Integrating Resource Acquisition and Repositioning Decisions into Tactical Transportation Planning under Uncertainty

With Mike Hewitt, Loyola University Chicago

ST. JOHN'S UNIVERSITY | THE PETER J. TOBIN COLLEGE OF BUSINESS

SZKOŁA GŁÓWNA HANDLOWA W WARSZAWIE

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Preparing people to lead extraordinary lives

What does a consolidation carrier do?

Transports customer time/day-“definite” shipments

Customer shipments small relative to trailer capacity

Customer A
From: Miami, FL
To: Chicago, IL

Customer B
From: Atlanta, GA
To: Chicago, IL

Two primary industries

Small package/Parcel

Less-than-truckload (LTL) freight

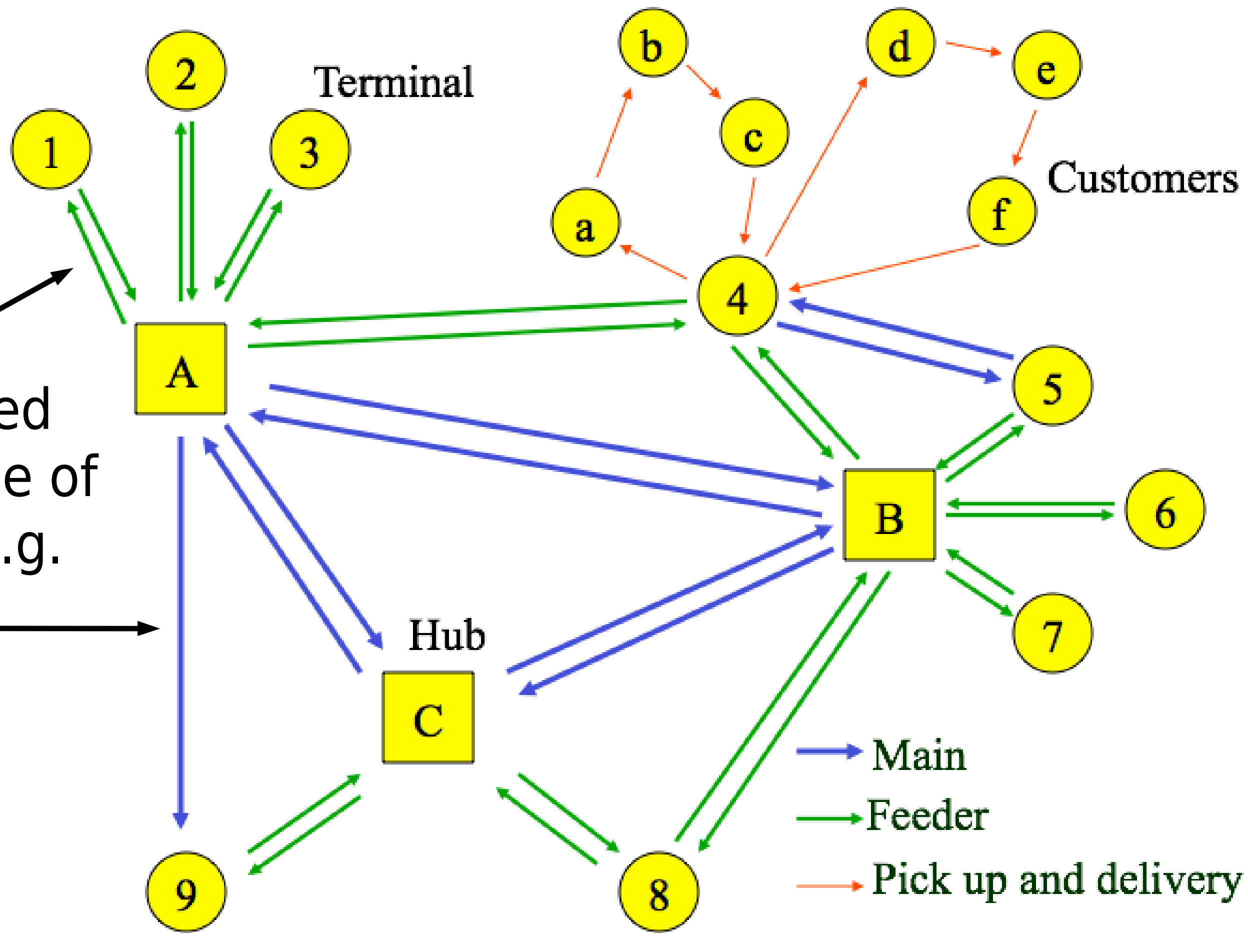
Consolidation enabled by a hub-and-spoke network

Moves executed by/with the use of "resources," e.g.

drivers,

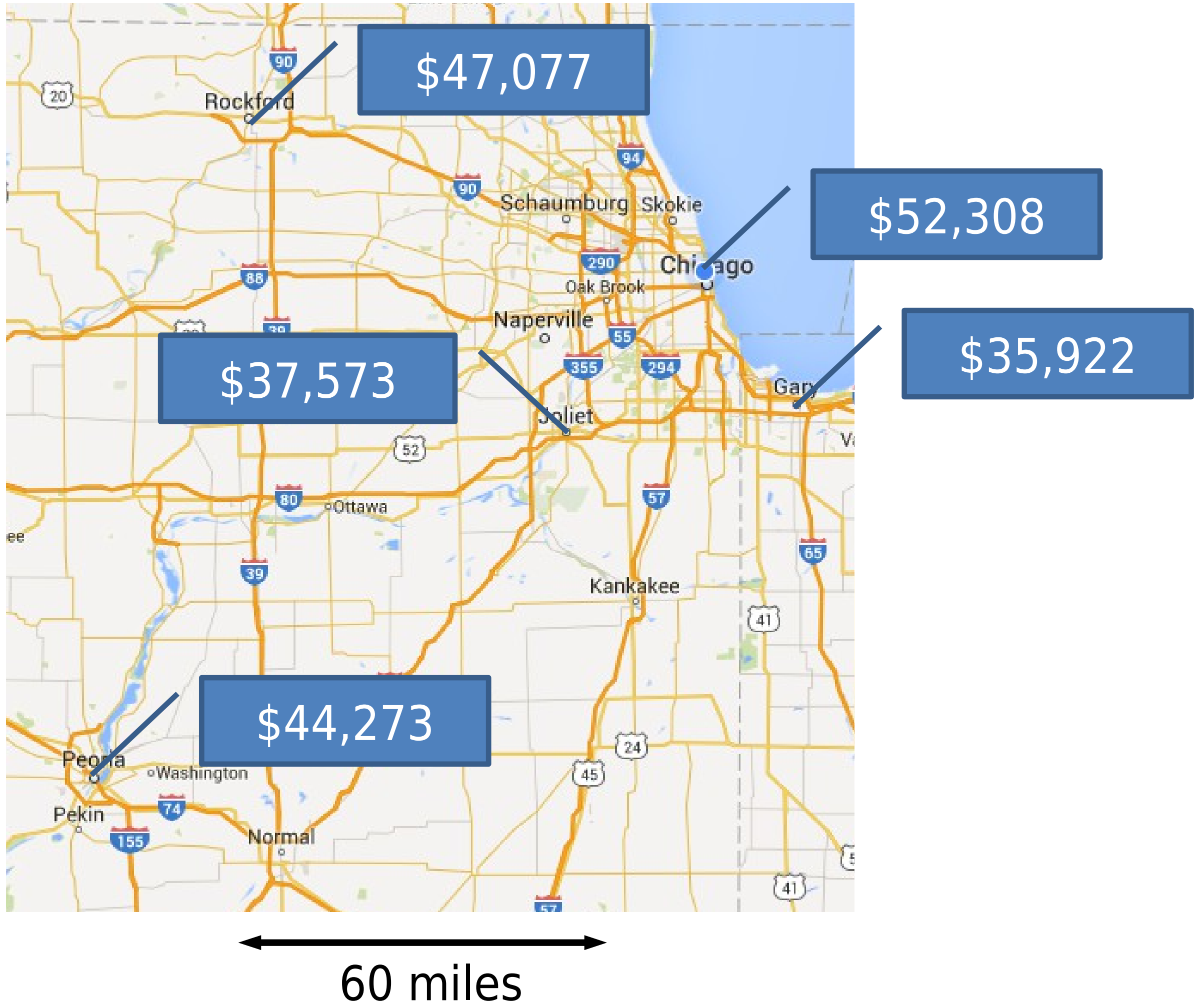
tractors,

containers



Every resource is not the same…

Median annual salary, Truck Driver

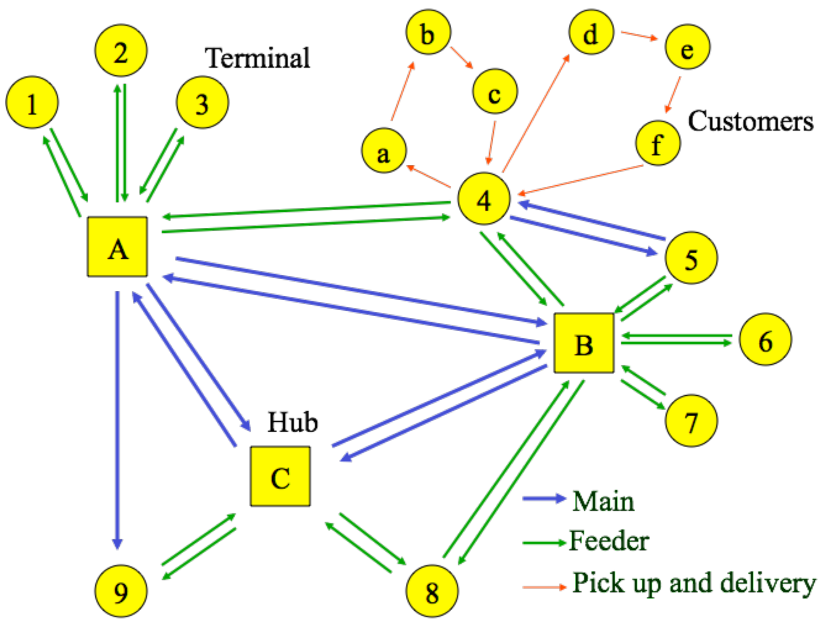


Source: www.payscale.com

Every resource is not the same…

- What are the per mile rates for…
  - Your own fleet?
  - A contracted fleet?
  - The spot market?
- When you make resource allocation decisions, what information is considered?

Three levels of planning



Strategic

Where should terminals be located?

How many resources should we acquire and where should they be located?

Tactical

What is the baseline plan for routing freight through terminal network?

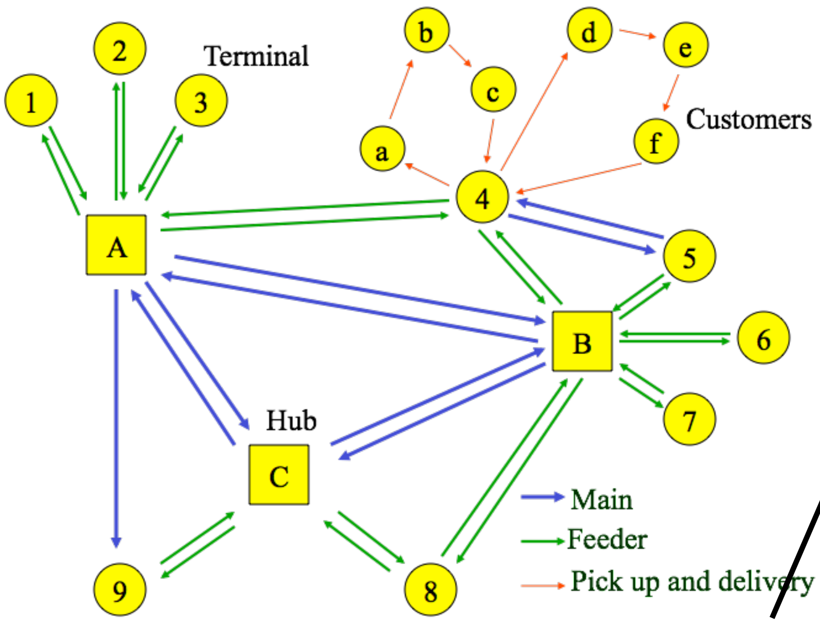
Should resources be reallocated?

Operational

Pickup and delivery routing

Trailer routing and matching

What we are doing



One model to answer these questions while recognizing uncertainty in freight volumes

<u>Strategic</u>

Where should terminals be located?

How many resources should we acquire and where should they be located?

<u>Tactical</u>

What is the baseline plan for routing freight through terminal network?

Should resources be reallocated?

<u>Operational</u>

Pickup and delivery routing

Trailer routing and matching

More explicitly recognizing resource moves and rules

Crainic, Hewitt, Touluse, Vu. Service Network Design with Resource Constraints. *Transportation Science*, to appear.

Model that recognizes terminal-level resource limits when designing service network and matheuristic that quickly produces high quality solutions

Deterministic models

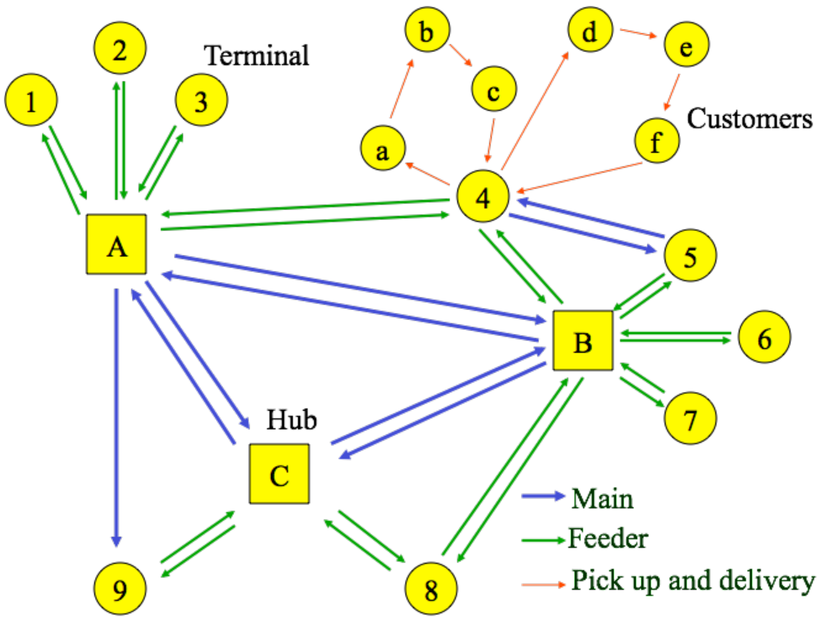
Crainic, Hewitt, Touluse, Vu. Location and Service Network Design with Resource Constraints. In preparation.

Model that (re-)allocates resources to terminals while recognizing terminal-level resource limits when designing service network and matheuristic that quickly produces high quality solutions

Stochastic model

Today's talk:
Same model as above, but recognizing uncertainty in freight volumes

Scheduled service network design with resource constraints model



- Select services/transportation moves to execute including when they should depart/dispatch
  - Route demand through resulting network of services
- Recognize that services require resources to operate
  - Restrictions on how resources may be used
  - Represent in model how resources move and when they should depart/dispatch

Model time with a time-space network

Assume fixed schedule length

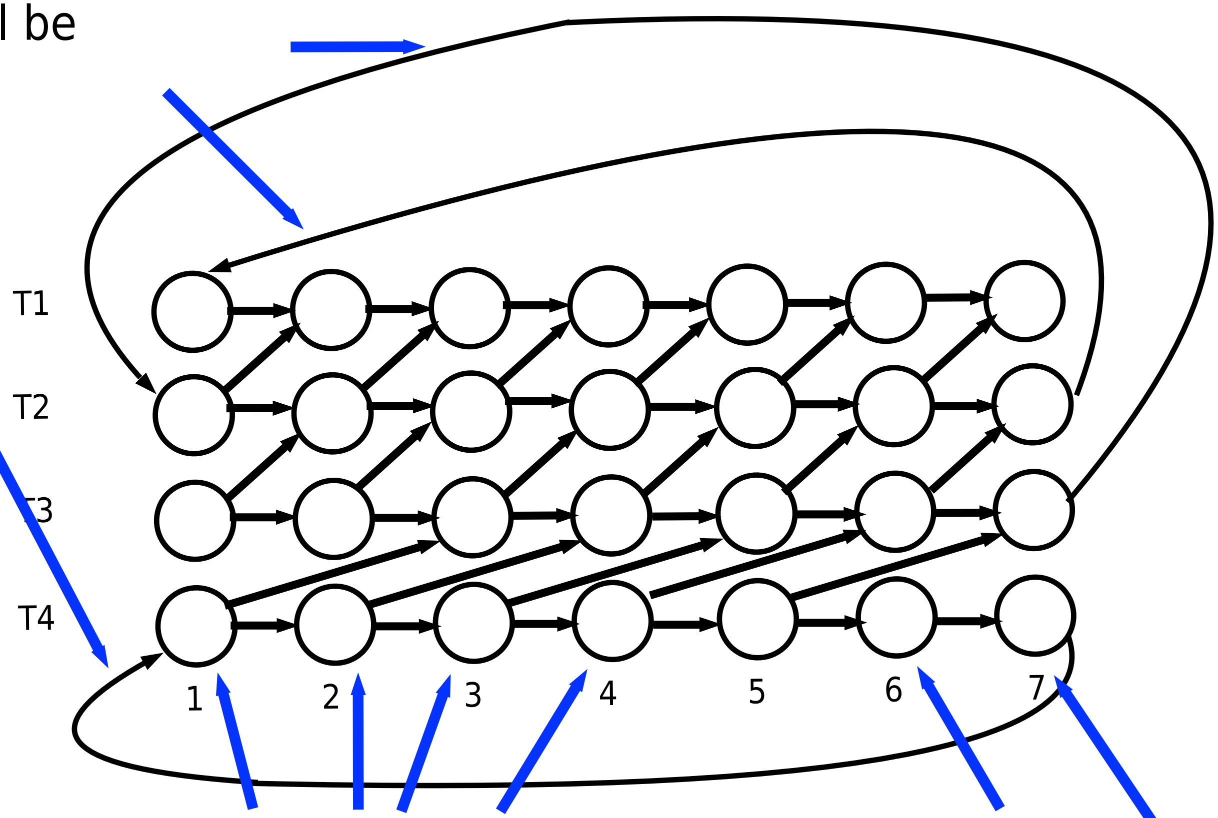
Solve model to produce a repeatable plan/schedule

Model uncertainty through scenario planning

Generate numerous scenarios based on distribution of past demand

Time-space network

“Wrap-around” arcs model that schedule will be repeated



Not all arcs shown

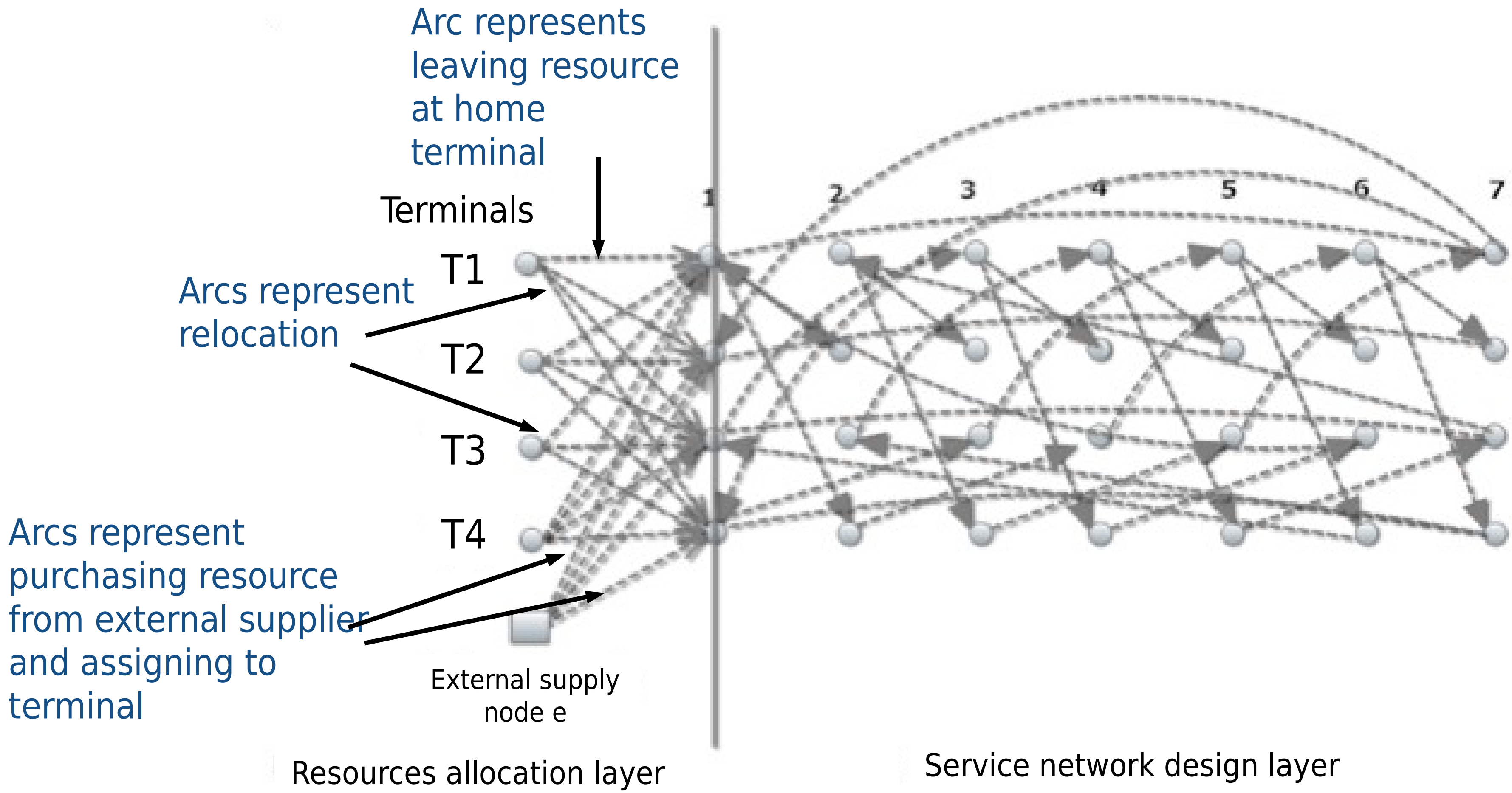
Multiple nodes for same terminal represent dispatching at different times

Model freight being held at a terminal or a resource idling

“Location” decisions

- Re-allocate resource to a new “home” terminal to account for demand modifications (e.g. change in season)
  - Fixed (resource) reposition cost by terminal pair
- Buy
  - Fixed (resource) cost = amortized buying cost + transportation to desired “home” terminal
- Outsource a given service (need not be covered by a resource cycle)
  - Fixed cost = transportation (at a markup)

Model location decisions by extending what a cycle variable encodes



Cycle variable now encodes:

- Original source of resource (it’s own home terminal, a terminal from which it was repositioned, or an external supplier)
- The resource’s (potentially new) home terminal
- The schedule for the resource for the planning horizon

Stochastic program for location and service network design under uncertainty (LSND-U)

$$\text{minimize} \sum_{w\in W}\sum_{h\in N}\sum_{\tau\in\theta_h} F^{\tau}_{wh} z^{\tau}_{wh} + \sum_{(i,j)\in A} f_{ij} y_{ij} + \sum_{s\in S} p_s \sum_{k\in K}\sum_{(i,j)\in A} c^{k}_{ij} x^{ks}_{ij}$$

subject to

$$y_{ij} \leq \sum_{w\in W}\sum_{h\in N}\sum_{\tau\in\theta_h} z^{\tau}_{wh} \quad \forall (i,j)\in A, \tag{1}$$

$$\sum_{h\in N}\sum_{h'\in N: h'\neq h}\sum_{\tau\in\theta_h} z^{\tau}_{hh'} \leq ub_h \quad \forall h\in N, \tag{2}$$

Commodity flow balance and capacity constraints per scenario

$$\sum_{j:(i,j)\in A} x^{ks}_{ij} - \sum_{j:(j,i)\in A} x^{ks}_{ji} = d^{ks}_i \quad \forall i\in N, k\in K, s\in S, \tag{3}$$

$$\sum_{k\in K} x^{ks}_{ij} \leq u_{ij} y_{ij} \quad \forall (i,j)\in A, s\in S. \tag{4}$$

$$z^{\tau}_{wh} \in \{0,1\} \;\; \forall w\in W, h\in N, \tau\in\theta_h, y_{ij}\in\{0,1\} \;\; \forall (i,j)\in A, \tag{5}$$

$$x^{ks}_{ij} \geq 0 \;\; \forall (i,j)\in A, k\in K, s\in S. \tag{6}$$

Should you choose resource with source w and home terminal h and schedule represented by cycle tau?

For each commodity have an “auxiliary” flow variable that represents outsourcing shipment transportation

Model where services can be outsourced

$$\text{minimize} \sum_{w\in W}\sum_{h\in N}\sum_{\tau\in\theta_h} F^{\tau}_{wh} z^{\tau}_{wh} + \sum_{(i,j)\in A} f_{ij} y_{ij} + \sum_{(i,j)\in A} f^{o}_{ij} y^{o}_{ij} + \sum_{s\in S} p_s \Big(\sum_{k\in K}\sum_{p\in P(k,s)} c^{k}_{p} d^{ks} x^{ks}_{p} + \sum_{(i,j)\in A} f^{os}_{ij} y^{os}_{ij} \Big)$$

subject to

Note outsourcing variables do not need to be covered by a resource cycle

$$y_{ij} \le \sum_{w\in W}\sum_{h\in N}\sum_{\tau\in\theta_h} z^{\tau}_{wh} \quad \forall (i,j)\in A, \tag{1}$$

$$\sum_{h\in N}\sum_{h'\in N:h'\neq h}\sum_{\tau\in\theta_h} z^{\tau}_{hh'} \le ub_h \quad \forall h\in N, \tag{2}$$

$$\sum_{j:(i,j)|inA} x^{ks}_{ij} - \sum_{j:(j,i)\in A} x^{ks}_{ji} = d^{ks}_{i} \quad \forall i\in N, k\in K, s\in S, \tag{3}$$

$$\sum_{k\in K} x^{ks}_{ij} \le u_{ij} y_{ij} \quad \forall (i,j)\in A, s\in S. \tag{4}$$

Model outsourcing as part of tactical planning (e.g. long-term contracts)

$$\sum_{k\in K} x^{ks}_{ij} \le u_{ij}(y_{ij} + y^{o}_{ij})$$

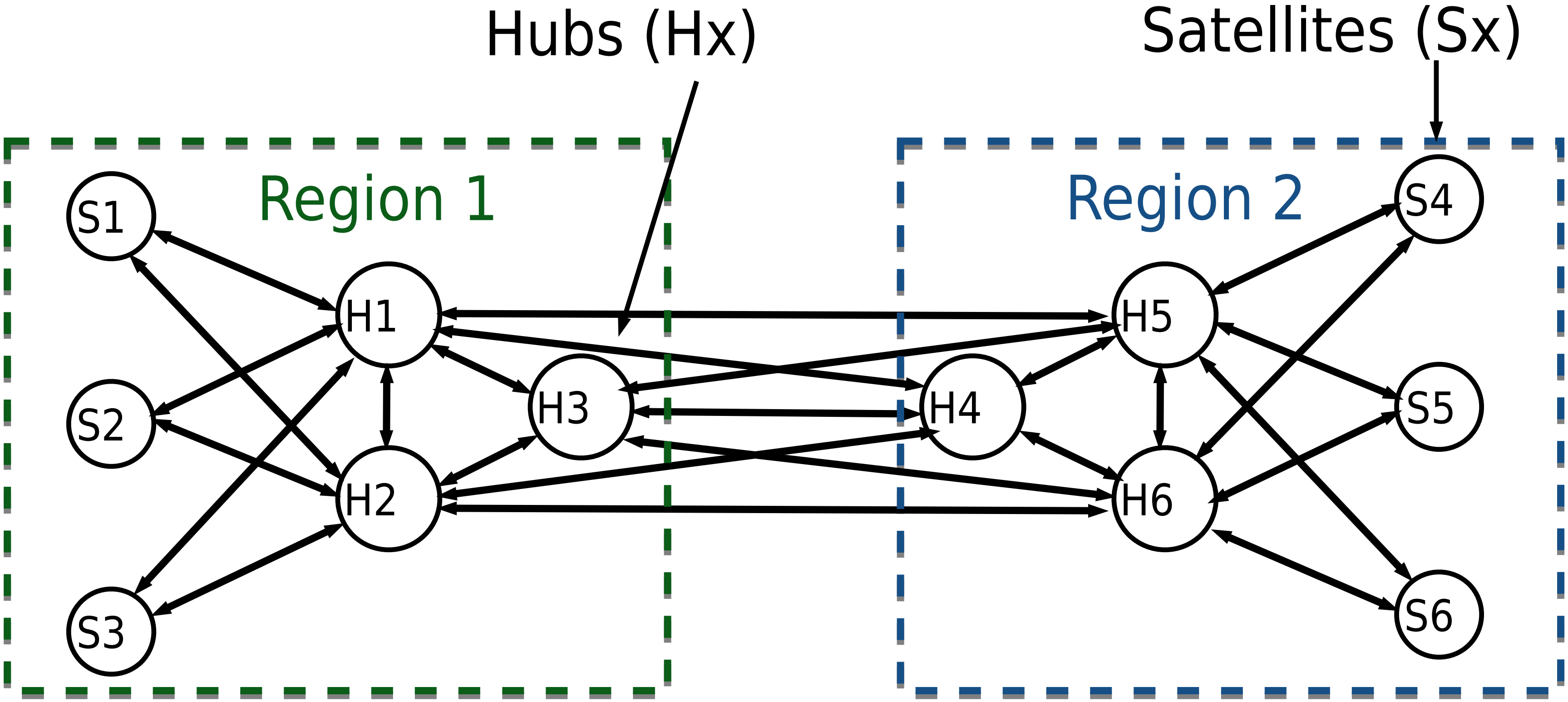
Also model outsourcing via on-demand “spot” market. Assume cost is higher than long-term contract cost

$$\sum_{k\in K} x^{ks}_{ij} \le u_{ij}(y_{ij} + y^{o}_{ij} + y^{os}_{ij})$$

What do we want to do with these models?

- Answer questions such as
  - How does uncertainty impact where you locate resources?
  - How does uncertainty impact outsourcing decisions?
  - How do various model parameters (e.g. contracting and spot-market outsourcing costs) impact decisions?

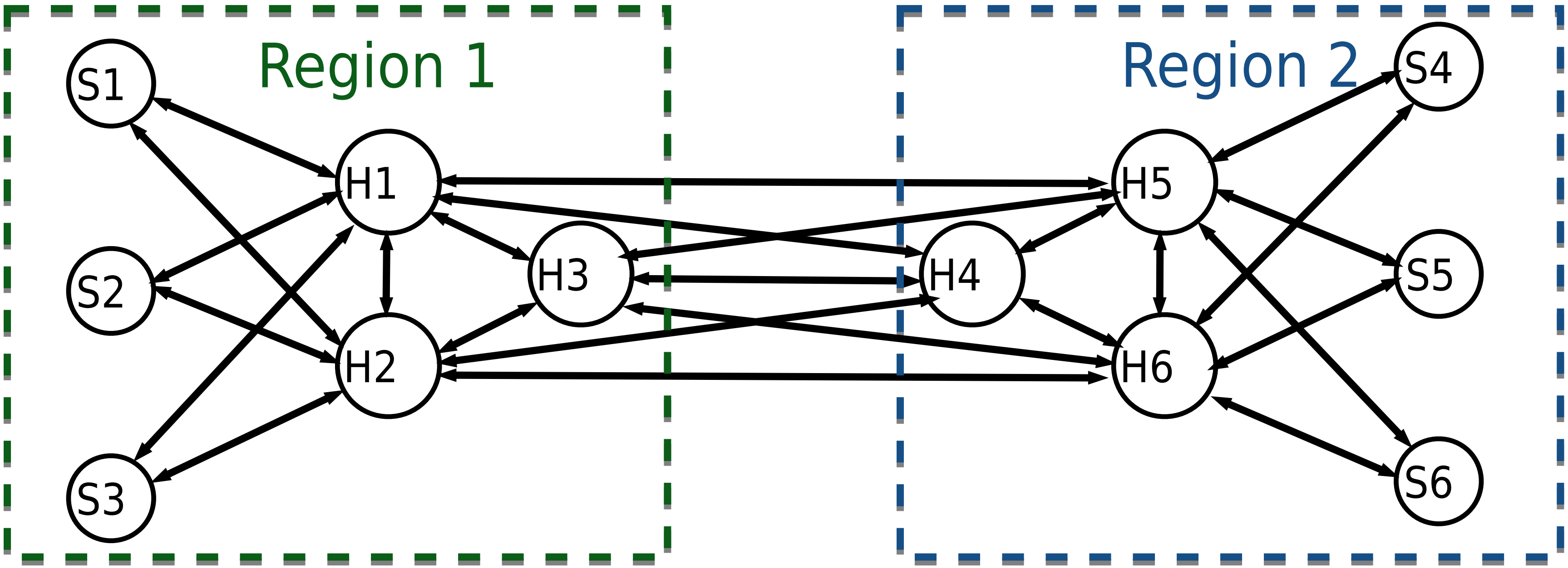
Network for initial experiments



Arcs between regions take 2 periods, all others take 1 period
Instance has 12 periods total (6-day week, 2 periods per day)

Trying to mimic hub-and-spoke structure in a network that will yield instances we can potentially solve…

Computational tractability



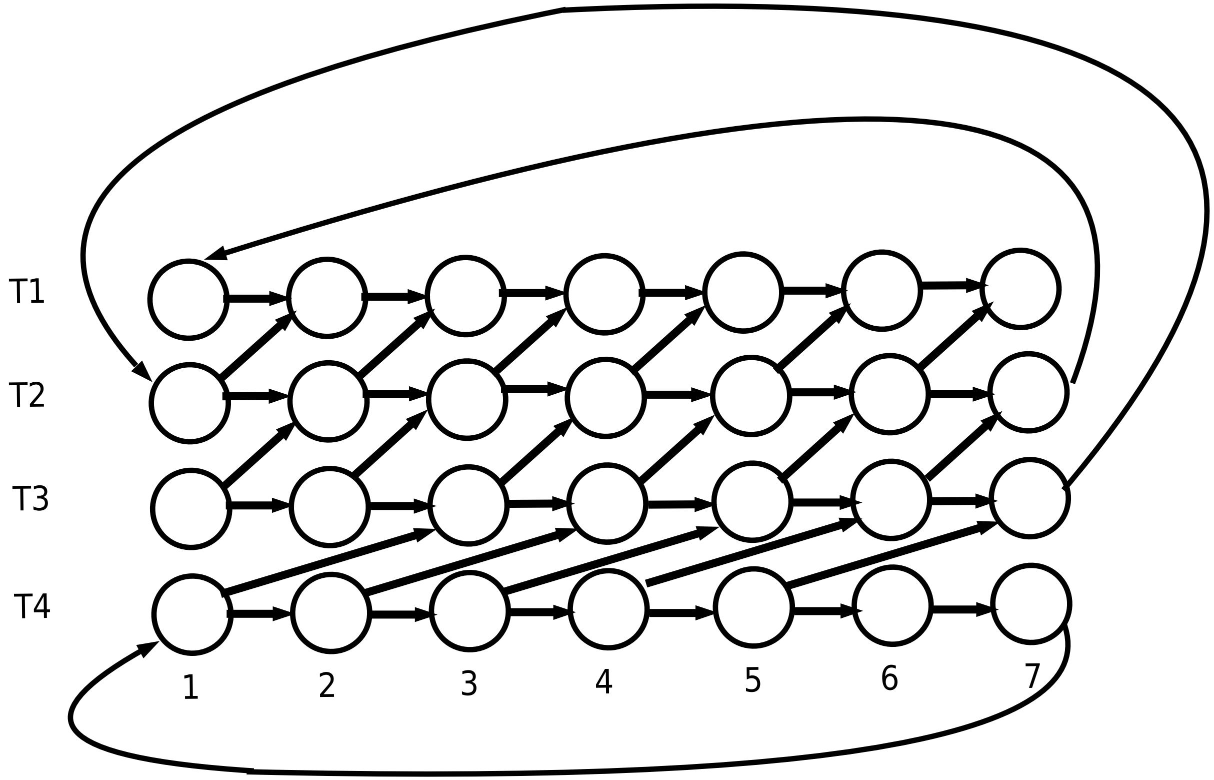
<u>Flat network</u>
12 nodes
50 arcs
80 commodities

<u>Time-expanded network</u>
144 nodes
600 arcs
240 commodities

<u>SP with 9 scenarios</u>
> 1,000,000 commodity flow variables. CPLEX bogs down solving root node LP

Generating all possible cycle variables also too time-consuming

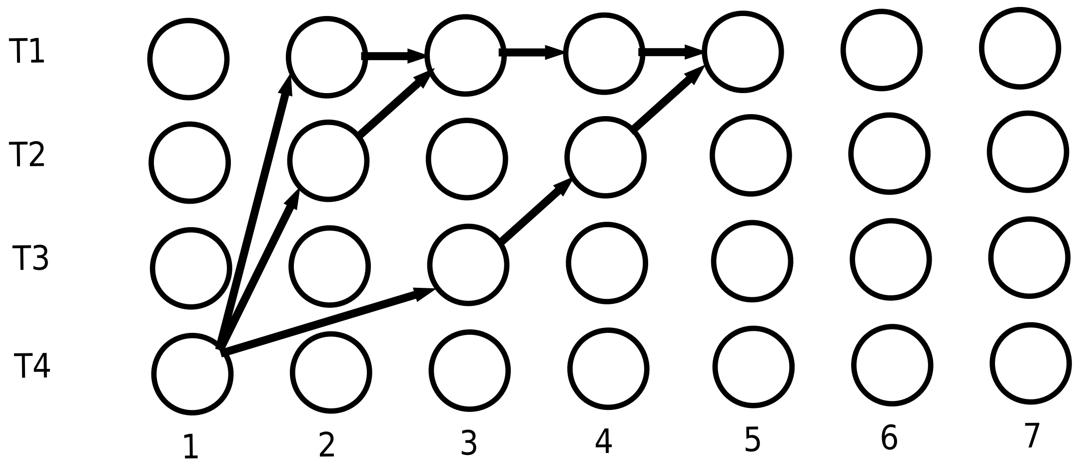
Time-space network



Not all arcs shown

Generating all possible cycle variables also too time-consuming

Time-space network



Generate paths that offer service for commodity from terminal 4 to 1

Includes direct path provided by outsourced transportation options

Reformulate to path-based model which we solve with column generation (Ext-LSND-U)

$$\text{minimize} \sum_{w\in W}\sum_{h\in N}\sum_{\tau\in\theta_h} F^{\tau}_{wh} z^{\tau}_{wh} + \sum_{(i,j)\in A} f_{ij} y_{ij} + \sum_{s\in S} p_s \sum_{k\in K}\sum_{p\in P(k,s)} c^k_p d^{ks} x^{ks}_p$$

subject to

$$y_{ij} \le \sum_{w\in W}\sum_{h\in N}\sum_{\tau\in\theta_h} z^{\tau}_{wh} \quad \forall (i,j)\in A, \tag{1}$$

$$\sum_{h\in N}\sum_{h'\in N: h'\neq h}\sum_{\tau\in\theta_h} z^{\tau}_{hh'} \le ub_h \quad \forall h\in N, \tag{2}$$

All of commodity k's demand must be sent

$$\sum_{p\in P(k,s)} x^{ks}_p = 1 \quad \forall k\in K, s\in S, \tag{3}$$

$$\sum_{k\in K}\sum_{p\in P(k,s):(i,j)\in p} d^{ks} x^k_p \le u_{ij}(y_{ij} + y^o_{ij} + y^{os}_{ij}) \quad \forall (i,j)\in A, s\in S. \tag{4}$$

$$z^{\tau}_{wh} \in \{0,1\} \;\; \forall w\in W, h\in N, \tau\in\theta_h, y_{ij}\in\{0,1\} \;\; \forall (i,j)\in A, \tag{5}$$

$$x^{ks}_p \in [0,1] \;\; \forall k\in K, s\in S, p\in P(k,s). \tag{6}$$

How much of commodity k's demand flows on path p in scenario s?

One of these paths models outsourcing transportation at the shipment level

Reformulate to path-based model which we solve with column generation (Ext-LSND-U)

$$\text{minimize} \sum_{w\in W}\sum_{h\in N}\sum_{\tau\in\theta_h} F_{wh}^{\tau} z_{wh}^{\tau} + \sum_{(i,j)\in A} f_{ij} y_{ij} + \sum_{s\in S} p_s \sum_{k\in K}\sum_{p\in P(k,s)} c_p^k d^{ks} x_p^{ks}$$

subject to

$$y_{ij} \leq \sum_{w\in W}\sum_{h\in N}\sum_{\tau\in\theta_h} z_{wh}^{\tau} \quad \forall (i,j)\in A, \tag{1}$$

$$\sum_{h\in N}\sum_{h'\in N:h'\neq h}\sum_{\tau\in\theta_h} z_{hh'}^{\tau} \leq ub_h \quad \forall h\in N, \tag{2}$$

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$$z_{wh}^{\tau} \in \{0,1\} \;\; \forall w\in W, h\in N, \tau\in\theta_h, y_{ij}\in\{0,1\} \;\; \forall (i,j)\in A, \tag{5}$$

$$x_p^{ks} \in [0,1] \;\; \forall k\in K, s\in S, p\in P(k,s). \tag{6}$$

Price path variables out for each commodity and each scenario with same shortest path-type problem seen in path-based formulations of capacitated network design problems

First CG-based heuristic (CG-Solve)

- Solve LP relaxation of Ext-LSND-U via column generation
- Choose all paths and cycles generated (including those not in final LP solution)
- Solve Ext-LSND-U with a MIP solver

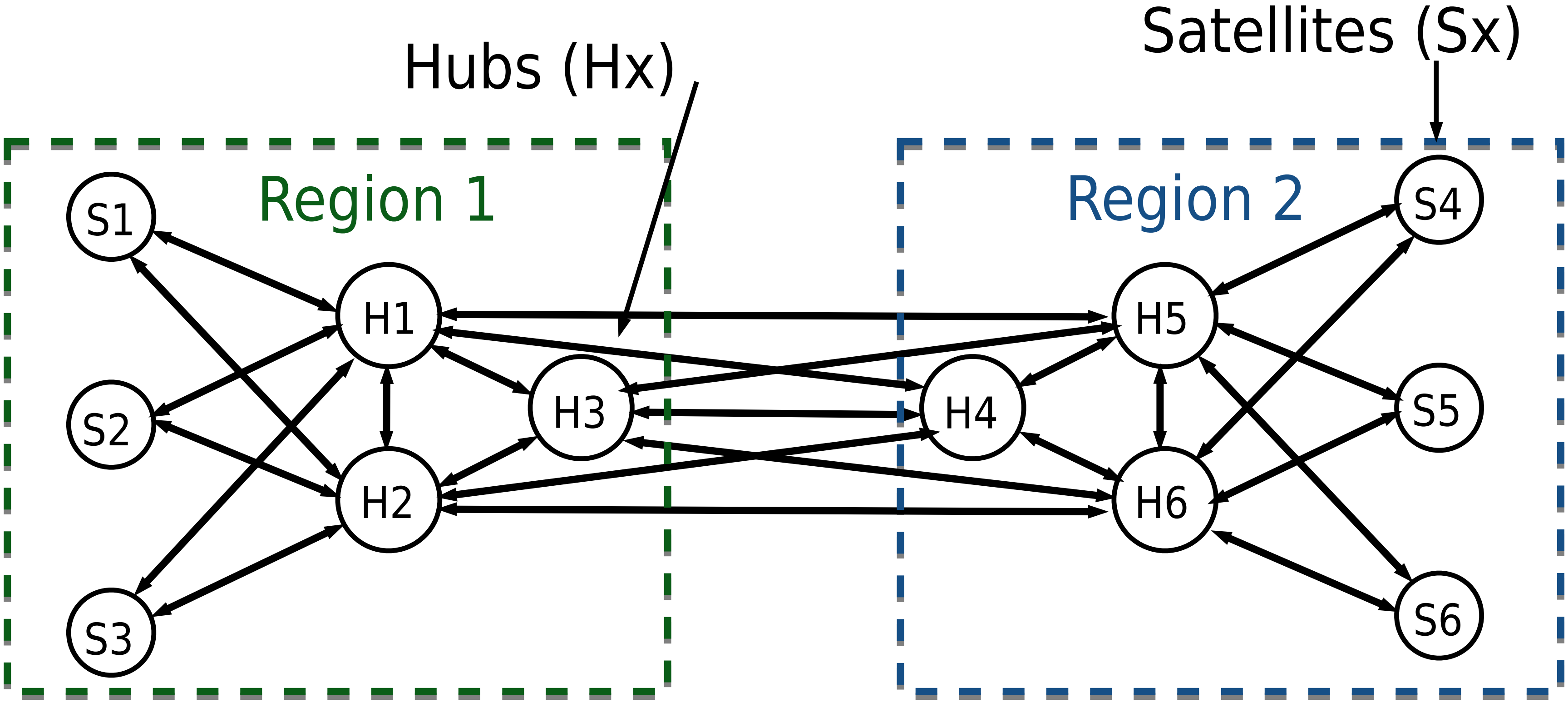
A CG-based Mathheuristic (IPS)

- Solve LP relaxation Ext-LSND-U via column generation for cycles C* and paths P*
- Solve Ext-LSND-U(C*,P*) to produce solution sol*
- Let C_{sol}, P_{sol} represent cycles and paths used in sol*
- Set C_{cand} = C*, P_{cand} = P*
- Determine neighborhood operator
  - if operator generates new cycles and paths then
    - Use operator to generate new cycles, C_{new} and paths, P_{new}
    - Set $C_{cand} = C_{cand}$ U C_{new}; $P_{cand} = P_{cand}$ U P_{new}
- Use operator to determine cycles, $C_{nbhd} = C_{cand}$ U C_{sol} defining neighborhood
- Use operator to determine paths, $P_{nbhd} = P_{cand}$ U P_{sol} defining neighborhood
- Solve Ext-LSND-U(C_{nbhd} U C_{sol}, P_{nbhd} U P_{sol}) for solution sol

Methods for choosing cycles to define neighborhood

- Neighborhoods that don't generate new cycles or paths
  - **RandomCycle**: Choose set of cycles randomly
  - **RandomHome**: Choose set of cycles with same home terminal randomly
  - **CoverFlow**: Choose cycles that cover flows on arcs in current solution, based on scoring mechanism
  - **CoverOutsource**: Choose cycles that cover arcs that are outsourced in current solution, based on scoring mechanism
- Neighborhoods that do generate new cycles and paths
  - Each generates new cycles and paths using skeleton solution of selected cycles and paths, excluding certain ones
  - **SolCG**: Use cycles that are most used in current solution
  - **CoverPathCG**: Only uses paths of current solution, with no consideration for cycles
  - **ScenCoverPathCG**: Only uses paths from subset of scenarios, with no consideration for cycles
  -

Factors in experimental study



Model a planning horizon of 12 periods

144 nodes in the network
600 Time-indexed service arcs
228 commodities

Schedule guidelines:
Each Sx has one shipment a week to 3 Sx
Each Sx has two shipments a week to 5 Hx
Each Hx has two shipments a week to 5 Sx
Each Hx has three shipments a week to each Hx

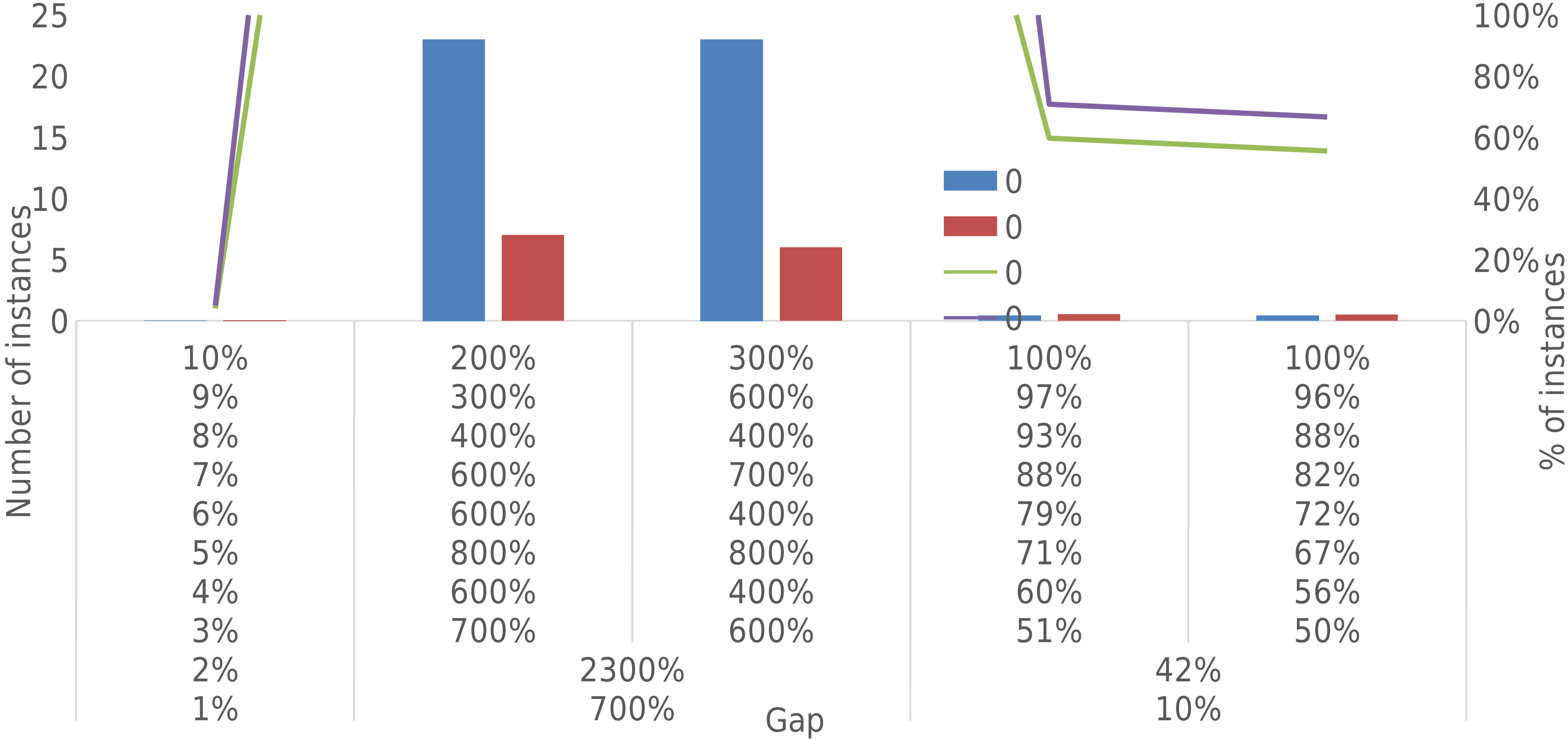
Scenarios

- Fit a distribution to trucking data from a large US LTL carrier
- Assumed one distribution for all commodities (means and standard deviations weren't that different)
- 24 demand scenarios per instance
- Six demand distributions tested
  - Variance
    - Original data
    - 2*original variance
    - 3*original variance
  - Mean
    - Original data
    - 5*original mean

Generated scenarios with code implementing "A Heuristic for Moment-matching Scenario Generation," Kjetil Høyland, Michal Kaut and Stein W. Wallace, published in *Computational Optimization and Applications*, 24 (2-3), pp. 169–185, 2003.

Comparing two heuristics

- Ran CG-Solve for 5 hours
- IPS was better in all 72 instances
-



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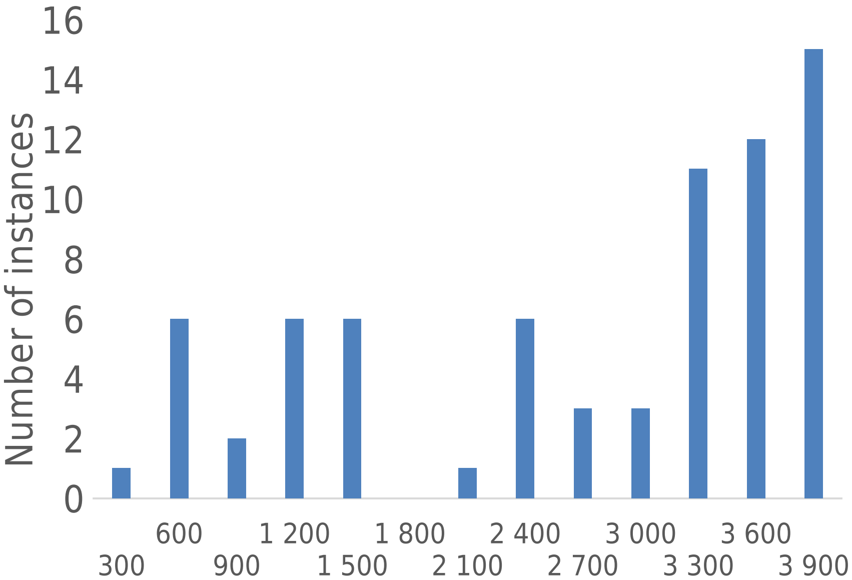
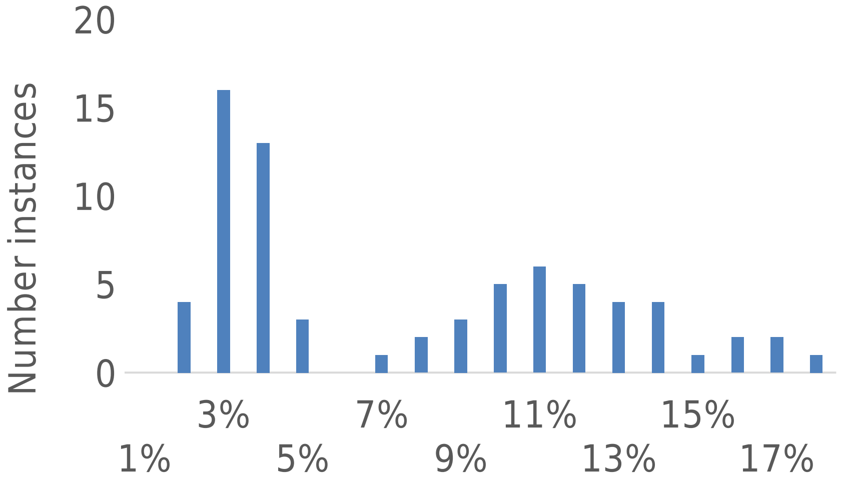
IPS Improvement

- IPS finds best solution in 42 minutes on average



Time to best solution



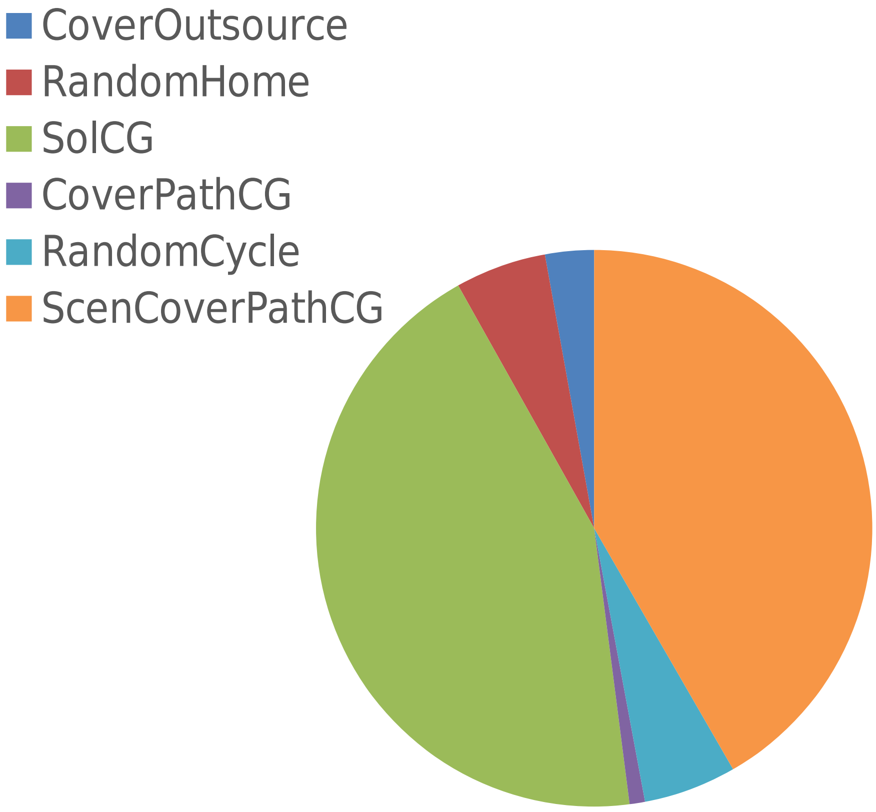
Improvement over first solution

- Best solution is 7.2% better than first solution on average

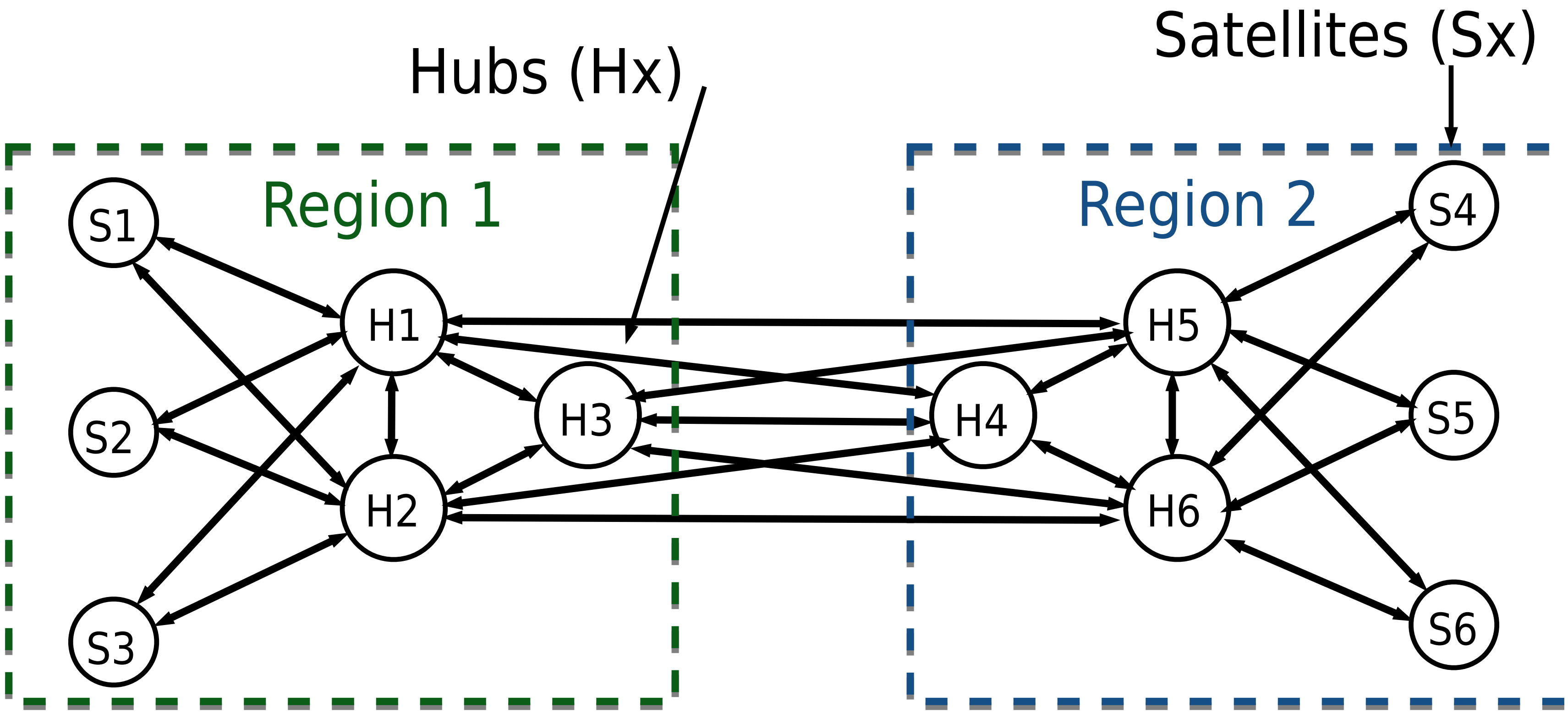
Best neighborhoods to improve solutions

- Proportion of improvements between first and best solution attributed to each neighborhood generating mechanism

New cycle and path generating neighborhoods



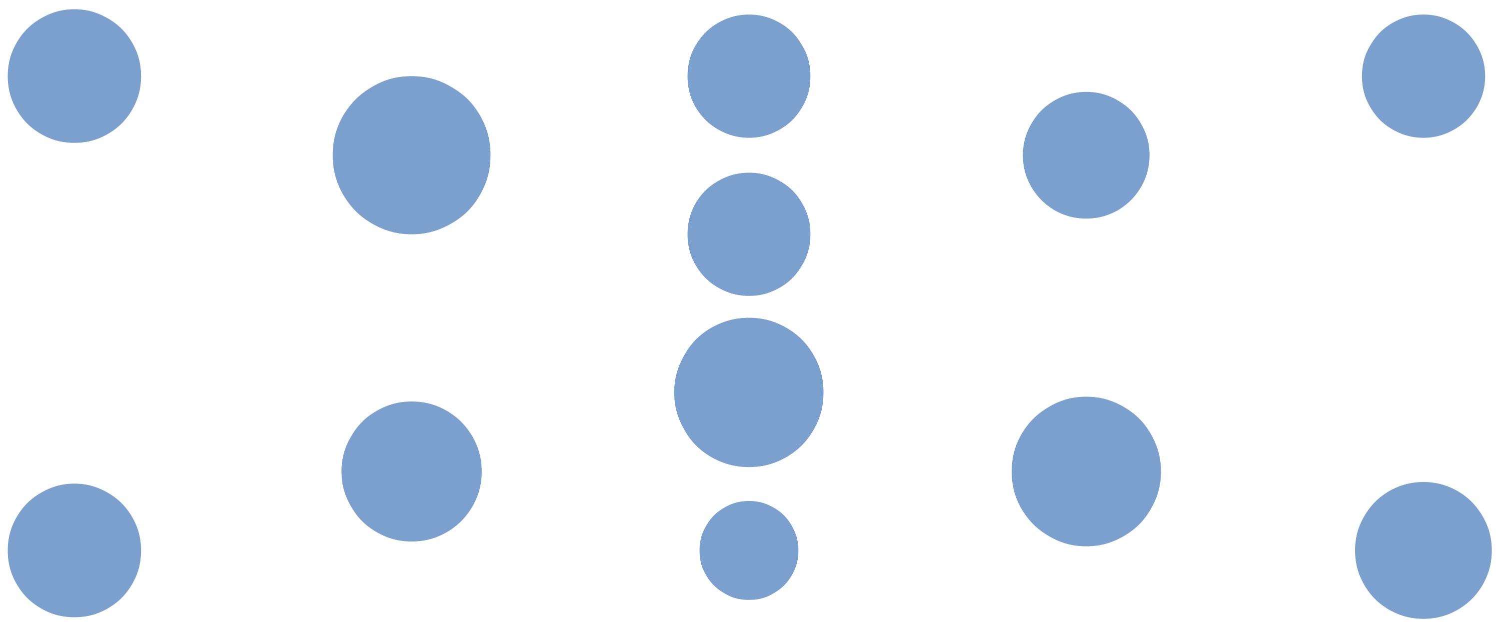
Model Validation



Resource acquisition costs by terminal

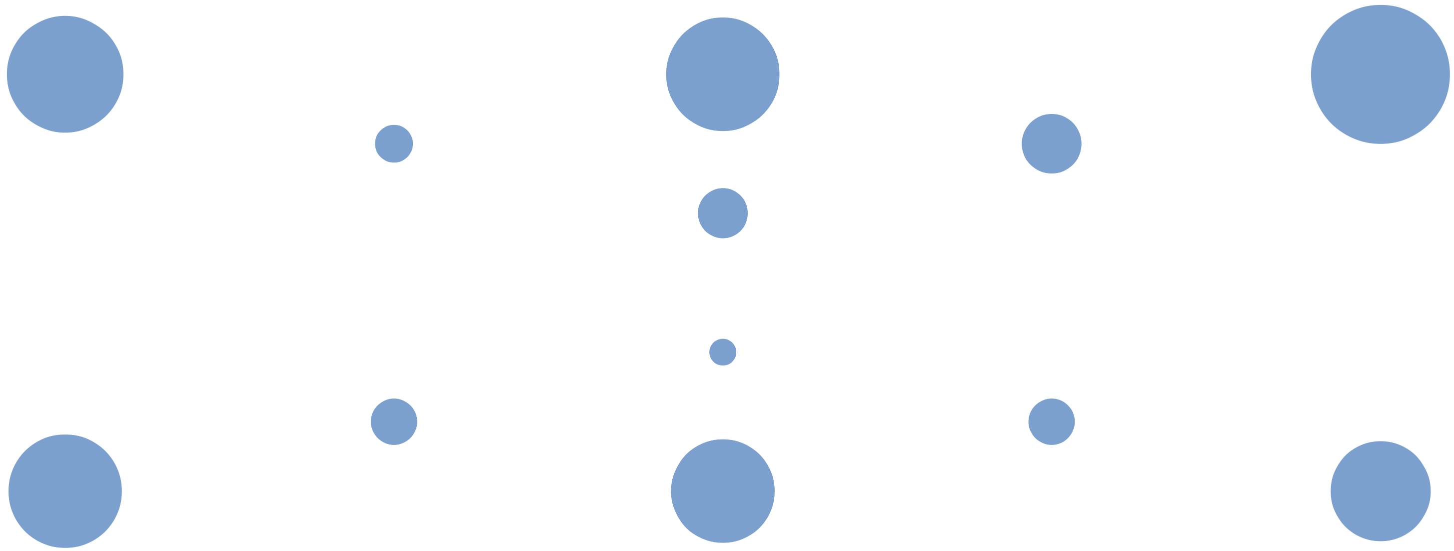
Cost 1: All nodes $1,800 to acquire resource
Cost 2: Satellites @ $1,800, Hubs @ $2,000
Cost 3: Satellites @ 2,000, Hubs @900
Cost 4: S1,H1,H3,S6 @ 1,800
S2,H6,S4 @ 1,900
Others @ 2,000

Percentage of resources per terminal



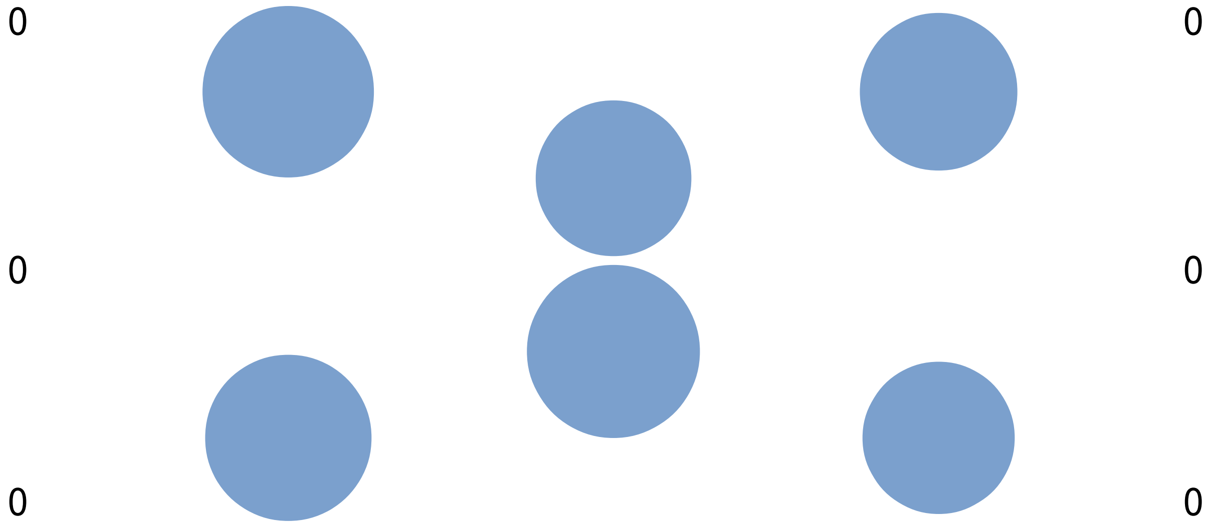
Cost 1: All $1,800 to acquire resource

Percentage of resources per terminal



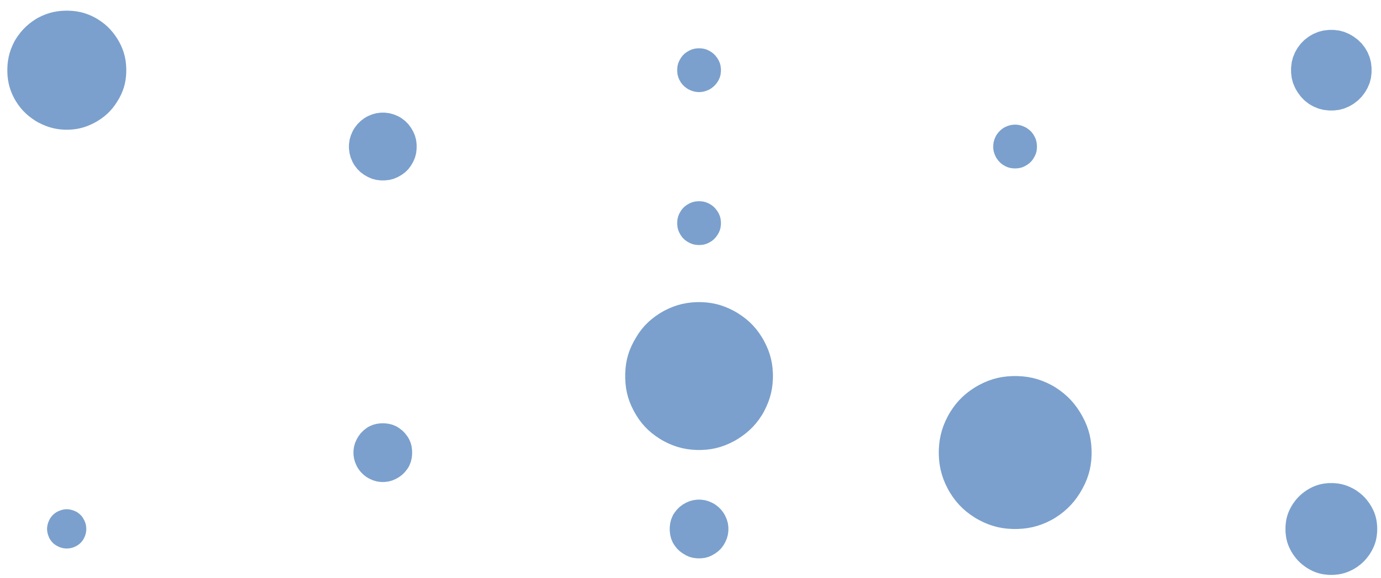
Cost 2: Satellites @ $1,800, Hubs @ $2,000

Percentage of resources per terminal



Cost 3: Satellites @ 2,000, Hubs @900

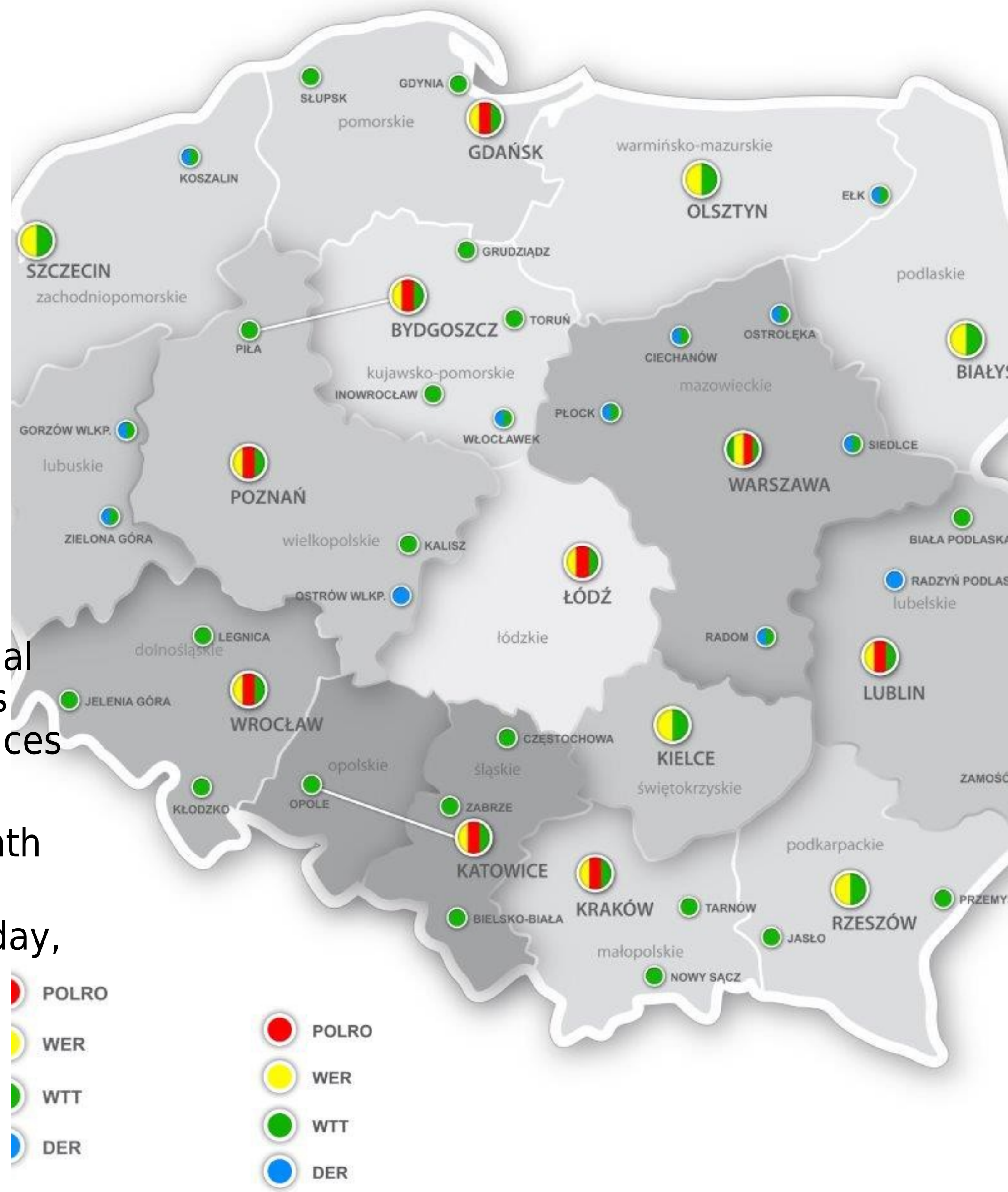
Percentage of resources per terminal



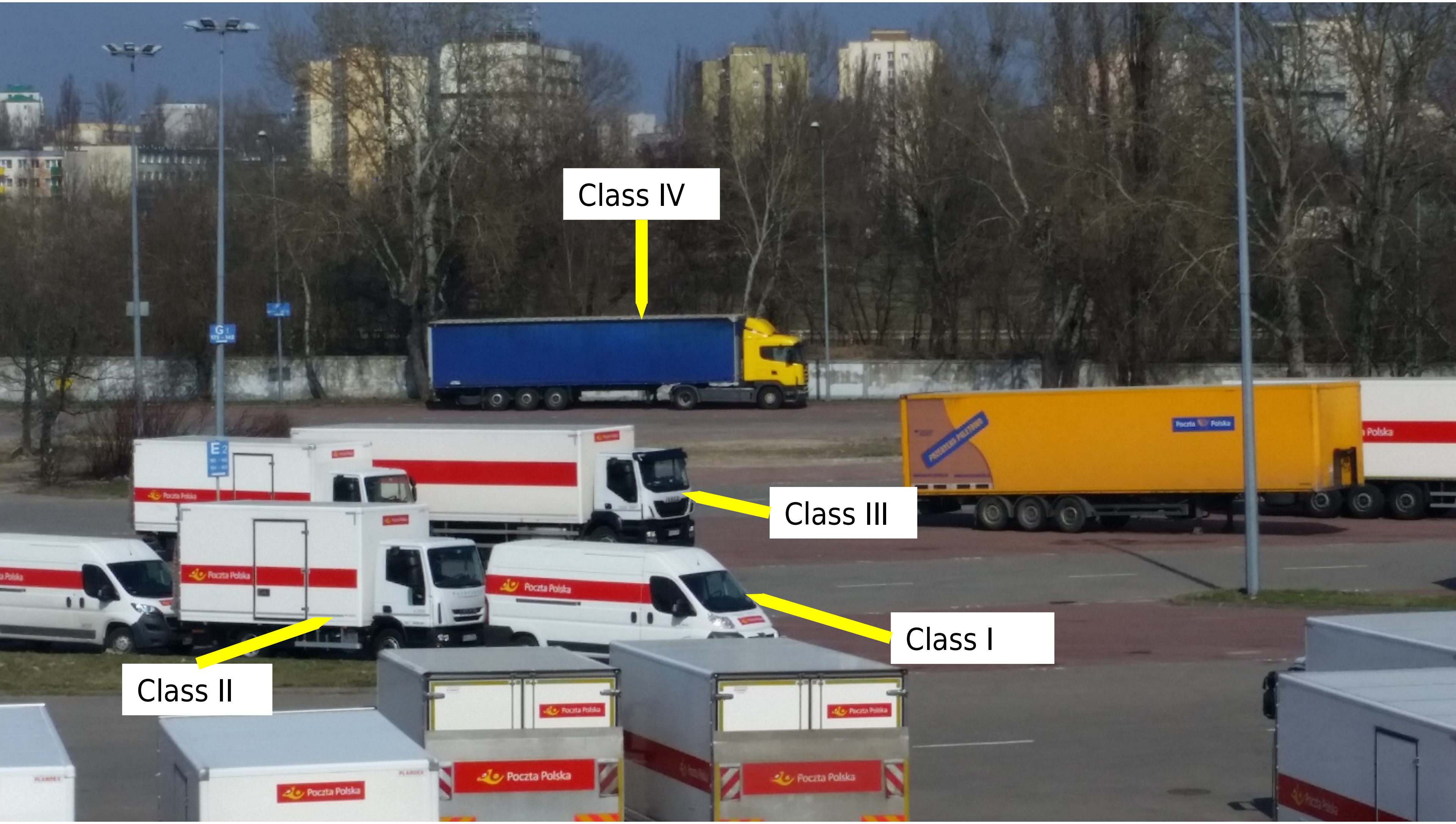
Cost 4: S1,H1,H3,S6 @ 1,800
S2,H6,S4 @ 1,900
Others @ 2,000

Polish Post Network

- 3382 nodes
  - 14 Primary Hubs (WER)
  - 13 Secondary Hubs (DER)
  - 180 Tertiary Terminals
- Nine regions that follow provincial lines, although some regions composed of multiple provinces
  - Costs vary by region
- 376,091 m^3 total volume in month evaluated
- Several types of service – next day, priority, economy
-



Vehicle classifications



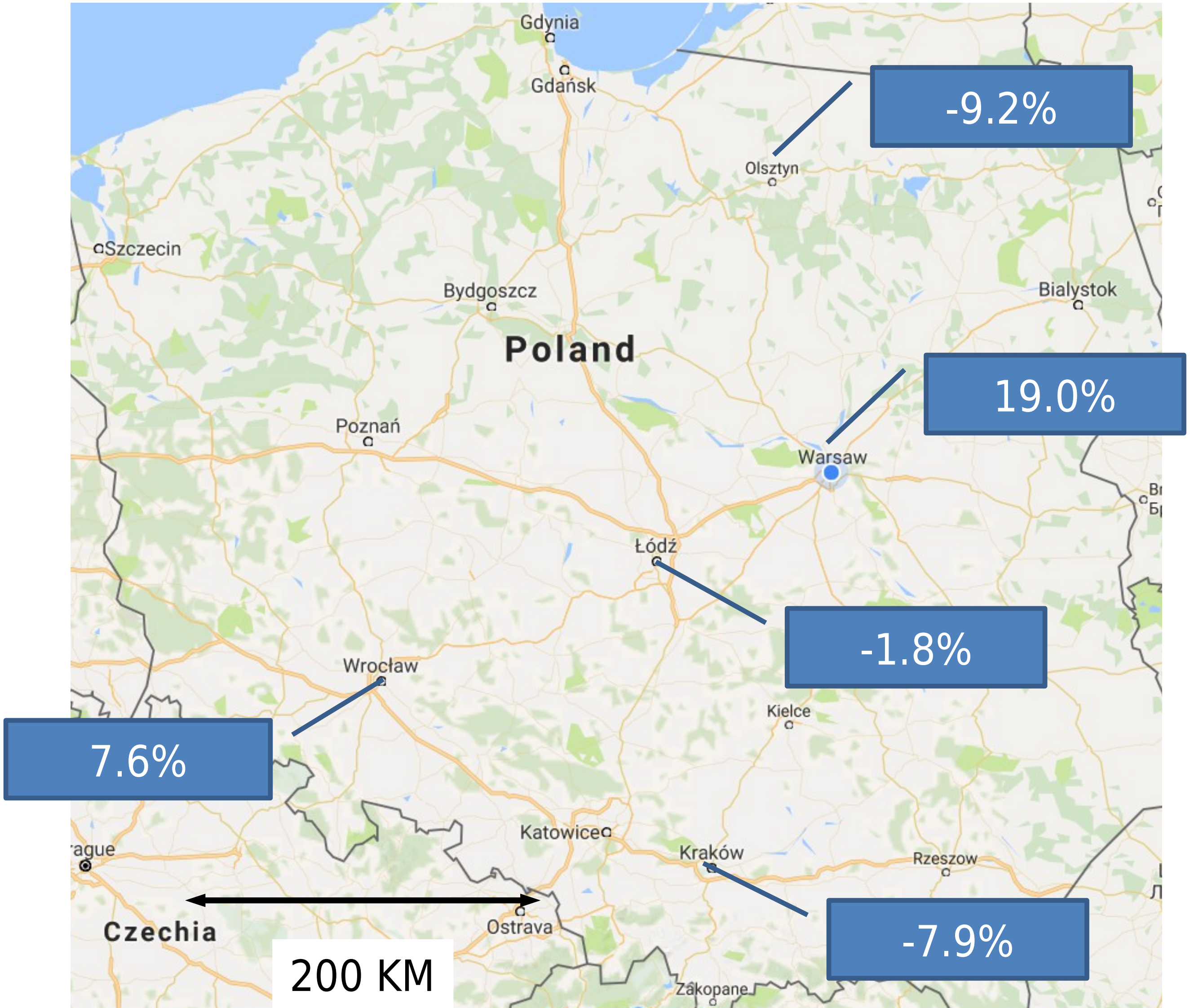
Vehicle classifications

- Volumes vary considerably by class (13, 33, 51, and 85 m^3)
- The cost of the vehicles vary by class, but do not vary across Poland
- All vehicles are leased
- The Polish Post is not interested in changing the number of resources, just allocating them correctly
- For some hubs, the vehicles are parked several kilometers away and there is an initial “fixed”

Class	I	II	III	IV
Number of segments	113,006 88%	9,686 8%	3,415 3%	1,730 1%
Volume (m^3)	179,972 49%	68,759 19%	63,182 17%	56,337 15%

Every resource is not the same...

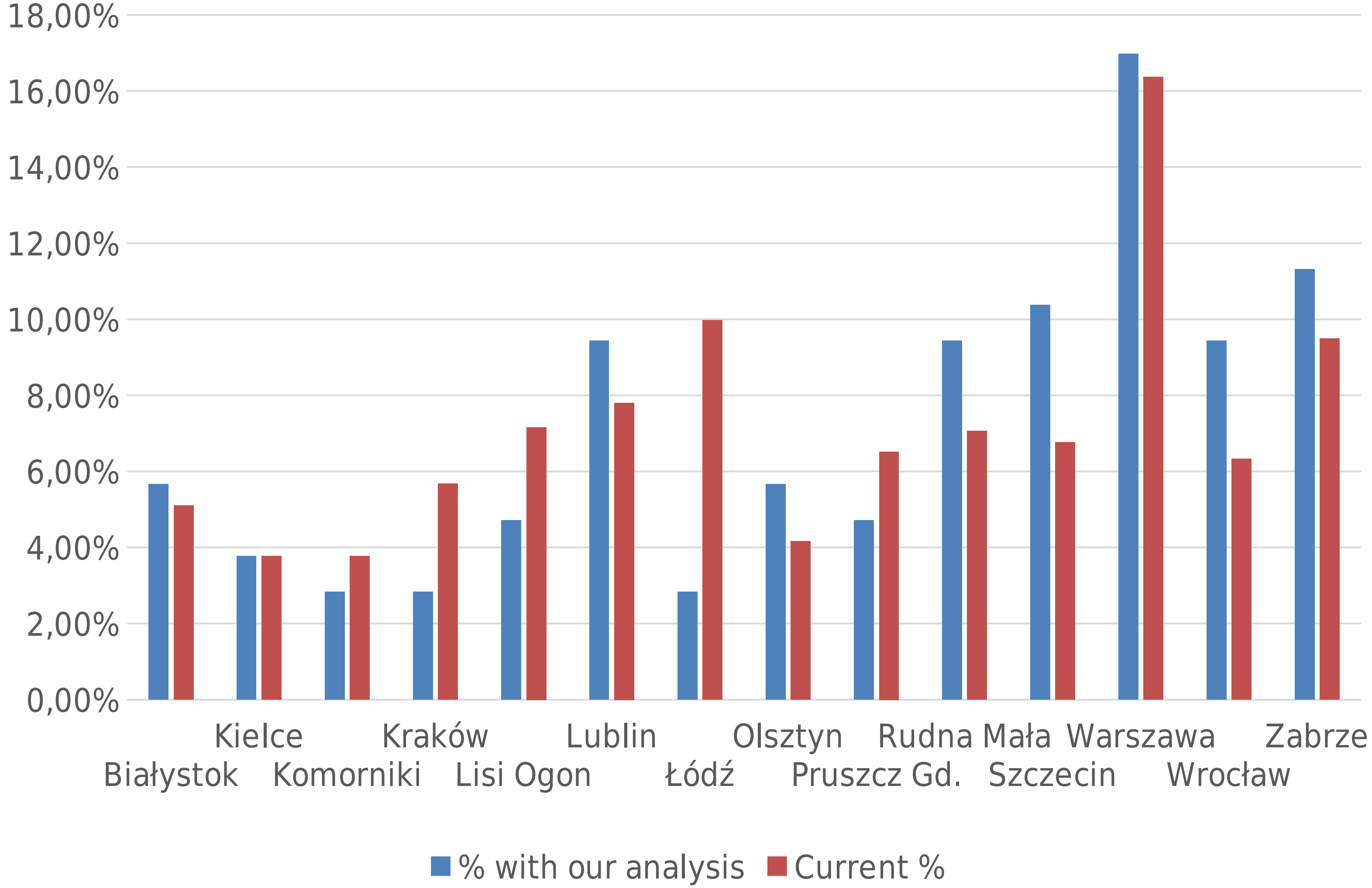
Salary as percentage of national average, Truck Driver, over 3.5 tons



Driver considerations

- Two driver types (under and above 3.5 tons)
  - Only class 1 trucks are under 3.5 tons
- Operate under EU guidelines
  - At most 12 hours per day, but should average out to eight hours per day over the week (40 hours per week)
  - 11 hours of uninterrupted rest per day
  - Breaks scattered throughout the day
- Largest driver populations in Warsaw and Krakow regions
- Reducing the work force would be complicated, reallocating is much more preferable

Percent of drivers by terminal

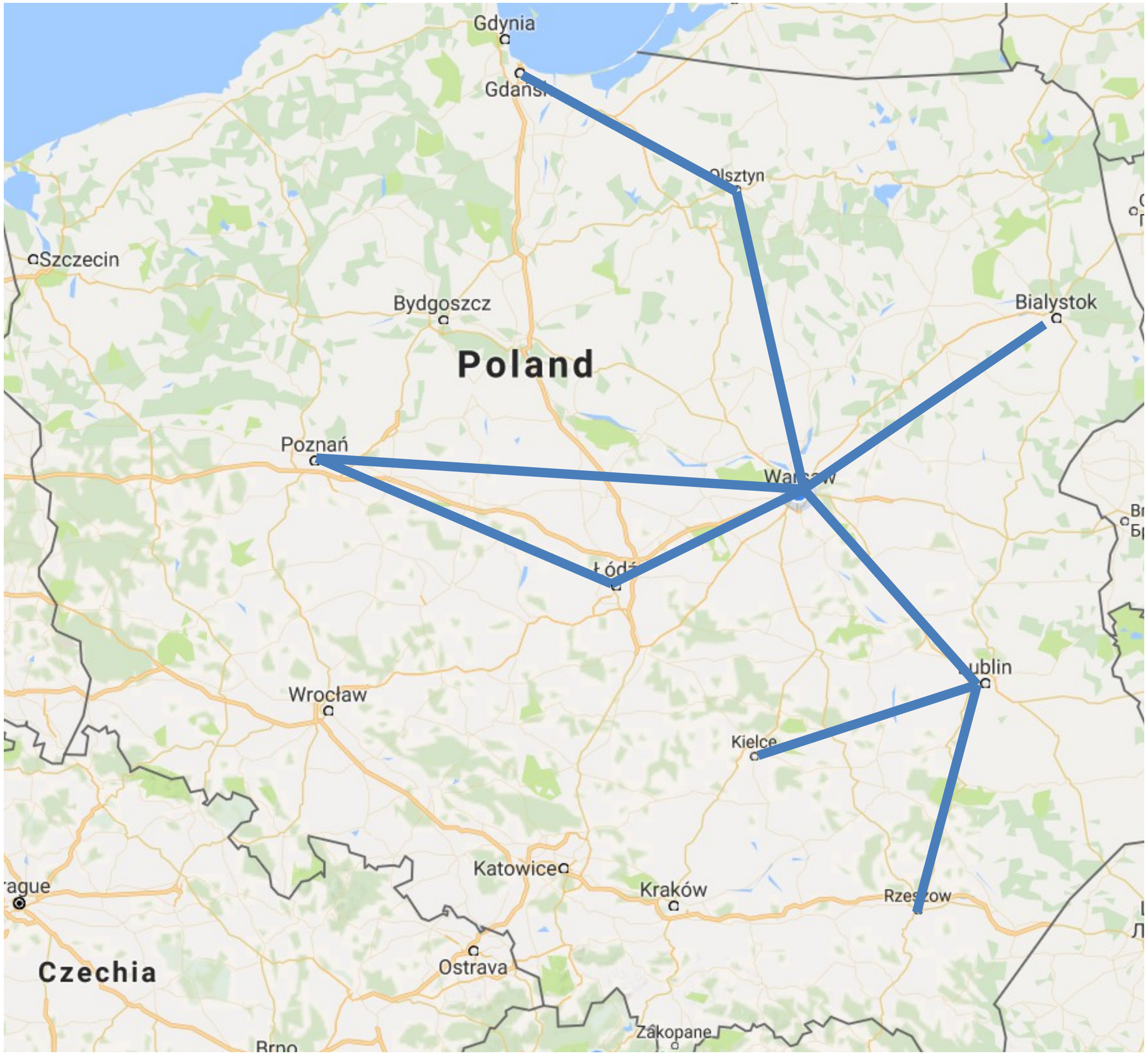


Number of Trucks by location

	Current # Class III	Current # Class IV	Proposed # Class III	Proposed # Class IV
Bialystok	16	5	3	2
Kielce	6	5	1	7
Komorniki	4	2	1	4
Kraków	3	12	3	5
Lisi Ogon	7	8	2	7
Lublin	7	17	0	5
Lódź	11	8	1	3
Olsztyn	18	0	2	3
Pruszcz Gd.	8	10	5	2
Rudna Mala	6	9	1	5
Szczecin	10	7	2	5
Warszawa	7	19	4	8
Wroclaw	6	13	3	7
Zabrze	10	14	2	6
Total	119	129	30	69

Force-directed layout

- Physics-based force-directed layout called OpenORD
  - Good for dense networks and to separate out clusters
  - Graph is **not constructed geographically**
  - Default parameters for each layout algorithm stage
  -
- "Betweenness centrality"
  - For each pair of vertices in the connected graph, there is at least one shortest path between the vertices, so that the number of edges passing through the path is minimized
  - Size of a node is relative to the number of shortest paths that pass through
  - The nodes that have the most connectivity are the largest


Gdynia
Gdansk
Olsztyn
Szczecin
Bydgoszcz
Bialystok
Poland
Poznań
Warsaw
Łódź
Lublin
Wrocław
Kielce
Katowice
Kraków
Rzeszow
Prague
Czechia
Ostrava
Zakopane
Brno


Gdynia
Gdansk
Olsztyn
Szczecin
Bydgoszcz
Bialystok
Poland
Poznań
Warsaw
Łódź
Wrocław
Lublin
Kielce
Katowice
Kraków
Rzeszow
Prague
Czechia
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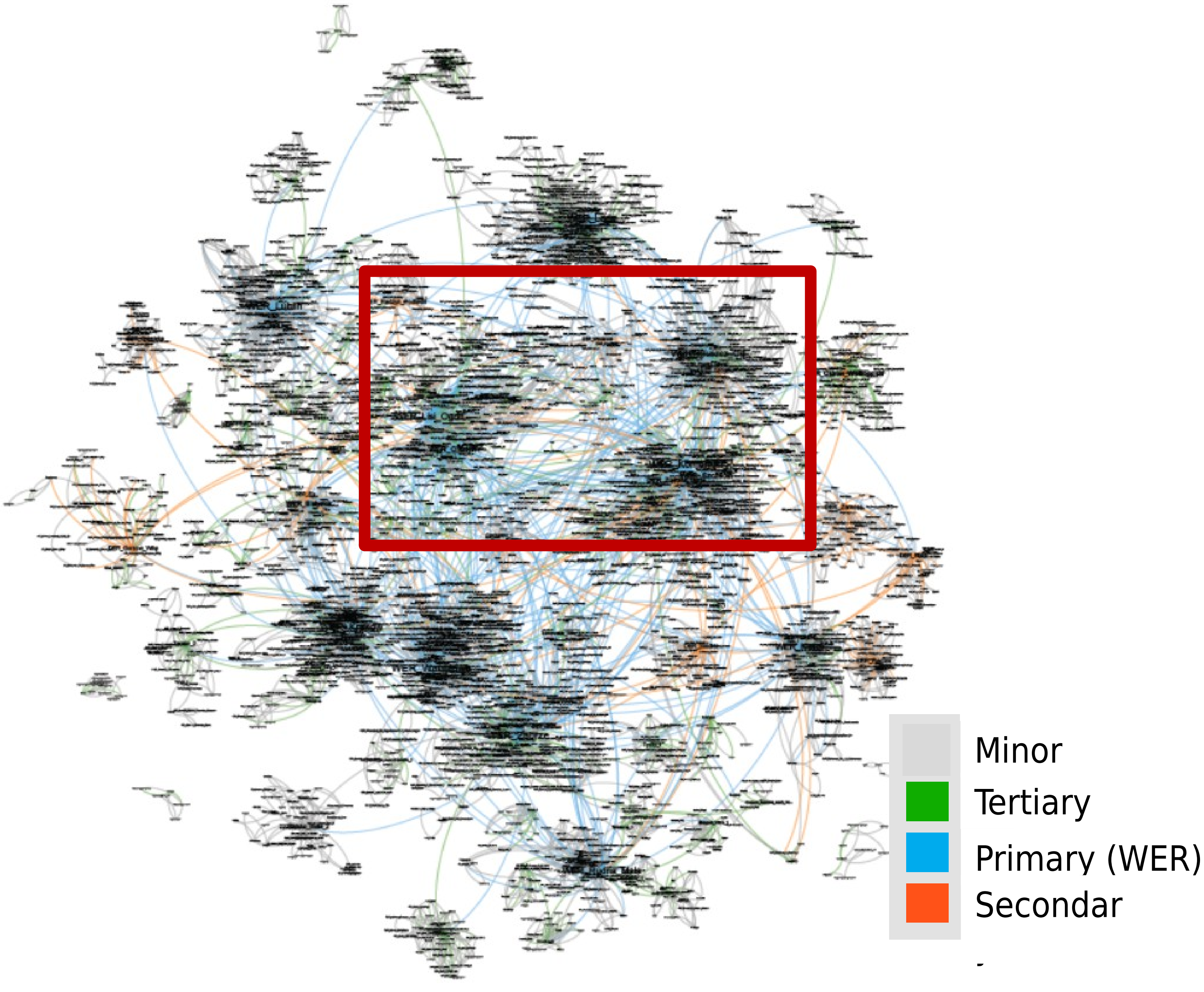
Olsztyn
Kielce

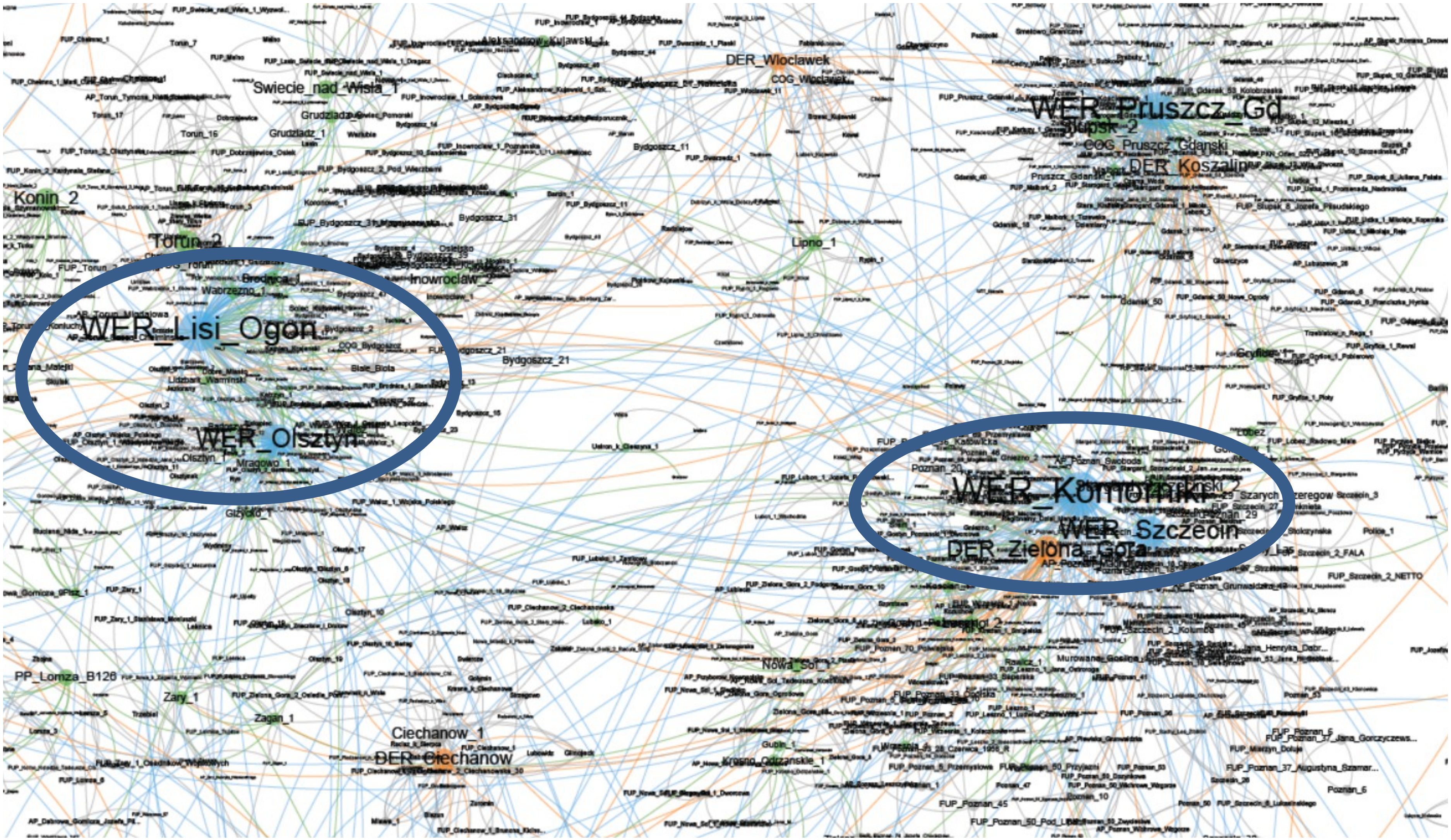
Force-directed layout

- Physics-based force-directed layout called OpenORD
  - Good for dense networks and to separate out clusters
  - Default parameters for each layout algorithm stage
  - Graph is **not constructed geographically**
- “Betweenness centrality”
  - For each pair of vertices in the connected graph, there is at least one shortest path between the vertices, so that the number of edges passing through the path is minimized.
  - The nodes that have the most connectivity are the largest
- Nodes in close proximity have similar connectedness
- Nodes are colored by terminal classification
- Edges are color-encoded by source and the edges are routed clockwise (source->target)
-



Minor
Tertiary
Primary (WER)
Secondar

Grouping of nodes indicating redundancy



Questions?