The Design of Capacitated Intermodal Hub Networks with Different Vehicle Types

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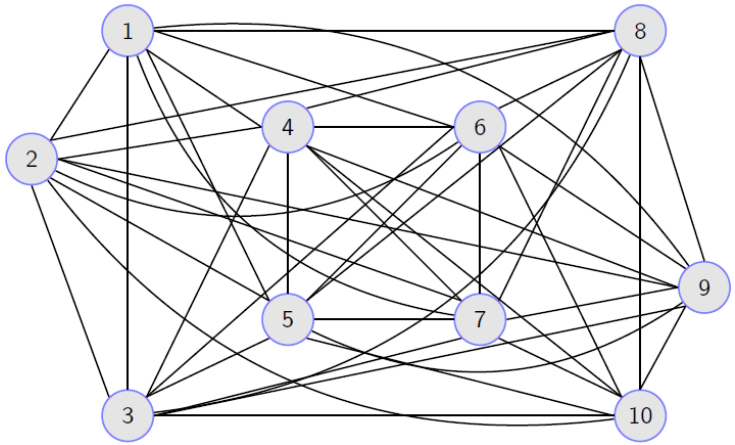
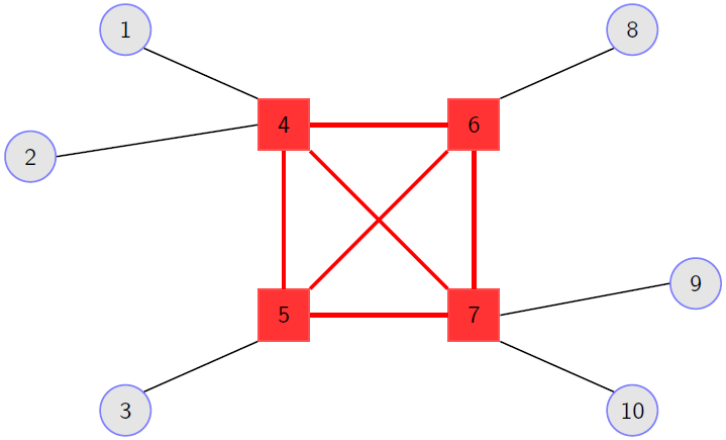
Agenda

- Introduction
- Problem Definition
- Mathematical Model
- Local Search Heuristic
- Computational Analysis
- Conclusions

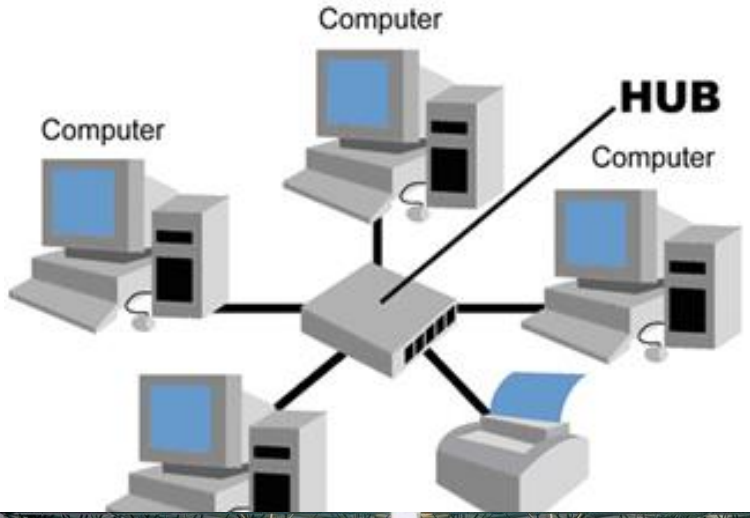
Hubs

- Special facilities that serve as switching, transshipment, and sorting points in many-to-many distribution systems
- Economies of scale





Hubs



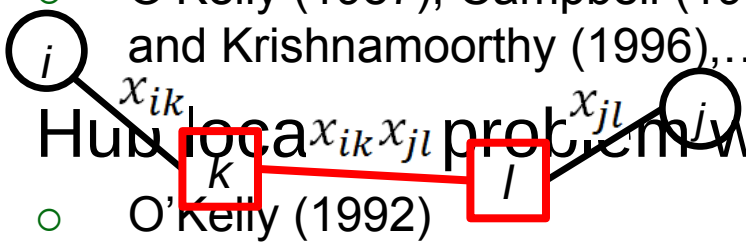
Hub Location Problem

- Find the location of hub facilities
- Allocate demand nodes to hubs
  - Single Allocation
  - Multiple Allocation
- Hub location literature

  Location analogous problems:
  - *p*-hub median,
  - hub location with fixed costs,
  - *p*-hub center,
  - hub covering problems

Classical Hub Location Problems

- *p*-hub median problem
  - O'Kelly (1987), Campbell (1994), Skorin-Kapov et al. (1996), Ernst and Krishnamoorthy (1996),…
- Hub location problem with fixed costs
  - O'Kelly (1992)
  - Uncapacitated and capacitated variants
- *p*-hub center problem
  - Campbell (1994), Kara and Tansel (2000), Meyer et al. (2009)
- Hub covering problems
  - Campbell (1994), Kara and Tansel (2003), Wagner (2008)
- Reviews and overviews
  - Campbell et al. (2002), Alumur and Kara (2008), Campbell and O'Kelly (2012), Farahani et al. (2013), Contreras (2015)



$x_{ik} = 1$ if node i is allocated to hub k, 0 otherwise.

$$\text{Min} \sum_{i\in N}\sum_{j\in N} W_{ij}\left(\sum_{k\in N} c_{ik}x_{ik} + \alpha \sum_{k\in N}\sum_{l\in N} c_{kl}x_{ik}x_{jl} + \sum_{l\in N} c_{lj}x_{jl}\right)$$

Quadratic

$$\text{s.t.} \quad \sum_{k\in N} x_{ik} = 1 \qquad \forall i \in N \qquad (1)$$

$$x_{ik} \le x_{kk} \qquad \forall i,k \in N \qquad (2)$$

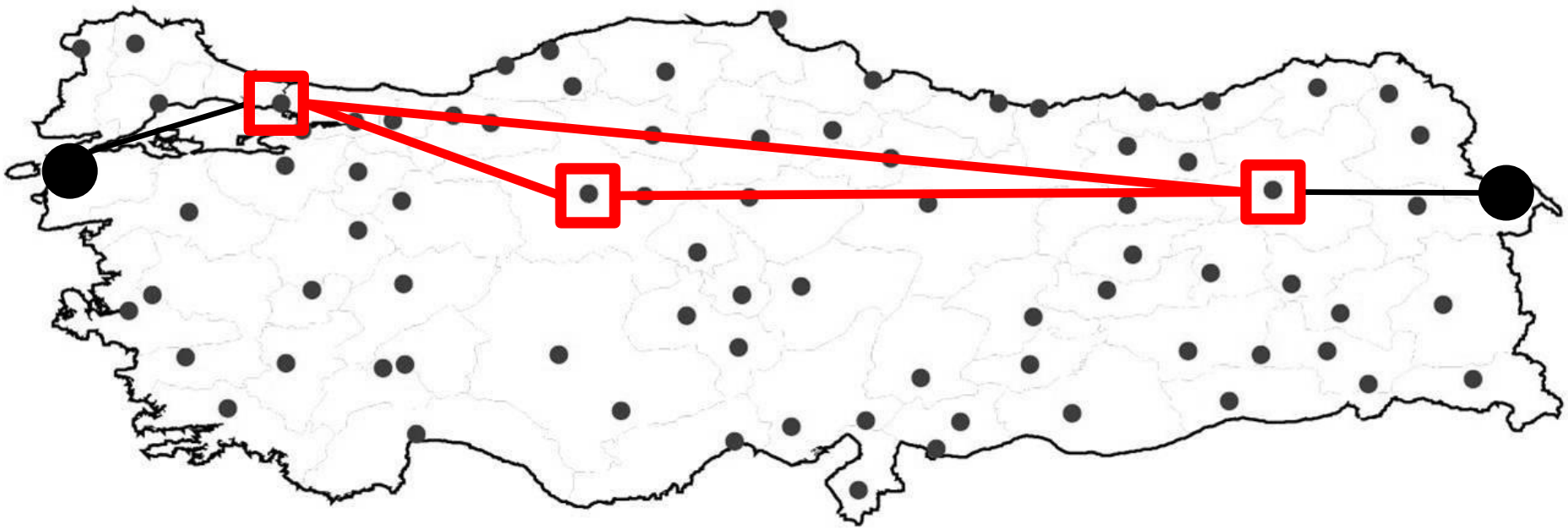
$$\sum_{k\in N} x_{kk} = p \qquad (3)$$

$$x_{ik} \in \{0,1\} \qquad \forall i,k \in N \qquad (4)$$

Basic Assumptions

1. The hub network is complete with a direct link between every hub pair
2. There is economies of scale incorporated by a discount factor (usually referred to as α) for using the inter-hub connections
3. No direct service (between two non-hub nodes) is allowed

Hub network is not complete!



In Turkey:

- Yurtiçi Cargo
- MNG Cargo
- Aras Cargo

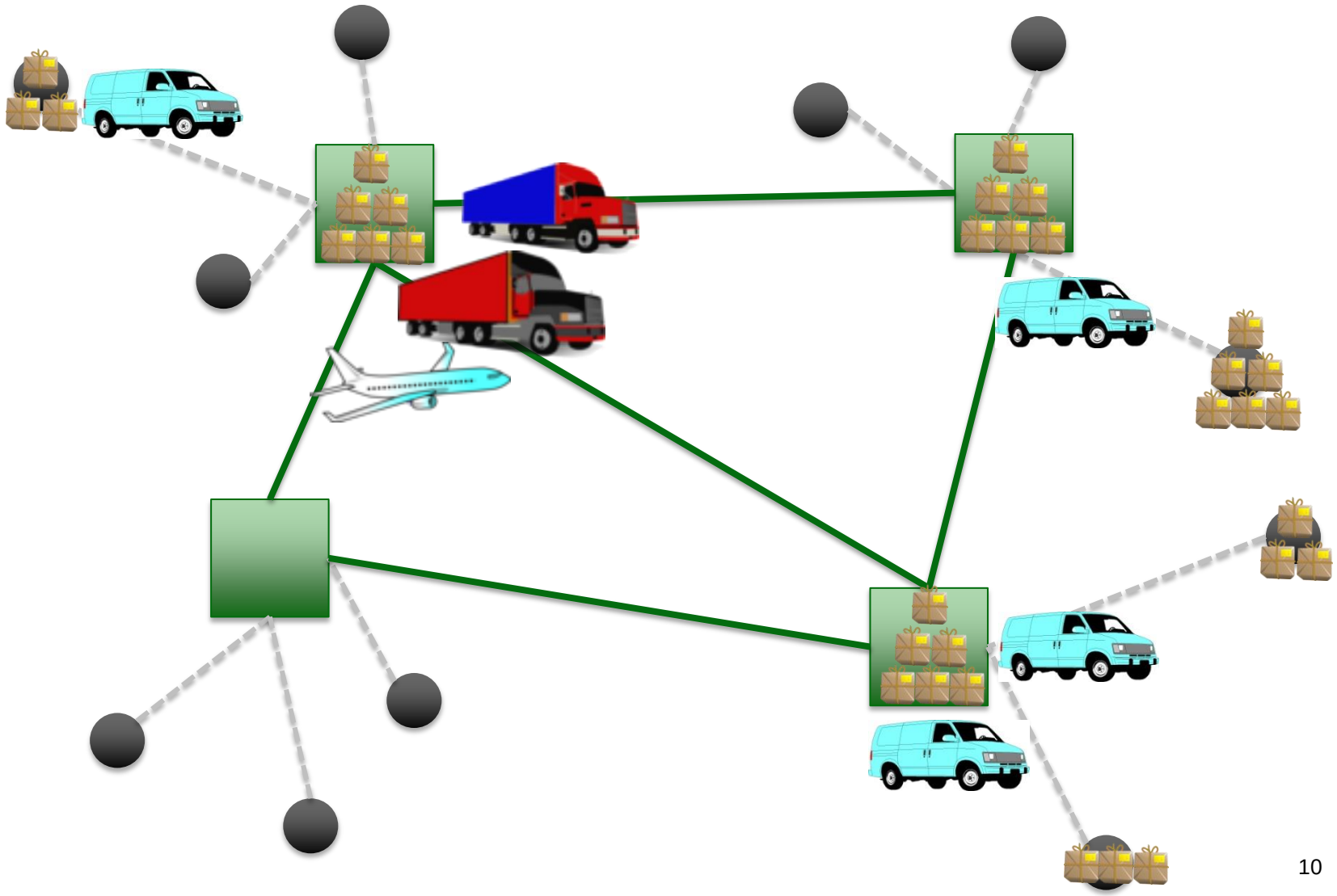
In the world:

- UPS
- FedEx
- DHL

Hub location and hub network design

- Multiple allocation minimizing total costs
  - Nickel et al. (2001), Yoon and Current (2008)
- Hub arc location problems
  - Campbell et al. (2005)
- Tree of hubs location problem
  - Contreras et al. (2010)
- Incomplete hub covering problems
  - Alumur and Kara (2009), Calik et al. (2009)
- Single allocation hub network design
  - Alumur et al. (2009)
- Hierarchical hub network design
  - Yaman (2009), Alumur et al. (2012)

Real-life parcel delivery



Decisions to be made

- Locations and capacities of hubs
- Transportation modes to serve at hubs
- Allocation of non-hub nodes to hubs
- Number of vehicles of each type to operate on the hub network
- Routes of the demand between origin-destination pairs

Literature

- Hub location and hub network design

  Nickel et al. (2001), Campbell et al. (2005), Yoon and Current (2008), Alumur et al. (2009), Contreras et al. (2010), Alumur et al. (2015), Martins de Sa et al. (2015)

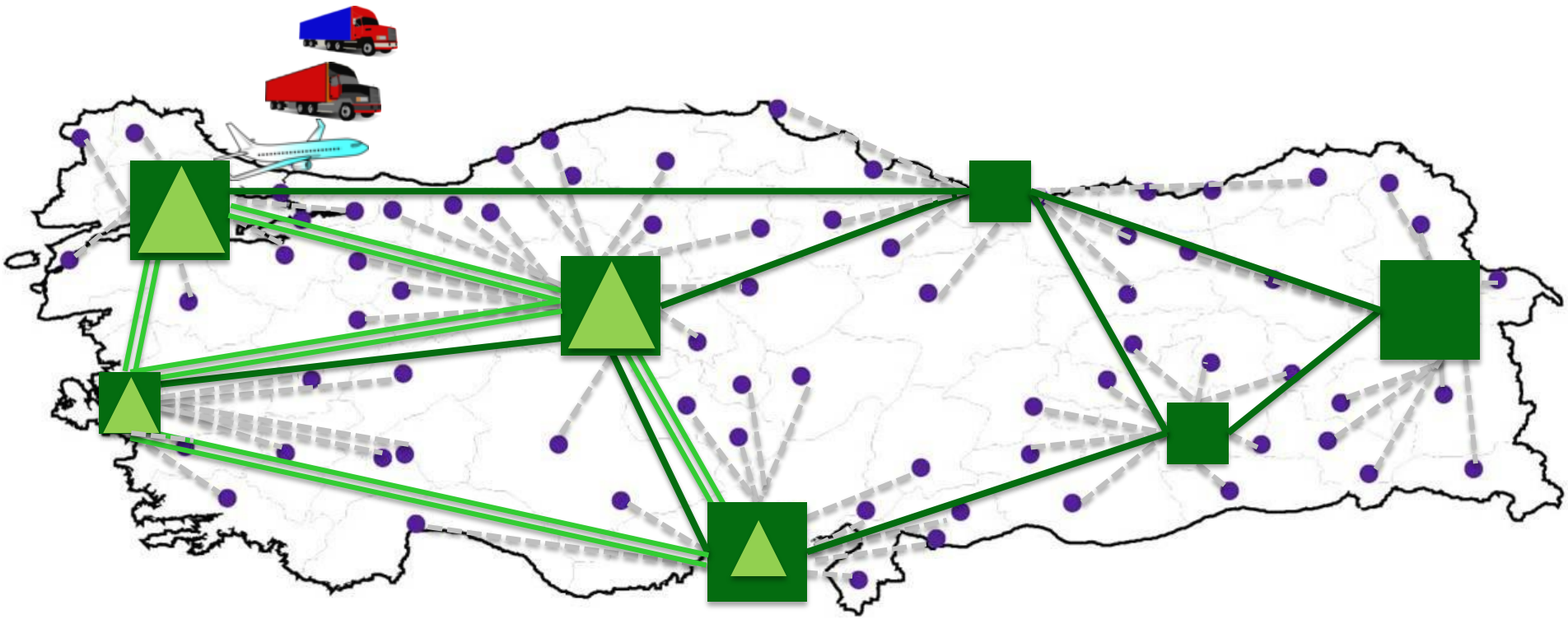
- Hub location in intermodal transportation networks

  Racunica and Wynter (2005), Limbourg and Jourquin (2009), Ishfaq and Sox (2011)

- Hub location and intermodal hub network design

  Meng and Wang (2011), Alumur et al. (2012a, 2012b)

Problem definition



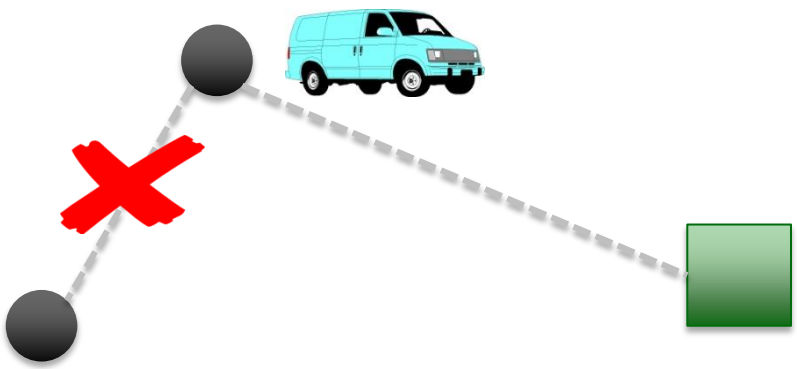
Problem definition

Assumptions:

1.

2.

3.



4. Each vehicle operates on a single connection

Mathematical model

Sets:

N : Set of demand nodes

H : Set of potential hub nodes

Q : Set of hub capacities

M : Set of transportation modes

V : Set of vehicle types

V_m : Set of vehicle types that can use transportation mode $m \in M$ $(V_m \in V)$

Mathematical model - Parameters

w_{ij}	Amount of flow originated at node $i \in N$ destined to node $j \in N$.
c_{ij}	Unit cost of transportation from node $i \in N$ to hub $j \in H$ on allocation connections.
c^v_{ij}	Unit cost of transportation from hub $i \in H$ to hub $j \in H$ using vehicle of type $v \in V$.
fc_j	Fixed cost of establishing a hub at node $j \in H$.
kc^m_{jq}	Cost of installing capacity $q \in Q$ for transportation mode $m \in M$ at a hub established at node $j \in H$.
k^v_q	Maximum number of vehicles of type $v \in V$ that a hub with capacity $q \in Q$ can handle.
u^v	Capacity of a vehicle of type $v \in V$.
o^v	Number of owned vehicles of type $v \in V$.
oc^v	Operational cost of a vehicle of type $v \in V$.
rc^v	Renting cost of a vehicle of type $v \in V$.

Mathematical model - Parameters

mhc_j	Material handling cost of one unit of flow arriving from a demand node to hub $j \in H$.
mhc_j^m	Material handling cost of one unit of flow arriving with transportation mode $m \in M$ to hub $j \in H$ from another hub.
a_i	Number of vehicles required to transport the flow originated at node $i \in N$.
b_i	Number of vehicles required to transport the flow destined to node $i \in N$.

$$O_i = \sum_{j \in N} w_{ij} \qquad a_i = \left\lceil \frac{O_i}{u} \right\rceil$$

$$D_i = \sum_{j \in N} w_{ji} \qquad b_i = \left\lceil \frac{D_i}{u} \right\rceil$$

Mathematical model – Decision variables

$$x_{ij} = \begin{cases} 1, & \text{if node } i \in N \text{ is allocated to a hub at node } j \in H, \\ 0, & \text{otherwise.} \end{cases}$$

($x_{jj} = 1$ indicates that a hub is established at node $j \in H$.)

$$y_{jq}^{m} = \begin{cases} 1, & \text{if capacity level } q \in Q \text{ is installed at hub } j \in H \text{ for transportation mode } m \in M, \\ 0, & \text{otherwise.} \end{cases}$$

$f_{ijk}^{v} =$ Amount of flow originated at node $k \in N$ and transported from hub $i \in H$ to hub $j \in H$ using vehicle of type $v \in V$.

$z_{ij}^{v} =$ Number of vehicles of type $v \in V$ used to travel from hub $i \in H$ to hub $j \in H$.

$r^{v} =$ Number of rented vehicles of type $v \in V$.

Mathematical model

Minimize

$$\sum_{i\in N}\sum_{j\in H} c_{ij} a_i x_{ij} + \sum_{i\in N}\sum_{j\in H} c_{ji} b_i x_{ij} + \sum_{i\in H}\sum_{j\in H}\sum_{v\in V} (c_{ij}^{v} + oc^{v}) z_{ij}^{v} + \sum_{v\in V} rc^{v} r^{v} + \sum_{j\in H} fc_j x_{jj}$$

$$+ \sum_{j\in H}\sum_{q\in Q}\sum_{m\in M} kc_{jq}^{m} y_{jq}^{m} + \sum_{i\in N}\sum_{j\in H} mhc_j O_i x_{ij} + \sum_{i\in H}\sum_{j\in H}\sum_{k\in N}\sum_{m\in M}\sum_{v\in V_m} mhc_j^{\ m} f_{ijk}^{v}$$

s.t.

$$\sum_{j\in H} x_{ij} = 1 \qquad \forall i \in N \qquad (1)$$

$$x_{ij} \le x_{jj} \qquad \forall i \in N, j \in H \qquad (2)$$

$$\sum_{q\in Q} y_{jq}^{m} \le x_{jj} \qquad \forall j \in H, m \in M \qquad (3)$$

Mathematical model

$$\sum_{j \in H,\, j \neq i} z_{ij}^{v} \leq \sum_{q \in Q} k_q^{v} y_{iq}^{m} \qquad \forall i \in H, m \in M, v \in V_m \qquad (4)$$

$$\sum_{i \in H,\, i \neq j} z_{ij}^{v} \leq \sum_{q \in Q} k_q^{v} y_{jq}^{m} \qquad \forall j \in H, m \in M, v \in V_m \qquad (5)$$

$$\sum_{j \in H,\, j \neq i} \sum_{v \in V} f_{ijk}^{v} - \sum_{j \in H,\, j \neq i} \sum_{v \in V} f_{jik}^{v} = O_k x_{ki} - \sum_{l \in N} w_{kl} x_{li} \qquad \forall i \in H, k \in N \qquad (6)$$

$$\sum_{k \in N} f_{ijk}^{v} \leq u^{v} z_{ij}^{v} \qquad \forall i, j \in H : i \neq j, v \in V \qquad (7)$$

$$\sum_{i \in H} \sum_{j \in H,\, j \neq i} z_{ij}^{v} \leq o^{v} + r^{v} \qquad \forall v \in V \qquad (8)$$

Mathematical model

$$f_{ijk}^{v} \geq 0 \qquad \forall i, j \in H, i \neq j, k \in N, v \in V \qquad (9)$$

$$z_{ij}^{v} \geq 0 \quad and \quad integer \qquad \forall i, j \in H, i \neq j, v \in V \qquad (10)$$

$$r^{v} \geq 0 \quad and \quad integer \qquad \forall v \in V \qquad (11)$$

$$x_{ij} \in \{0,1\} \qquad \forall i \in N, j \in H \qquad (12)$$

$$y_{jq}^{m} \in \{0,1\} \qquad \forall j \in H, q \in Q, m \in M \qquad (13)$$

Local Search Algorithm

- Start with an initial solution with *p* hubs
  - A greedy starting solution algorithm
- Apply neighborhood generation
  - 6 different generation procedures
- Assign vehicles
  - 2 different greedy type algorithms with improvement steps

    (Type I and II)
- Generate neighbors and continue until the limit for the max number of solutions is reached

Heuristic

$Solution = \emptyset, Neighborhood = \emptyset$

Apply **Initial Solution**, add the initial solution to $Neighborhood$

repeat

    Select the next neighbor, n, from the set $Neighborhood$

    Apply **Neighborhood Generation** to n, add all new neighbors to $Neighborhood$

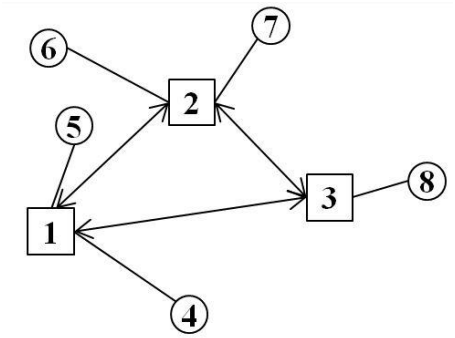
    Apply **Vehicle Assignment** to n, calculate total cost.

    Delete n from $Neighborhood$ and add it to $Solution$

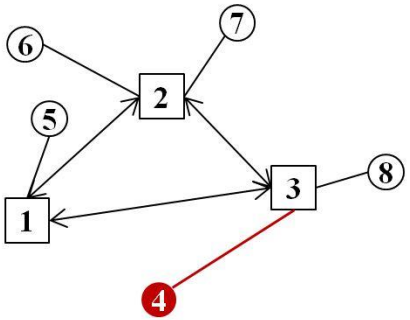
until $|Solution| \geq$ *max number of solutions*

Report the solution that has the minimum cost in $Solution$

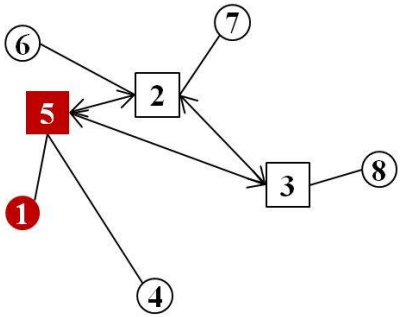
Neighborhood



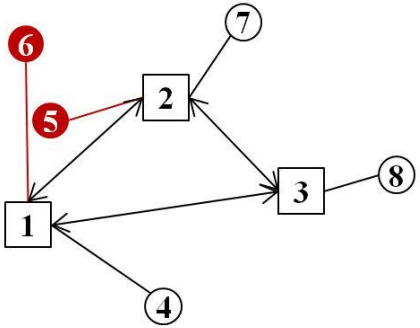
(a) Initial solution



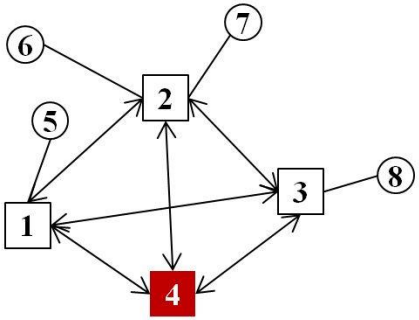
(b) Allocate a non-hub to a different hub



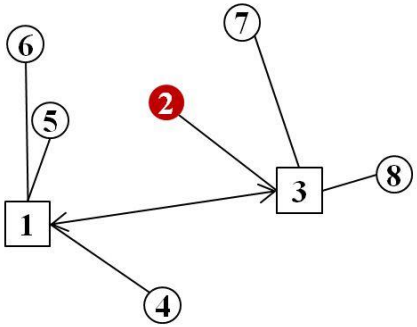
(c) Exchange a hub with a non-hub



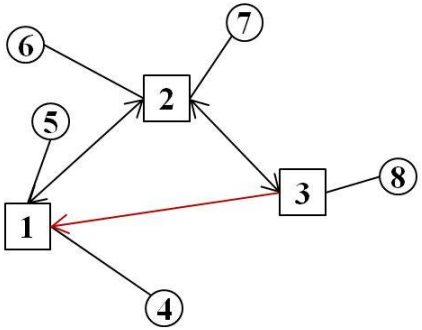
(d) Exchange allocations of two non-hubs



(e) Increase number of hubs by one



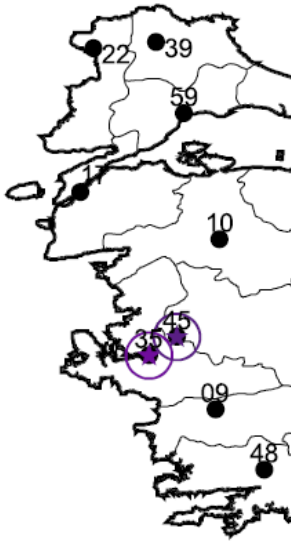
(f) Decrease number of hubs by one

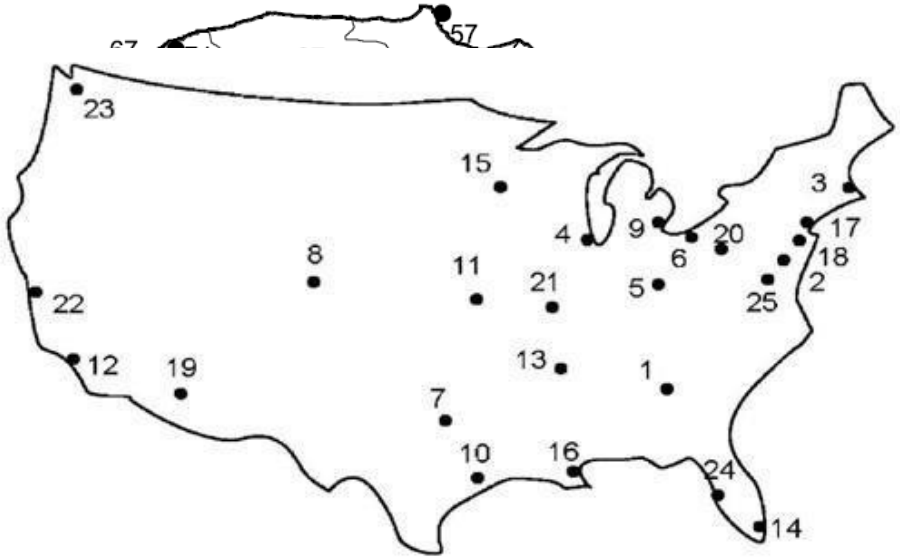


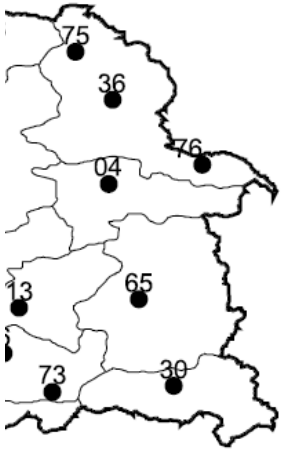
(g) Delete a hub arc

Computational Analysis

- Turkish network (16 and 81 nodes)
- CAB data set (25 nodes)







1. Atlanta	6. Cleveland	11. Kansas City	16. New Orleans	21. St. Louis
2. Baltimore	7. Dallas- Fort Worth	12. Los Angeles	17. New York	22. San Francisco
3. Boston	8. Denver	13. Memphis	18. Philadelphia	23. Seattle
4. Chicago	9. Detroit	14. Miami	19. Phoenix	24. Tampa
5. Cincinnati	10. Houston	15. Minneapolis	20. Pittsburg	25. Washington DC

Computational Analysis

- Application parameters:

Parameter	Turkish network	CAB data set
$\|N\| = \|H\|$	16, 81	25
Q	Small, Large	
M	Ground and air transportation	
V	Van, truck, trailer, airplane	

	Van	Truck	Trailer	Airplane
Capacity (ton)	3.5	15	25	200
Fuel cost (TL/km)	0.5	1	1.2	6.4
Fuel cost /Capacity (TL/km-ton)	0.143	0.067	0.048	0.032
Economies of scale parameter, α	**1**	**0.467**	**0.336**	**0.224**

Performance of the heuristic

- Eclipse Java EE IDE, Version: Juno Service Release 1
- CPLEX 12.4
- HP Z600 workstation 2 x Intel Xeon 2.40 GHz processor
  48 GB of RAM

Capacity	# of solutions	Vehicle assign.	$p = \sqrt{n} - 2$	$p = \sqrt{n}$	$p = \sqrt{n} + 2$
Loose	6,000	I	7 instances * 5 runs	7 instances * 5 runs	7 instances * 5 runs
		II	7 instances * 5 runs	7 instances * 5 runs	7 instances * 5 runs
	12,000	I	7 instances * 5 runs	7 instances * 5 runs	7 instances * 5 runs
		II	7 instances * 5 runs	7 instances * 5 runs	7 instances * 5 runs
Tight	6,000	I	7 instances * 5 runs	7 instances * 5 runs	7 instances * 5 runs
		II	7 instances * 5 runs	7 instances * 5 runs	7 instances * 5 runs
	12,000	I	7 instances * 5 runs	7 instances * 5 runs	7 instances * 5 runs
		II	7 instances * 5 runs	7 instances * 5 runs	7 instances * 5 runs

840 runs with the Turkish network

# of solutions	Vehicle assign.	$p = \sqrt{n} - 2$	$p = \sqrt{n}$
12,000	I	7 instances * 5 runs	7 instances * 5 runs
	II	7 instances * 5 runs	7 instances * 5 runs
24,000	I	7 instances * 5 runs	7 instances * 5 runs
	II	7 instances * 5 runs	7 instances * 5 runs

280 runs with the CAB data set

Performance of the heuristic

Turkish network (16 nodes)

Fixed cost	Optimal solution		Heuristic with generating 12,000 solutions							
	Obj. func. value	Solution time (sec)	Vehic. Assign	$p=\sqrt{n}-2$		$p=\sqrt{n}$		$p=\sqrt{n}+2$		
				Solution time (sec)	Gap (%)	Solution time (sec)	Gap (%)	Solution time (sec)	Gap (%)	# of solutions
60,000	562,800	2,636	I	43	1.67	59	1.59	83	1.67	6,000
			II	42	1.52	77	1.60	38	1.60	
70,000	602,800	4,195	I	44	1.52	55	1.54	100	1.56	12,000
			II	41	1.51	73	1.39	57	1.50	
80,000	642,800	4,189	I	46	1.33	59	1.33	93	1.45	6,000
			II	40	1.40	68	1.38	77	1.40	
90,000	682,800	3,015	I	43	1.36	54	1.38	98	1.37	12,000
			II	39	1.23	78	1.32	52	1.30	
100,000	721,156	409	I	37	0.46	62	0.66	96	1.02	
			II	32	0.47	69	0.65	98	1.18	
110,000	743,961	18	I	39	0.06	68	0.57	95	1.34	
			II	46	0.09	70	0.34	38	1.27	
120,000	763,961	9	I	39	0.05	80	0.09	100	1.37	
			II	43	0.09	70	0.11	58	1.90	
Average		**2,067**	**I**	**42**	**0.92**	**62**	**1.02**	**95**	**1.40**	
			II	**40**	**0.90**	**72**	**0.97**	**60**	**1.45**	

Capacity

Loose

Tight

Vehicle assignment	$p=\sqrt{n}-2$	$p=\sqrt{n}$	$p=\sqrt{n}+2$
I	0.95	1.12	1.52
II	0.91	1.08	1.78
I	0.92	1.02	1.40
II	0.90	0.97	1.45
I	1.16	1.28	1.94
II	0.97	1.24	1.66
I	1.02	1.02	1.58
II	0.97	1.01	1.58

Performance of the heuristic

CAB data set (25 nodes)

Fixed cost	Optimal Solution		Heuristic				
	Obj. func. value	Solution time (sec)	Vehic. Assign	$p=\sqrt{n}-2$		$p=\sqrt{n}$	
				Solution time (sec)	Gap (%)	Solution time (sec)	Gap (%)
60,000	848,888	17,849	I	126	6.95	192	4.79
			II	128	7.35	224	3.24
70,000	898,888	5,945	I	129	6.03	214	3.29
			II	137	6.18	246	2.16
80,000	948,888	4,332	I	126	4.90	201	2.69
			II	146	4.80	228	2.81
90,000	998,888	4,680	I	137	3.58	229	3.01
			II	124	3.56	216	2.27
100,000	1,048,888	11,354	I	135	2.53	231	1.95
			II	156	2.44	255	1.86
110,000	1,098,275	18,909	I	125	1.59	243	1.56
			II	148	1.65	230	1.47
120,000	1,138,275	10,362	I	136	1.50	245	1.54
			II	154	1.42	224	1.47
Average		**10,490**	**I**	**131**	**3.87**	**222**	**2.69**
			II	**142**	**3.91**	**232**	**2.19**

# of solutions	Vehicle assignment	$p=\sqrt{n}-2$	$p=\sqrt{n}$
12,000	I	3.88	3.69
	II	4.03	3.71
24,000	I	3.87	2.69
	II	3.91	2.19

Lower bound

- By relaxing the integer variables (z_{ij}^{v} and r^{v})

Fixed cost	Optimal Solution		Lower bound		
	Obj. func. value	Solution time (sec)	Obj. func. value	Solution time (sec)	Gap (%)
60,000	563,052	1,345	557,242	24	1.03
70,000	603,052	1,639	597,242	17	0.96
80,000	643,052	906	637,242	27	0.90
90,000	683,052	998	677,242	18	0.85
100,000	721,656	347	717,242	32	0.61
110,000	744,361	14	743,651	9	0.10
120,000	764,361	15	763,651	4	0.09
Average	-	**752**	-	**19**	**0.65**

Turkish network – Tight capacity

Fixed cost	Optimal Solution		Lower bound		
	Obj. func. value	Solution time (sec)	Obj. func. value	Solution time (sec)	Gap (%)
60,000	562,800	2,636	557,093	40	1.01
70,000	602,800	4,195	597,093	19	0.95
80,000	642,800	4,189	637,093	20	0.89
90,000	682,800	3,015	677,093	40	0.84
100,000	721,156	409	717,093	16	0.56
110,000	743,961	18	743,251	13	0.10
120,000	763,961	9	763,251	9	0.09
Average	-	**2,067**	-	**22**	**0.63**

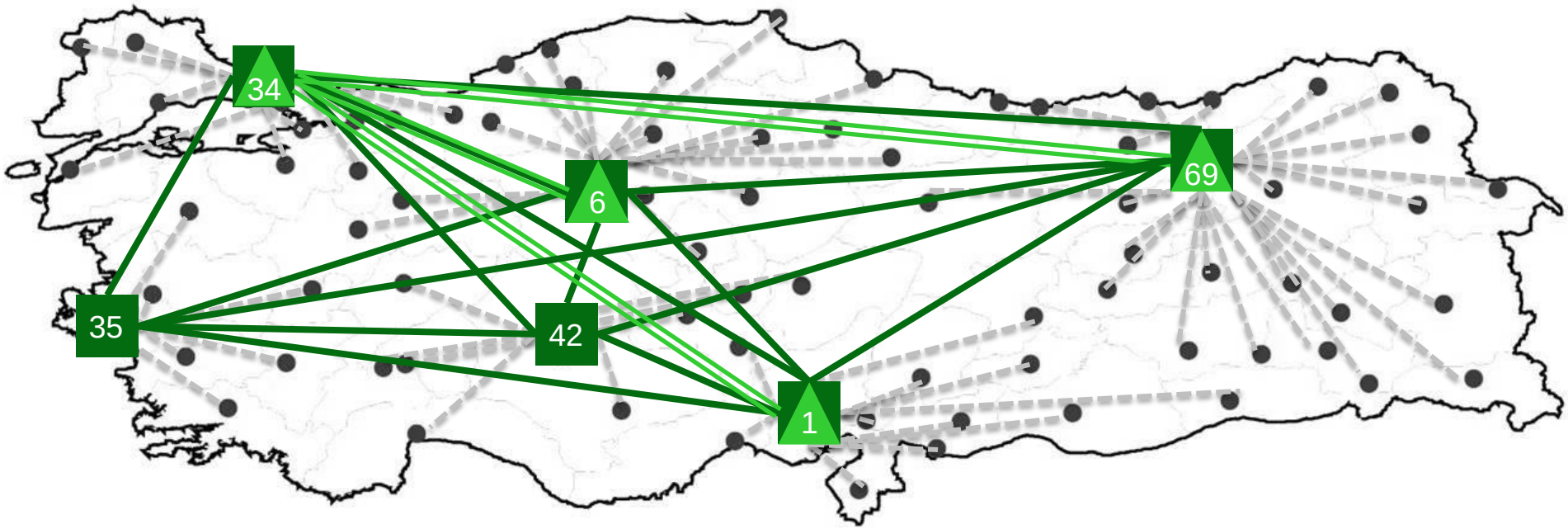
Turkish network – Loose capacity

- LB gap with the CAB data set: 0.49%

Computational Analysis

- Sensitivity analysis with the complete Turkish network data (81 nodes)
  - Fixed costs
  - Hub capacities
  - Fleet size
  - Vehicle renting costs
- 75,000 solutions with $p = \sqrt{n} = 9$
- Average solution time: 15.2 minutes
- Average gap from the lower bound: ~7%

Computational Analysis



: Small ground hub

: Small air hub

: Ground hub link

: Air hub link

: Allocation link

Node	1			6			34			35			42		69	
Vehicles	A	Tr	T	A	Tr	T	A	Tr	T	Tr	T	Tr	T	A	Tr	T
1	-	-	-	-	12	-	-	17	-	-	15	-	13	-	12	-
6	-	12	-	-	-	-	2	-	2	9	-	-	13	-	12	1
34	2	-	4	2	-	5	-	-	-	13	1	12	-	2	-	4
35	-	6	5	-	9	-	-	12	1	-	-	-	10	-	9	-
42	-	-	13	-	-	13	-	11	-	-	10	-	-	-	-	13
69	-	12	-	-	12	-	2	-	2	-	15	-	13	-	-	-

Conclusions

- Hub location problem from a service network design perspective
- Alternative transportation modes and different types of vehicles on the hub network
- A mixed-integer programming formulation correctly modeling economies of scale
- Hub capacities and material handling costs
- An efficient local search heuristic
- Extensive computational analysis on the CAB and Turkish network data sets
- Solved problems with the 81-node Turkish network

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THANK YOU

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