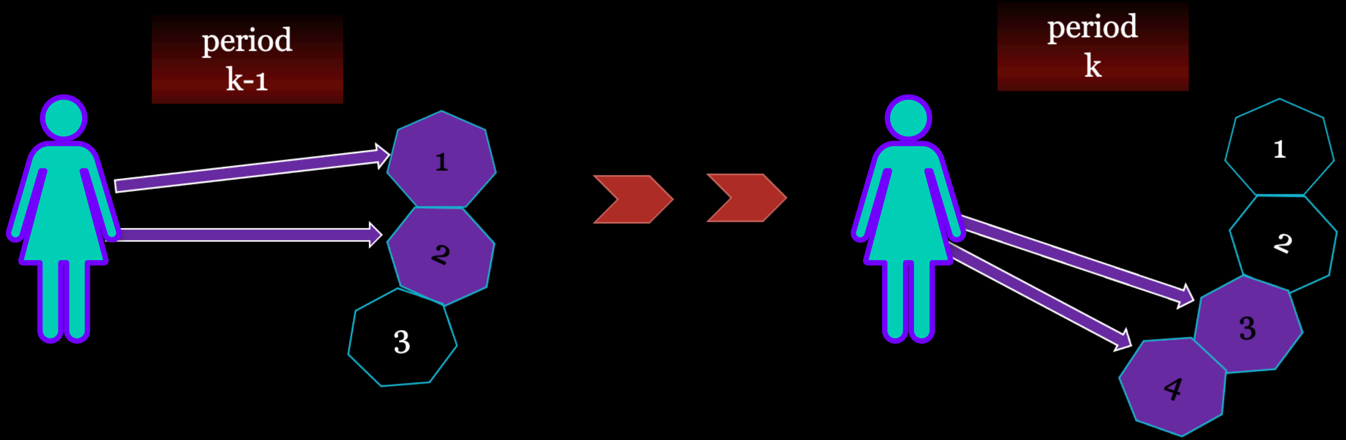
Handling Handovers–Approach #1: Minimize #Handovers



New constraints with binary variables $z_{i,j,k}$=1 if a dispatcher i gets a new area j in period k:

$$x_{i,j,k} - x_{i,j,(k-1) mod p} \leq z_{i,j,k} \quad \forall i \in D, \forall j \in A, \forall k \in P$$

New objective function: $\min . \sum_{i \in D} \sum_{j \in A} \sum_{k \in P} z_{i,j,k}$

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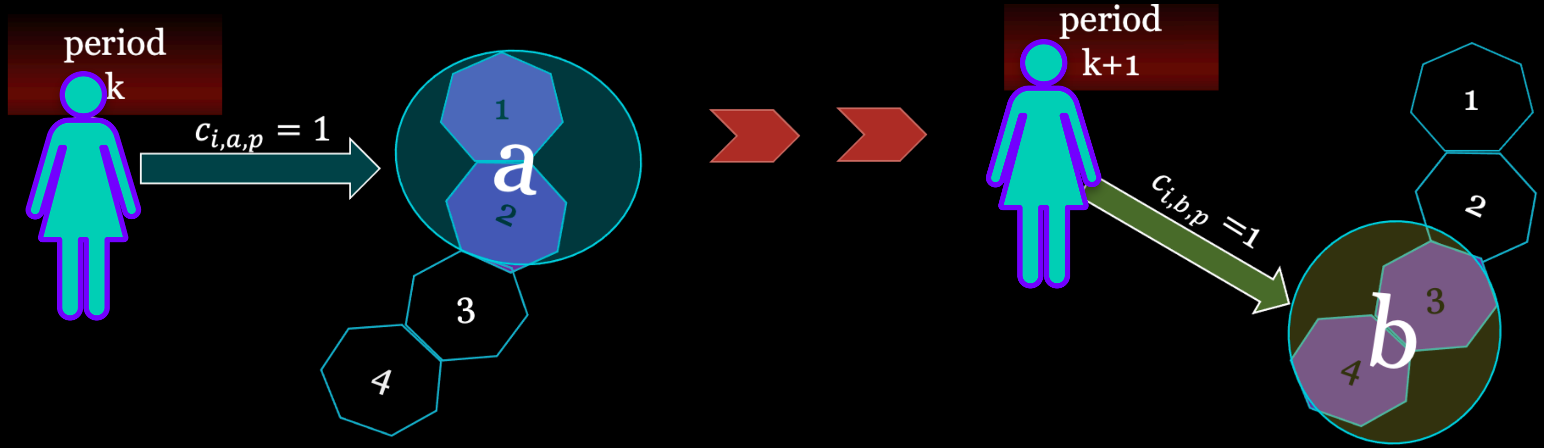
Handling Handovers–Approach #2: Minimize #Handovers of CCs

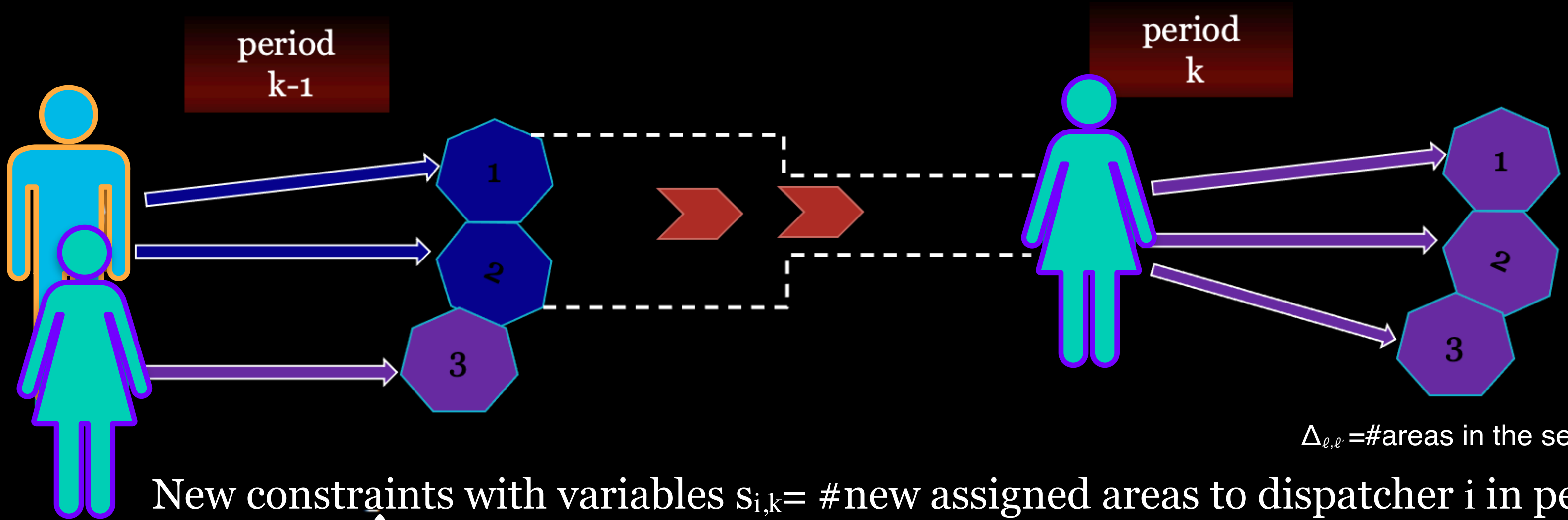


New constraints with new variables $h_{i,k}=1$ if dispatcher i is involved in a handover:

$$h_{i,k} \geq c_{i,\ell,k} - c_{i,\ell,(k-1) mod p} \quad \forall i \in D, \forall \ell \in C \setminus \{0\}, \forall k \in P$$

New objective: $$\min . \sum_{i \in D} \sum_{k \in P} h_{i,k}$$

Handling Handovers–Approach #3: Minimize #Newly Assigned Areas



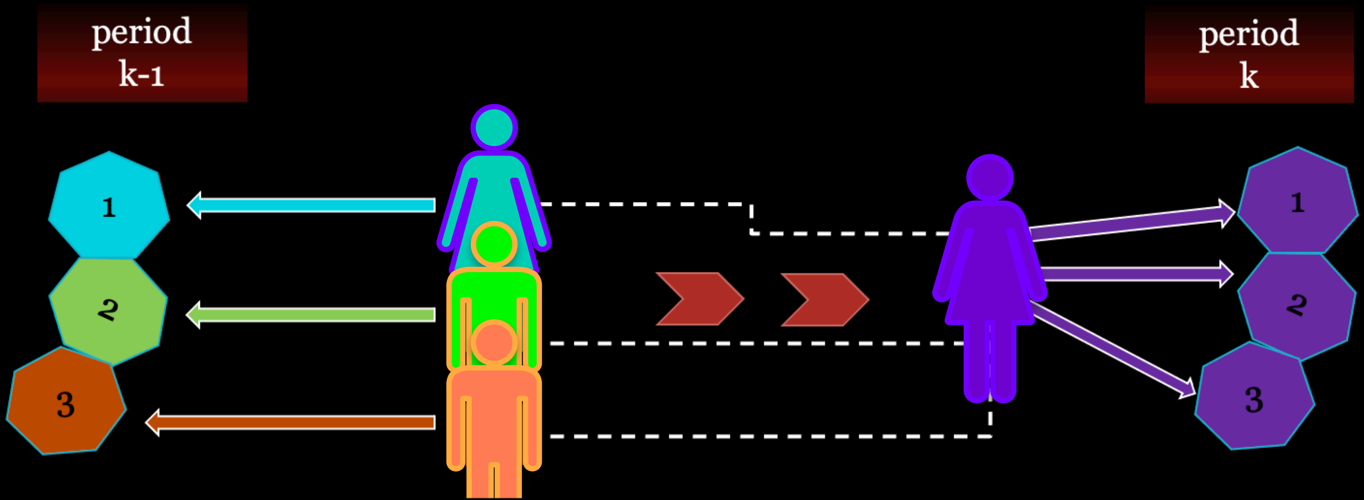
$\Delta_{\ell,\ell'}$ =#areas in the set ℓ and not in ℓ'.

New constraints with variables $s_{i,k}$= #new assigned areas to dispatcher i in period k:

$$\Delta_{\ell,\ell'} \cdot (c_{i,\ell,k} + c_{i,\ell',(k-1) mod p} - 1) \leq s_{i,k} \qquad \forall i \in D, \forall k \in P, \quad \forall \ell' \in C, \forall \ell \in C \setminus \{0\}$$

New objective: $$\min . \sum_{i \in D} \sum_{k \in P} s_{i,k}$$

Handling Handovers–Approach #4: Minimize #Givers



$b_{\ell,\ell'}$ = 1 whenever area combinations ℓ and ℓ' have at least one common area

$u_{\ell,k}$ =# dispatchers (givers) that, in the previous time period k – 1, were controlling the areas in the area combination ℓ

$$u_{\ell,k} + M \cdot (1 - c_{i,\ell,k}) \geq \sum_{\substack{i' \in D : i' \neq i \\ \ell' \in C \setminus \{0\}}} b_{\ell,\ell'} \cdot c_{i',\ell',(k-1) mod p} \qquad \forall i \in D, \forall k \in P, \forall \ell \in C \setminus \{0\}$$

$$\min . \quad \sum_{\ell \in C} \sum_{k \in P} u_{\ell,k}$$

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Experiments

Small instance with 8 areas and 5 periods (night, morning, noon, early evening, late evening), 8 used dispatcher:

	sm min. $\#disp$	Approach 1 min. $\sum z_{i,j,k}$	Approach 2 min. $\sum h_{i,k}$	Approach 3 min. $\sum s_{i,k}$	Approach 4 min. $\sum u_{l,k}$
#rows #columns	239 896	1160 1488	992 928	15648 928	1085 994
runtime (s)	0.2	0.6	3.25	600	220
$\sum z_{i,j,k}$	31	16	18	16	16
$\sum h_{i,k}$	29	14	13	15	14
$\sum s_{i,k}$	31	16	18	16	16
$\sum u_{\ell,k}$	26	11	18	13	11

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	sm min.$\#disp$	Approach 1 min.$\sum z_{i,j,k}$	Approach 2 min.$\sum h_{i,k}$	Approach 3 min.$\sum s_{i,k}$	Approach 4 min.$\sum u_{l,k}$
#rows	239	1160	992	15648	1085
#columns	896	1488	928	928	994
runtime (s)	0.2	0.6	3.25	600	220
$\sum z_{i,j,k}$	31	16	18	16	16
$\sum h_{i,k}$	29	14	13	15	14
$\sum s_{i,k}$	31	16	18	16	16
$\sum u_{\ell,k}$	26	11	18	13	11

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	sm min.#$disp$	Approach 1 min.$\sum z_{i,j,k}$	Approach 2 min.$\sum h_{i,k}$	Approach 3 min.$\sum s_{i,k}$	Approach 4 min.$\sum u_{l,k}$
#rows	239	1160	992	15648	1085
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runtime (s)	0.2	0.6	3.25	600	220
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$\sum u_{\ell,k}$	26	11	18	13	11

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Experiments

Fixed the time resolution: 12 periods, 2h/period

		Approach 1 min.$z_{i,j,k}$			Approach 2 min.$h_{i,k}$		
#ar	d	row; col	R (s)	$\sum (z_{i,j,k}, h_{i,k}, s_{i,k}, u_{\ell,k})$	row; col	R (s)	$\sum (z_{i,j,k}, h_{i,k}, s_{i,k}, u_{\ell,k})$
8	11	3800; 5115	277	16,11,16,14	3440; 3245	15	16,11,16,14
10	13	5408; 8112	454	20,13,20,18	5255; 5304	49	20,13,20,20
12	16	7804; 12384	84	24,16,24,22	9324; 9930	282	24,16,24,22

Fixed #areas: 12 areas

		Approach 1 min.$z_{i,j,k}$			Approach 2 min.$h_{i,k}$		
#pr	d	row; col	R (s)	$\sum (z_{i,j,k}, h_{i,k}, s_{i,k}, u_{\ell,k})$	row; col	R (s)	$\sum (z_{i,j,k}, h_{i,k}, s_{i,k}, u_{\ell,k})$
5	11	2250; 3465	4.02	24,21,24,22	1963; 2288	58	29,19,29,22
8	15	4848; 7755	229	24,15,24,20	4551; 5130	18	24,15,24,20
12	16	7804; 12384	84	24,16,24,22	9324; 9930	282	24,16,24,22

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Experiments: Real-World-Sized Instance

	pr.0	pr.1	pr.2	pr.3	pr.4	pr.5	pr.6	pr.7	pr.8	pr.9	pr.10	pr.11	pr.12	pr.13	pr.14	pr.15	pr.16	pr.17	pr.18	pr.19	pr.20	pr.21	pr.22	pr.23
D1														4	10	1 2	14	8	3	5	14 15	9		
D2										4 6	11	14 15	1	1 2	9	12	8	3	2	1 2				
D3	9	9	5														3	9	8	15	1 2	3 8	12 13	8
D4									14 15	10 14	9	1 2	6	5	13	14	5	6	4					
D5	12 13	14	11 14 15	14 15	6 7 10	6 10 11	1 2	5 8 9	6														11 14 15	2
D6						1 2 3	3 4	6 7	7 10	1 2	8 10 14	8 9	12 13	3 8	2 3	13								
D7							5 8 9	3 4	11 12	7 8 9	6 7	6	5 8 9											
D8	15	6	9	7 10 11	12 13														7	13	8 9	4 7	6	9
D9	3	5 7 10	7	4 6	8 9	14 15	14 15	12 13														1 2	2	5 7
D10									3 4	15	1 2 3	11 12 13	11	11 12 13	1	15	6	2	11 12					
D11	1 2	12 13														9	4 7	12 13	13	11 12	10 11	11 12 13	3	3
D12	11														4	7	9	1	15	14	6 7	10 14 15	4	13
D13	10 14	4	6 8 10	13															10	6	5	5	1	4
D14	5	15	12 13	12	11 14 15	5 8 9	12 13	1 2	1														8 10	11 12
D15									2	13	15	10	2	9	15	8	2	5	14					
D16	4	8 11	3	5 8 9	3 5	4 7	10 11	14 15	5 8 9														9	14 15
D17											12 13	5 7	7	7	12	6	10 11	4 7	1	8 10				
D18										11 12	4 5	3 4	3 4	6 10	6 7	5	1	15	9	9				
D19															11 14	10 11	12 13	10 11	6	3	3 4	6	5 7	1
D20													10 14 15	14 15	5 8	3 4	15	14	5	4 7	12 13			
D21	6 7 8	1 2 3	1 2 4	1 2 3	1 2 4	12 13	6 7	10 11	13	3 5														6 10

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Approach 1: optimal solution in about 102 minutes
Approach 2: optimality gap even after 72 hours, but with good handover-measure values.

Experiments: Real-World-Sized Instance

	pr.0	pr.1	pr.2	pr.3	pr.4	pr.5	pr.6	pr.7	pr.8	pr.9	pr.10	pr.11	pr.12	pr.13	pr.14	pr.15	pr.16	pr.17	pr.18	pr.19	pr.20	pr.21	pr.22	pr.23
D1														4	10	1 2	14	8	3	5	14 15	9		
D2										4 6	11	14 15	1	1 2	9	12	8	3	2	1 2				
D3	9	9	5														3	9	8	15	1 2	3 8	12 13	8
D4									14 15	10 14	9	1 2	6	5	13	14	5	6	4					
D5	12 13	14	11 14 15	14 15	6 7 10	6 10 11	1 2	5 8 9	6														11 14 15	2
D6						1 2 3	3 4	6 7	7 10	1 2	8 10 14	8 9	12 13	3 8	2 3	13								
D7							5 8 9	3 4	11 12	7 8 9	6 7	6	5 8 9											
D8	15	6	9	7 10 11	12 13														7	13	8 9	4 7	6	9
D9	3	5 7 10	7	4 6	8 9	14 15	14 15	12 13														1 2	2	5 7
D10									3 4	15	1 2 3	11 12 13	11	11 12 13	1	15	6	2	11 12					
D11	1 2	12 13														9	4 7	12 13	13	11 12	10 11	11 12 13	3	3
D12	11														4	7	9	1	15	14	6 7	10 14 15	4	13
D13	10 14	4	6 8 10	13															10	6	5	5	1	4
D14	5	15	12 13	12	11 14 15	5 8 9	12 13	1 2	1														8 10	11 12
D15									2	13	15	10	2	9	15	8	2	5	14					
D16	4	8 11	3	5 8 9	3 5	4 7	10 11	14 15	5 8 9														9	14 15
D17											12 13	5 7	7	7	12	6	10 11	4 7	1	8 10				
D18										11 12	4 5	3 4	3 4	6 10	6 7	5	1	15	9	9				
D19															11 14	10 11	12 13	10 11	6	3	3 4	6	5 7	1
D20													10 14 15	14 15	5 8	3 4	15	14	5	4 7	12 13			
D21	6 7 8	1 2 3	1 2 4	1 2 3	1 2 4	12 13	6 7	10 11	13	3 5														6 10

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

	pr.0	pr.1	pr.2	pr.3	pr.4	pr.5	pr.6	pr.7	pr.8	pr.9	pr.10	pr.11	pr.12	pr.13	pr.14	pr.15	pr.16	pr.17	pr.18	pr.19	pr.20	pr.21	pr.22	pr.23
D1						10 11	10 11	10 11	10	12 13	12 13	12	12	12	12	12								
D2	6	6														6	6	6	6	6	6 7	6 7	6 7	6
D3									11	10 11	6 10 11	6 10 11	6 10 11	6 10 11	6 10 11	10 11	10 11	10 11	10					
D4											3	3	3	3	3	3	3	3	3	3	3			
D5											14 15	14 15	14 15	14 15	14	14	14	14	14	14	14			
D6	3	3	3	3	3 4	3 4	3 4	3 4	3 4	3														3
D7	4 5	4 5	4 5	4															4	4	4 5	4 5	4 5	4 5
D8									1 2	1 2	1 2	1 2	1 2	1 2	1 2	1 2	2	2	2					
D9	10 11	10 11	10 11	10 11	10 11														11	10 11	10 11	10 11 14	10 11 14	10 11
D10										4	4 7	4 7	4 7	4 7	4 7	4 7	4 7	4 7	7	7				
D11												13	13	13	13	13	12 13	12 13	12 13	12 13	12 13	12 13		
D12															8	8	8	8	8	8	8 9	8 9		
D13																	1	1	1	1 2	1 2	1 2	1 2	1
D14	8 9	8 9	8 9	5 8 9	5 8 9	5 8 9	5 8 9	5 8 9	5 8 9														8 9	8 9
D15															15	15	15	15	15	15	15	15	15	
D16	12 13	12 13	12 13	12 13	12 13	12 13	12 13	12 13	12 13														12 13	12 13
D17										9	9	9	9	9	9	9	9	9	9	9				
D18										5 8	5 8	5 8	5 8	5 8	5	5	5	5	5	5				
D19	1 2	1 2	1 2	1 2	1 2	1 2	1 2	1 2														3	3	2
D20	14 15	14 15	14 15	14 15	14 15	14 15	14 15	14 15	14 15	14 15														14 15
D21	7	7	6 7	6 7	6 7	6 7	6 7	6 7	6 7	6 7														7

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Outlook: Current and Future Research

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- Expand the time horizon

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- New project (04/2024-09/2026) Dispatching Areas: Combinations and Design (DACoD)

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- Planning for en-route ATCOs (Area Control Centers and even Virtual Centers)

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- Expand the time horizon
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- Which combinations of area qualifications are good?
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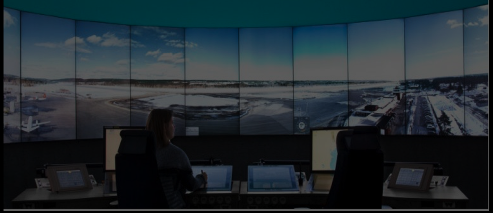
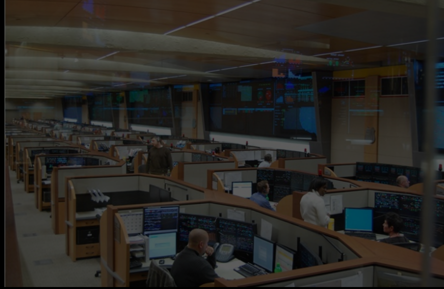
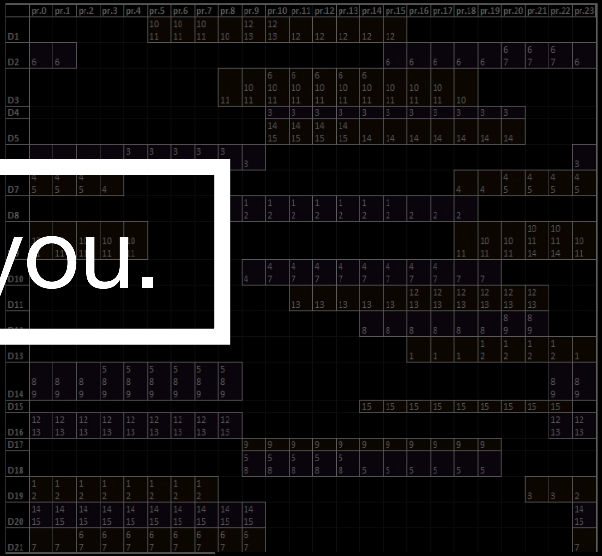
- Deduct and integrate workload thresholds into the framework

- Planning for en-route ATCOs (Area Control Centers and even Virtual Centers)
- Continued study of ATCO workload

https://www.itn.liu.se/~chrsc91/
christiane.schmidt@liu.se







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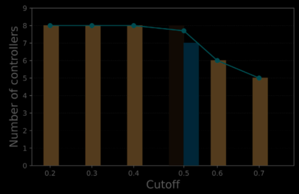

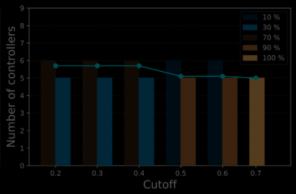

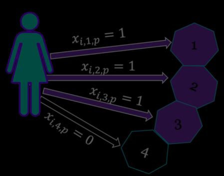

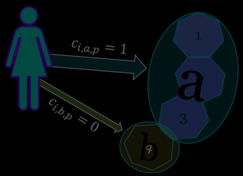

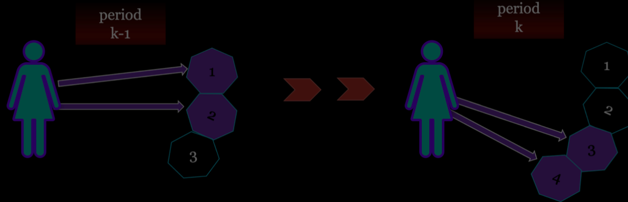

Assigning Airports to Remote Tower Modules–Constraints

$$
\begin{aligned}
\sum_{j\in A} period_{i,j,k} &\leq RTM_{i,k} \cdot mA && \forall i \in R, \forall k \in P \\
\sum_{j\in A} mov_{i,j,k} &\leq mMov && \forall i \in R, \forall k \in P \\
\sum_{i\in R} period_{i,j,k} &\leq 1 && \forall j \in A, \forall k \in P \\
mov_{i,j,k} &\leq period_{i,j,k} \cdot mMov && \forall i \in R, \forall j \in A, \forall k \in P \\
\sum_{i\in R} mov_{i,j,k} &= Amov_{j,k} && \forall j \in A, \forall k \in P \\
\sum_{i\in R} period_{i,j,k} &\geq op_{j,k} && \forall j \in A, \forall k \in P
\end{aligned}
$$

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Assigning Airports to Remote Tower Modules–Constraints

1. Number of airports assigned to one module ≤ mA

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

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

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Assigning Airports to Remote Tower Modules–Constraints

1. Number of airports assigned to one module ≤ mA

2. Total number of movements within a module ≤maxMov

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

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

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

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

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

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Assigning Airports to Remote Tower Modules–Constraints

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

$$
\begin{aligned}
\sum_{j \in A} period_{i,j,k} &\leq RTM_{i,k} \cdot mA && \forall i \in R, \forall k \in P \\
\sum_{j \in A} mov_{i,j,k} &\leq mMov && \forall i \in R, \forall k \in P \\
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Assigning Airports to Remote Tower Modules–Constraints

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

$$
\begin{aligned}
\sum_{j\in A} period_{i,j,k} &\leq RTM_{i,k} \cdot mA && \forall i \in R, \forall k \in P \\
\sum_{j\in A} mov_{i,j,k} &\leq mMov && \forall i \in R, \forall k \in P \\
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Assigning Airports to Remote Tower Modules–Constraints

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

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

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

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Assigning Airports to Remote Tower Modules–Objectives

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

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

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

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

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

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

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

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

Assigning Airports to Remote Tower Modules–Objectives

1. Minimize the number of remote tower modules in use

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

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

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

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

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

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

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

Assigning Airports to Remote Tower Modules–Objectives

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

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

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

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

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

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

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

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

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

Assigning Airports to Remote Tower Modules–Objectives

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

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

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

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

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

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

As much as possible!

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

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

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

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

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

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

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

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