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Optimizing Airspace Sectors for Varying Demand Patterns using Multi-Controller Staffing

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Outline

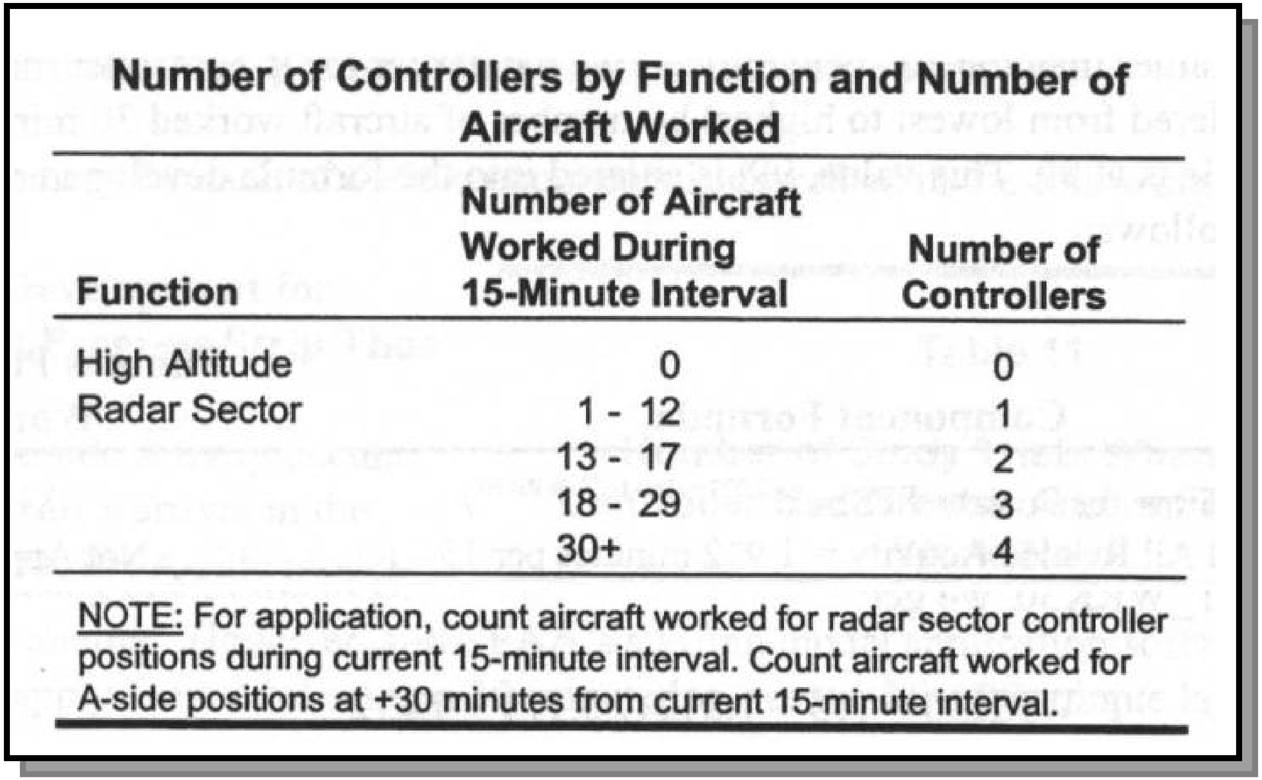
- Introduction
- Motivating Example
- Formulation of Mixed Integer Program
- Numerical Experiment
- Concluding Remarks

Introduction

- Enroute sector boundary design should consider not only balancing controller workload but also efficient controller staffing.
- Traditional sectorization schemes input demand data aggregated over the planning horizon
    - E.g. one day, one month.
    - Variance in demand might result in inefficient usage of controller workforce.
- We propose new design concepts in clean-sheet sectorization:
    - Address demand variation across the planning horizon.
    - Consider efficient staffing plans for multi-period demand patterns.

Introduction (cont'd)

- In the U.S., a common way to deal with temporary demand peaks in a sector is to use multiple controller teams.
  - E.g. a Radar-side controller plus a Data-side controller.



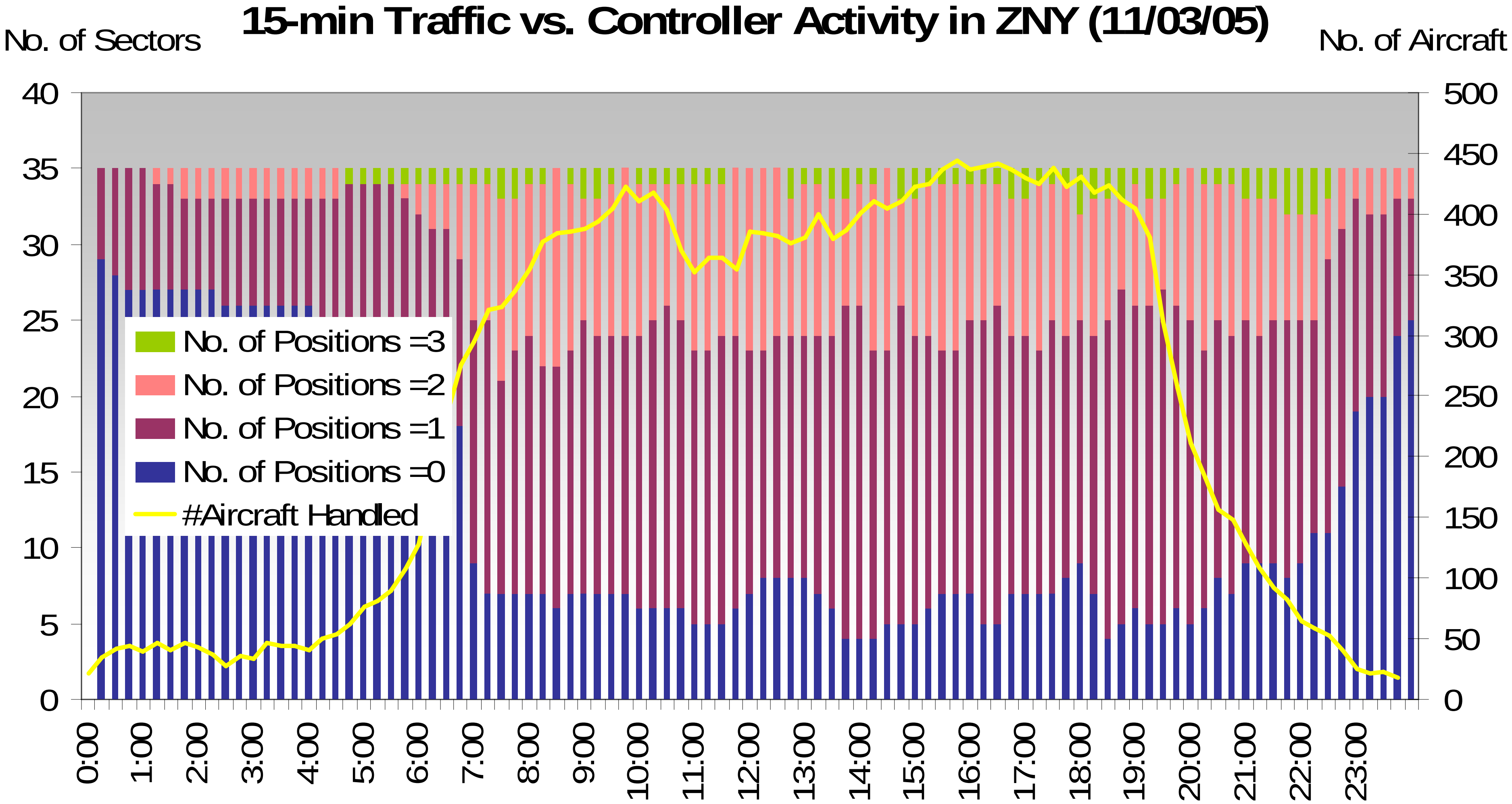
Number of Controllers by Function and Number of Aircraft Worked

Function	Number of Aircraft Worked During 15-Minute Interval	Number of Controllers
High Altitude Radar Sector	0	0
	1 - 12	1
	13 - 17	2
	18 - 29	3
	30+	4

NOTE: For application, count aircraft worked for radar sector controller positions during current 15-minute interval. Count aircraft worked for A-side positions at +30 minutes from current 15-minute interval.

Effects of Number of Controllers on Sector Capacities
(Source: ARTCC Radar Sector Staffing Models, 1997)

Staffing vs. Traffic

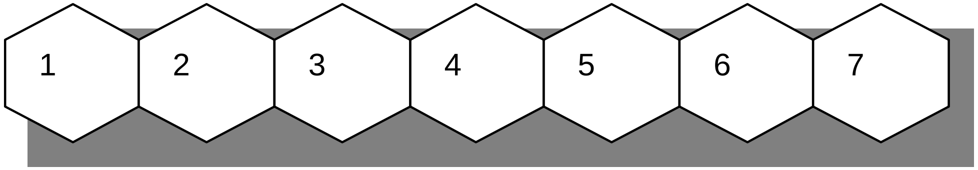


Enroute Air Traffic Controllers

- Functions:
  - F1 – Pilot communication/direction (verbal)
    - Tell pilot how to move.
  - F2 – ATC coordination
    - E.g. neighboring controllers.
  - F3 – Data processing
    - Flight strip marking and juggling.
  - Common configuration: R-side (F1, F2) + D-side (F3)
- Scarce and expensive resources:
  - The FAA will hire and train more than 15,000 controllers over the next decade.
  - Controller labor costs have increased from $82.98 per flight in FY1998 to $137.81 per flight in FY2006.

Motivating Example

- Consider seven connected hex-cells to be grouped into 2 sectors



Only 6 ways to do this, since sectors must be contiguous!

- Cell Demand Across Time Periods (T = 1, 2, 3):

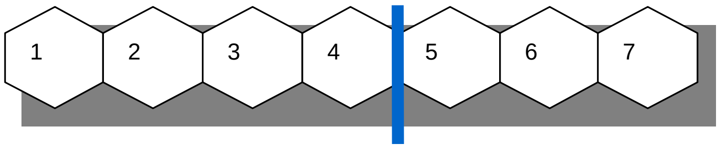
Cell		***1***	***2***	***3***	***4***	***5***	***6***	***7***
Demand By Period	***T=1***	2	3	0	2	4	2	5
	T=2	5	3	3	1	5	3	5
	T=3	0	2	1	2	1	3	2
	Sum:	7	8	4	5	10	8	12

- Compare two design concepts:
  - Aggregated Demand with Balancing Sector Workloads
  - Multi-period Demand with Awareness of Controller Capability

Motivating Example (cont’d)

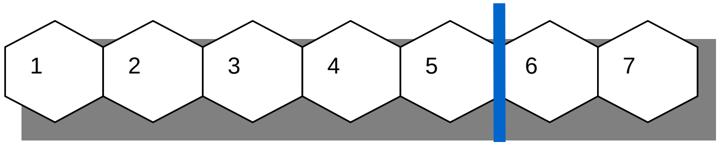
- Suppose that 1 controller can only handle up to 10 demand units in a time period.

Optimal Workload Balancing:



Controller Usage		**Partition**	
		[1,2,3,4]	***[5,6,7]***
Period	***T=1***	1	2
	T=2	2	2
	T=3	1	1
Total		9	

Multi-period Model Considering Controller Capability:



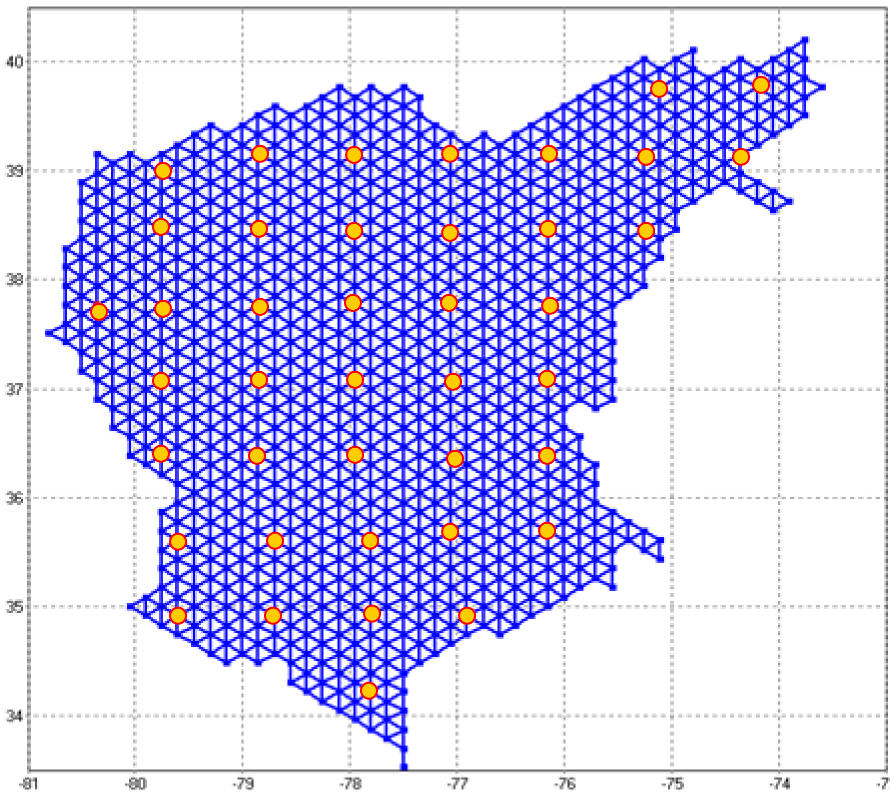
Controller Usage		**Partition**	
		[1,2,3,4,5]	***[6,7]***
Period	***T=1***	2	1
	T=2	2	1
	T=3	1	1
Total		8	

9 controller-hours required, versus 8 controller-hours

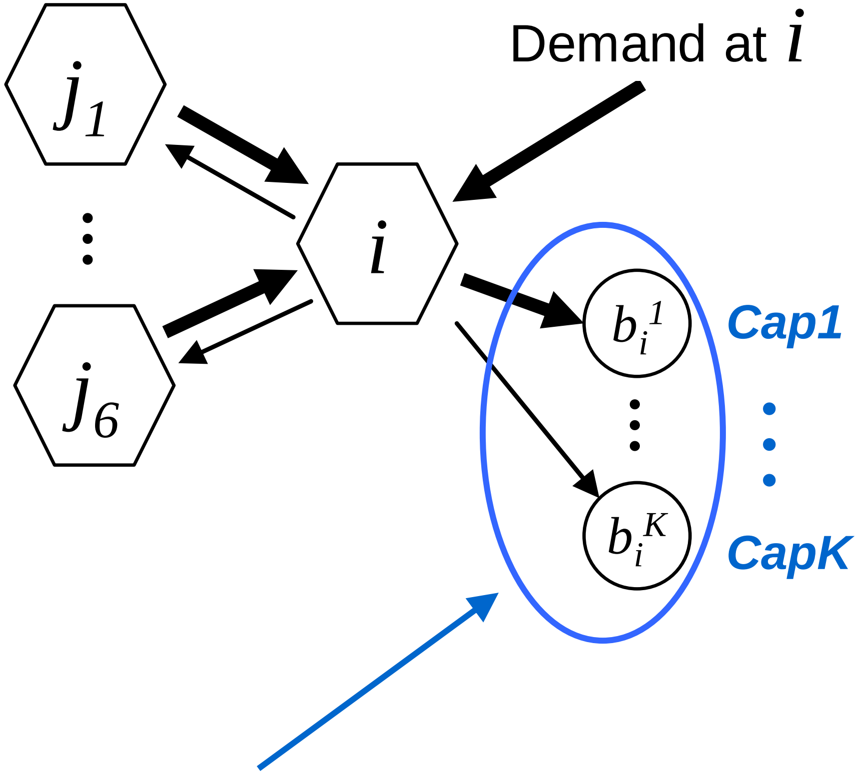
Proposed Approach

- Tile-and-group
  - A mixed integer program is formulated to group the hex-cells.
- Model Features:
  - Time-varying demand patterns as input.
  - Sector capacity changing over time by varying controller staffing.
  - Sector shape in alignment with major traffic.

Underlying Network for Target Airspace

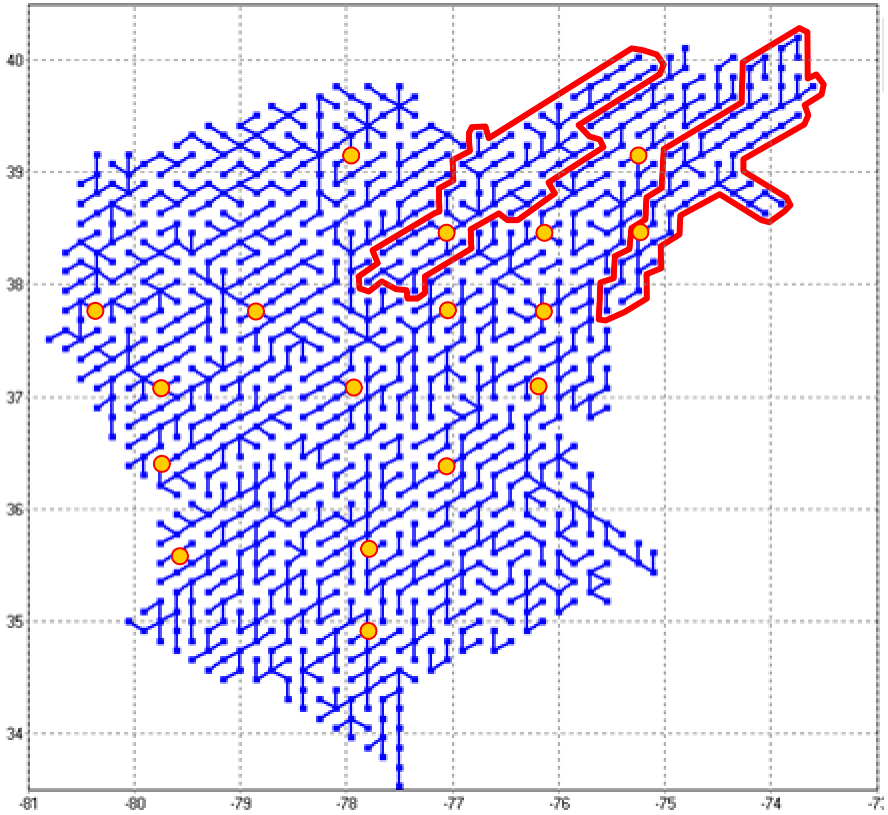


Network Structure at a Seed Node



Dummy nodes and links for sector capacity values.

Sample Solution for Target Airspace



Multi-Period Variable Controller Model (MPVC)

A Variant of Fixed-Charged Network Design Problem (FCND)

Controller Cost

Flow Alignment Penalty

$$\text{Minimize} \sum_{\substack{i\in S,\, j\in B_i\\ t\in\{1,..,T\}}} f_{ij}^t\, p_{ij}^t + \mu \sum_{\substack{i\in\{1,\ldots,I\}\\ j\in A_i\\ t\in\{1,..,T\}}} c_{ij}^t\, x_{ij}^t$$

Flow conservation

$$\sum_{j\in A_i} x_{ji}^t + d_i^t = \begin{cases} \displaystyle\sum_{j\in A_i} x_{ij}^t & \text{for all} \quad i\notin S, t\in\{1,\ldots,T\} \\ \displaystyle\sum_{j\in A_i\cup B_i} x_{ij}^t & \text{for all} \quad i\in S, t\in\{1,\ldots,T\} \end{cases} \tag{1}$$

One Outbound Flow

$$\sum_{j\in A_i} q_{ij} = \begin{cases} 1 & \text{for all} \quad i\notin S \\ 1-\displaystyle\sum_{j\in B_i} p_{ij}^t & \text{for all} \quad i\in S,\ t\in\{1,\ldots,T\} \end{cases} \tag{2}$$

Link Selection

$$x_{ij}^t \le M_{ij} q_{ij} \qquad \text{for all} \quad i\in\{1,\ldots,I\},\ j\in A_i, t\in\{1,\ldots,T\} \tag{3}$$

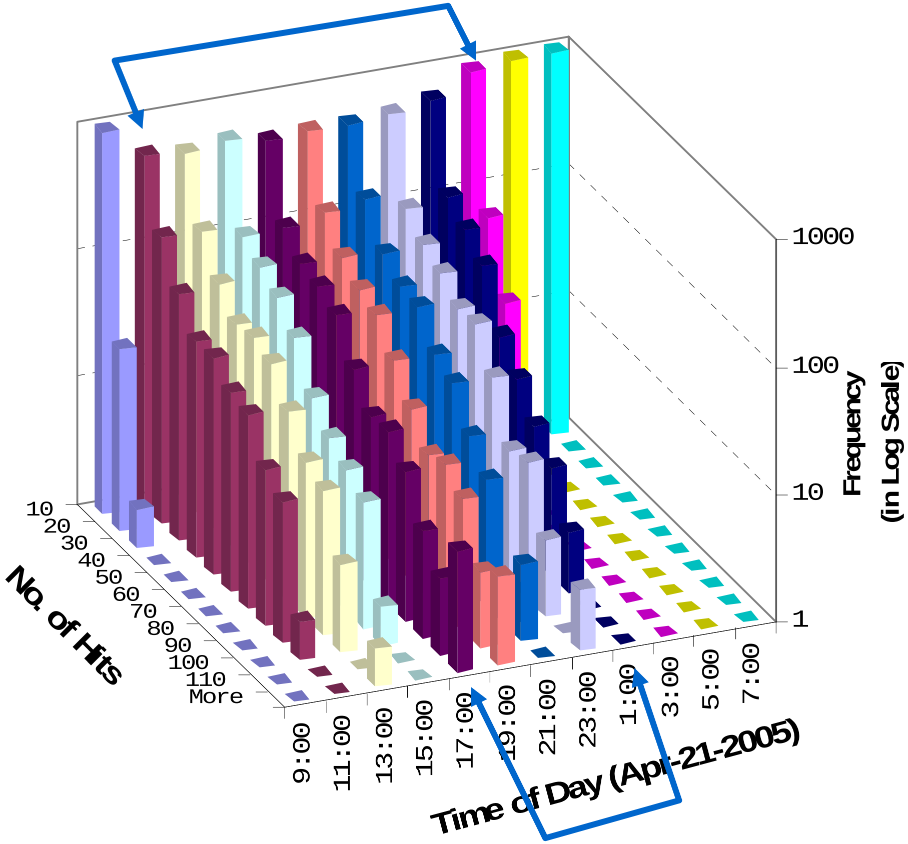
Controller Staffing Selection

$$M_{i,b_i^{k-1}}\, p_{i,b_i^k}^t \le x_{i,b_i^k}^t \le M_{i,b_i^k}\, p_{i,b_i^k}^t \qquad \text{for all} \quad i\in S,\ \ k\in\{1,\ldots,K\},\ t\in\{1,\ldots,T\} \tag{4}$$

Numerical Experiments

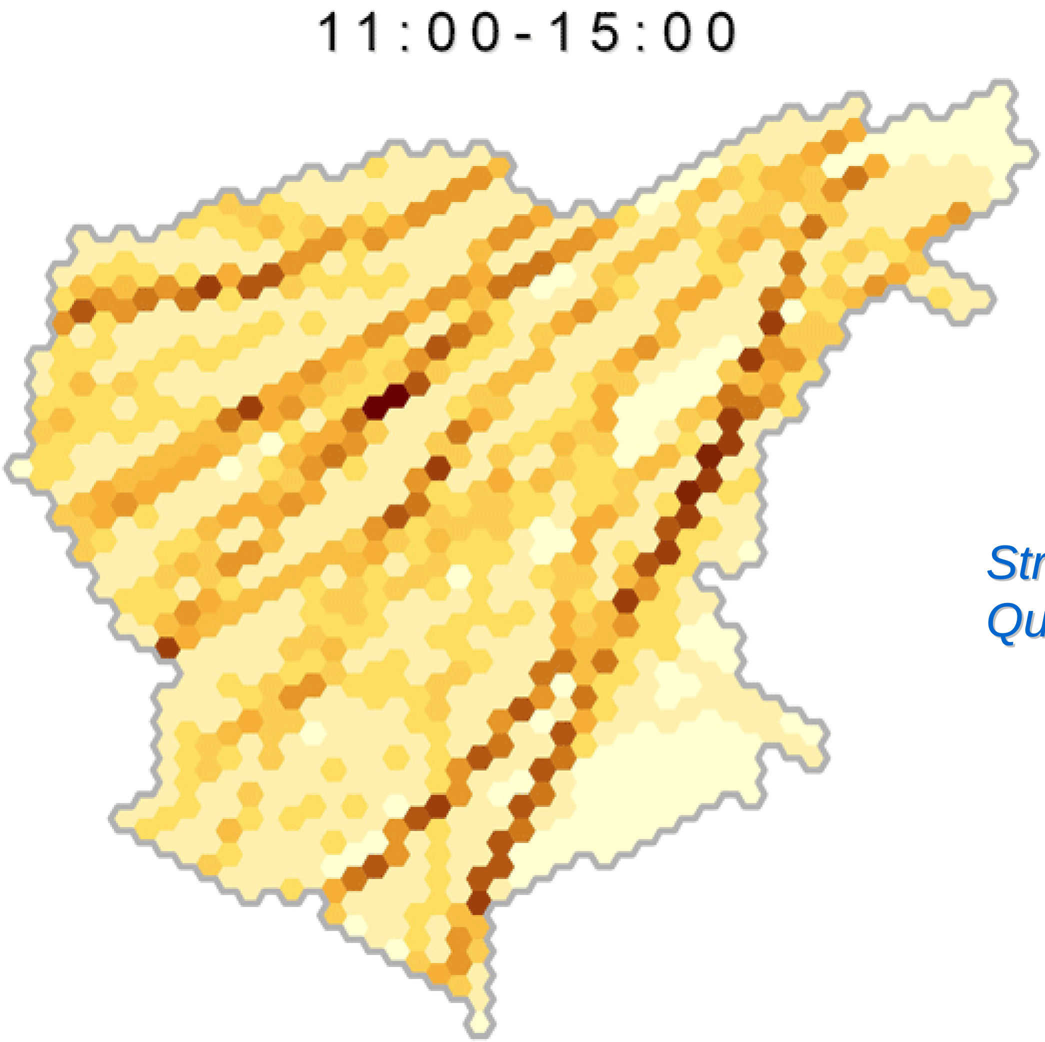
- Basic Settings:
  - ZDC airspace is translated into a network of 1043 nodes, 2961 links, and 41 seed nodes.
  - 2 choices of sector capacity values are considered
    - I.e. at most 2 controller positions per sector.
- Experiments
  - High Variation Case (4 periods x 4 hours)
  - Low Variation Case (4 periods x 2 hours)

High Demand Variation Case, 11:00 –03:00



Low Demand Variation Case, 17:00 – 01:00

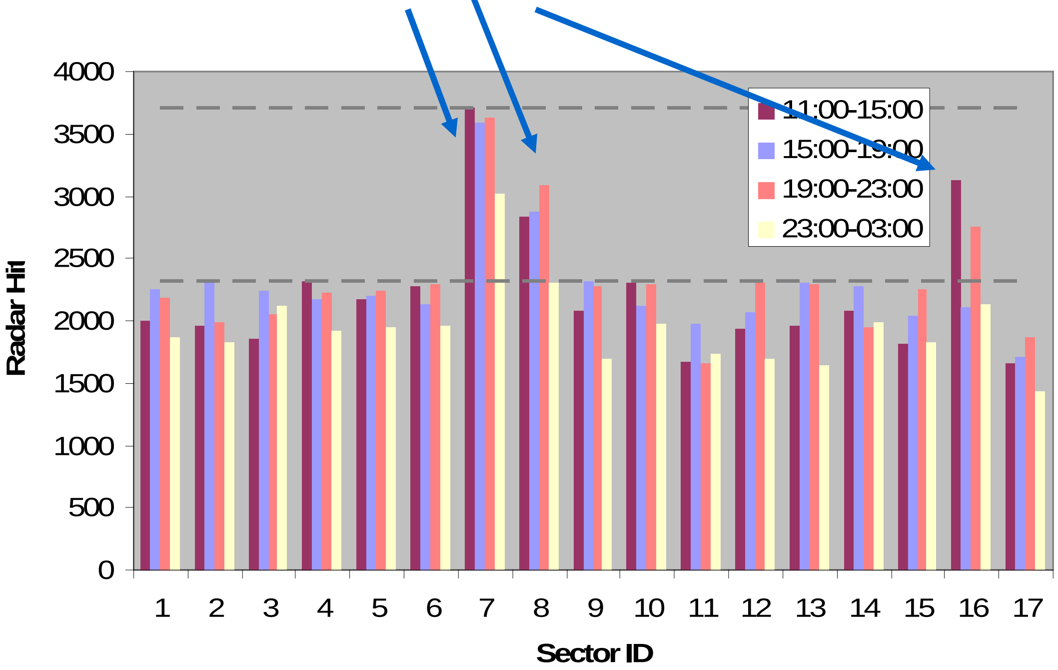
ZDC Demand Variation on April 21 2005

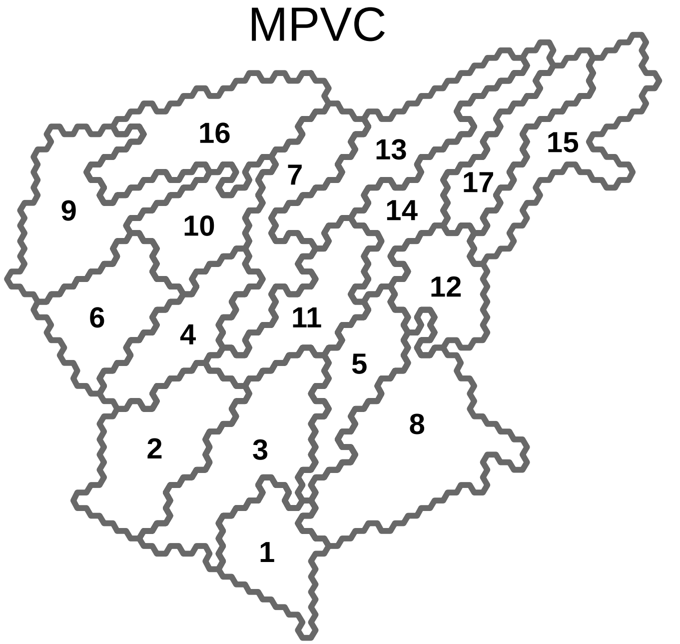


Strong directional patterns.
Quiet at midnight.

MPVC Results
(High Demand Variation Case)

Two controller team required.





Resulting No. of Sectors	Resulting No. of Controller Shifts				Capacity Assumed	
	11:00 | 15:00	*15:00 | 19:00*	*19:00 | 23:00*	*23:00 | 03:00*	*Using 1 Position*	*Using 2 Positions*
17	20	19	20	18	2315	3704

Total Controller Hours:
(20+19+20+18)×4 = 308

Setting of YMIP

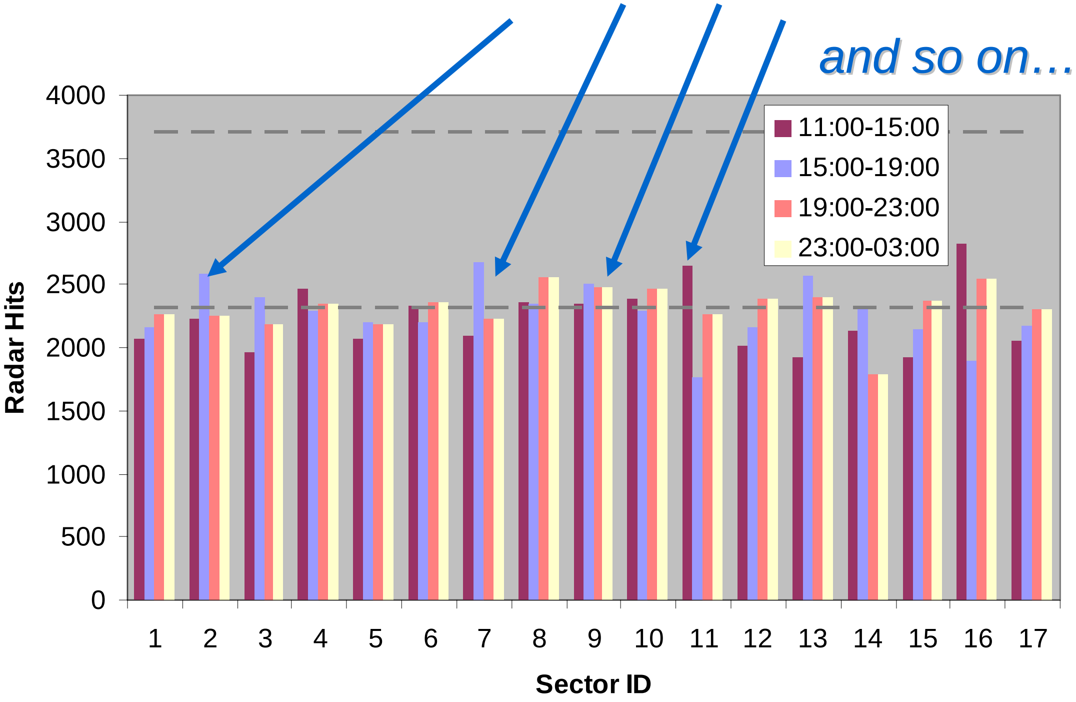
- Yousefi et al (2007) developed a workload balancing model with the following characteristics:
  - Optimizing sector boundaries to align with traffic.
  - Workload deviation among sectors is controlled within a tolerance value.
  - Number of sectors is set as an input value.
  - Demand is aggregated across the planning horizon.
- By imposing additional constraints and set T=1 and K=1, we can obtain YMIP results:

$$\sum_{i \in S,\, j \in B_i} p_{ij}^{t} = \text{Desired No. of Sectors}$$

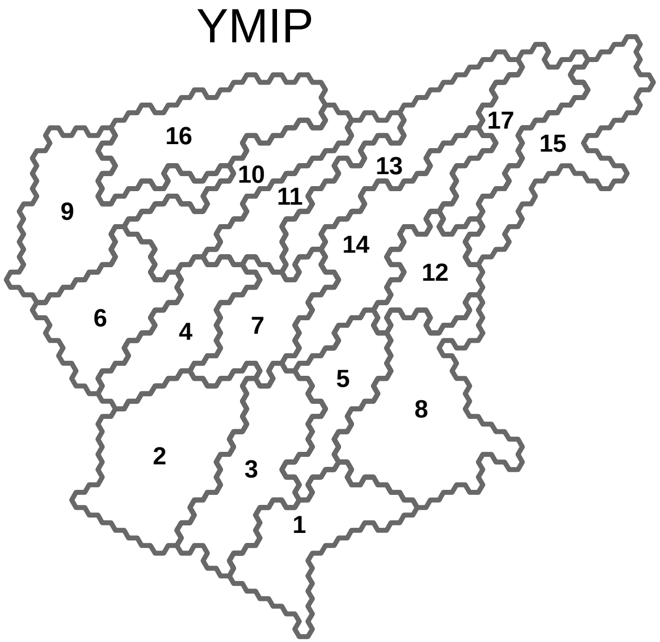
$$p_{i,b_i^1}^{t}(1-\gamma)\mathrm{W}_{\text{target}} \le x_{i,b_i^1}^{t} \le p_{i,b_i^1}^{t}(1+\gamma)\mathrm{W}_{\text{target}} \qquad \text{for all } i \in S$$

YMIP Results
(High Demand Variation Case)

All bars over dashed line invoke a 2-controller team



and so on…



Resulting No. of Sectors	Resulting No. of Controller Shifts				Capacity Assumed	
	11:00 | 15:00	*15:00 | 19:00*	*19:00 | 23:00*	*23:00 | 03:00*	*Using 1 Position*	*Using 2 Positions*
17	24	24	26	17	2315	3704

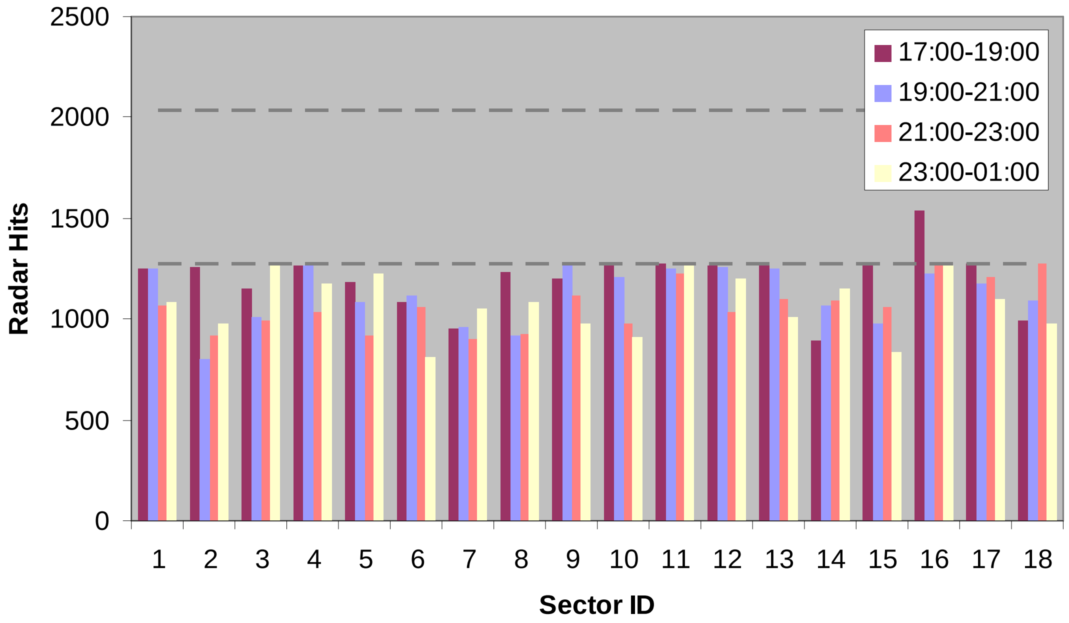
Total Controller Hours: (24+24+26+17)×4 = 364

18% more in controller hours than MPVC result!

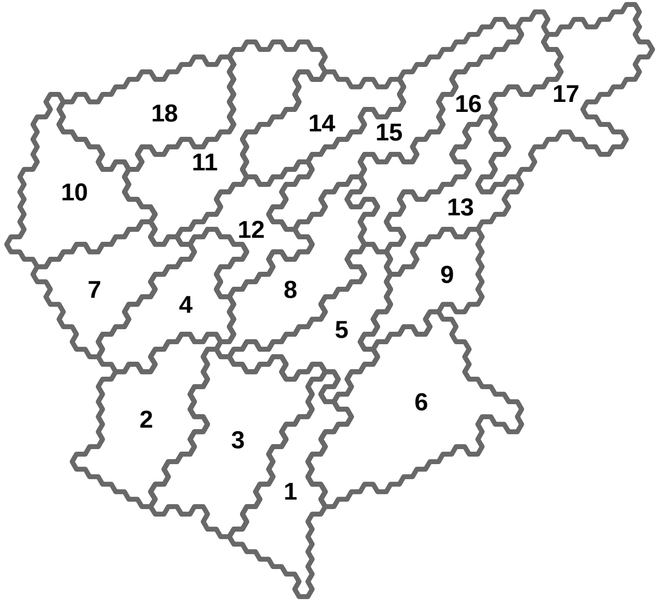
Notes on High Demand Variation Case

- Unawareness of controller team sizes might create an inefficient design (e.g. second controller needed but not well utilized).
- Different design strategies of implementing YMIP:
  - Limiting the target workload under 1-controller threshold:
    - In this instance, YMIP requires 20 sectors and thus 320 controller hours (still higher than the MPVC result).
  - Applying YMIP for individual periods:
    - Periodic reapplication probably requires wholesale boundary changes during “the heat of battle”.

MPVC Results
(Low Demand Variation Case)



MPVC



Resulting No. of Sectors	Resulting No. of Controller Shifts				Capacity Assumed	
	17:00 | 19:00	*19:00 | 21:00*	*21:00 | 23:00*	*23:00 | 01:00*	*Using 1 Position*	*Using 2 Positions*
18	19	18	18	18	1272	2035

When demand is steady, creating two 1-controller sectors is more efficient than one 2-controller sector!

Total Controller Hours: (19+18+18+18)×2 = 146

Numerical Results Summary

Test Case	**High Demand Variation**		**Low Demand Variation**	
Planning Horizon	16 Hrs		8 Hrs	
Duration per Period	4 Hrs		2 Hrs	
Model (MIP)	**MPVC**	**YMIP**	**MPVC**	**YMIP**
Design Objective	Minimize no. of controller shifts and sectors; Minimize flow alignment cost	Balance workload among sectors; Minimize flow alignment cost	Minimize no. of controller shifts and sectors; Minimize flow alignment cost	Balance workload among sectors; Minimize flow alignment cost
Required Controller-hours	308	364	146	162
Avg. Flight Dwell Time	8.0	8.5	7. 8	8.2
BalDev+	59.1%	5.0%	18.8%	5.0%
BalDev-	-23.7%	-5.0%	-13.4%	-5.0%

Conclusion Remarks

- We extend the scope of workload-balancing sectorization techniques in the literature to allow for imbalances that align with controller team sizes.
- Multi-controller positions are used to address demand variation over multiple periods.
- Multi-period design also avoids frequent and disruptive wholesale resectorization throughout the day.
- Our work can be extended by taking weekday or seasonal effects into account.

Future Works

- Quality sector design has multi-objectives. There are other factors to be considered (e.g. intersection and flow proximity to sector boundary).
- The linkage between controller staffing and sector capacity values should be further explored.
- The running time of MPVC increases with the number of periods and the size of the underlying network. More efficient solution method is needed.
- Further extensions might include:
  - Non-controller resource constraints on sector capacity (e.g. radio frequencies).
  - The uncertainty of capacity estimates and demand forecasts.

Thank you!