Public Logistics Networks

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Public vs Private Logistics Networks

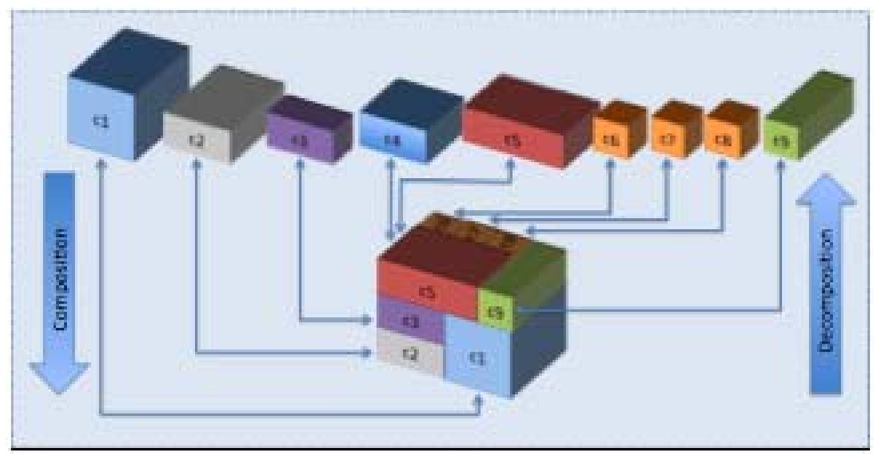
Public Network	Private Network
Each vehicle and facility can be operated by *different* firm	*Single* firm (UPS, Amazon) coordinates network, owning all critical resources
Each vehicle/facility has access to potentially all of network's demand $\Rightarrow$ *scale economies* and *dense* network	Each vehicle/facility has access to only single firm's portion of demand $\Rightarrow$ *sparse* network
Decentralized control via open standards and coordination protocols $\Rightarrow$ *low* barrier to entry	*Centralized* control via firm-specific proprietary standards and coordination procedures $\Rightarrow$ *high* barrier to entry

- **High** degree of public facilities for ocean and air logistics
- **Mix** of public/private networks for rail
- **Few** public networks for intercity trucking and urban logistics
  - Public terminals on outskirts of cities in Japan used to consolidate deliveries to stores in congested city centers

Logistics vs Computer Networks

Public Logistics Network	Internet
Packages transported	Packets transmitted
Distribution centers (DCs)	Routers
Vehicles	Wire, fiber
Slow speed allows node/DC based control	Edge-control due high node throughput

- **Physical Internet Initiative:**
  - Benoit Montreuil, Eric Ballot
  - Open global logistics system based on physical, digital, and operational interconnectivity
  - Encapsulation, interfaces and protocols
  - π-containers provide standard for interoperability



Research

- Goal:
  - Provide tools for expanded role of public logistics networks in intercity trucking and urban logistics
- Approach:
  - Develop open distributed coordination mechanism that
    1. Achieves same operational efficiencies as single integrated private network
    2. Can lower cost through scale economies of serving all demand
       - Something only monopoly-private or government-run networks can currently do
- Main Tool:
  - Algorithmic Mechanism Design

Basic Mechanism for Public Networks

- Mechanism determines:
  - Which shipments form a load
  - How cost paid to carrier (vehicle) to transport load is allocated to shipments
- Mechanism tries to match shipments that value transport the highest with vehicles that can provide it at least cost:
  - Shipment(s) bid for transport (reverse of Uber)
  - Strong incentives for early bidding
  - *Public data + Computationally efficient online protocols* →
    - Shipments can determine their exact cost prior to bidding
    - Most processing is planning done locally by shipments/vehicles

Two Examples

1. **Intercity Trucking:**

   – Mechanism used to create consolidated multi-stop truckloads
   – Alternative to current 3PL and TL/LTL carriers

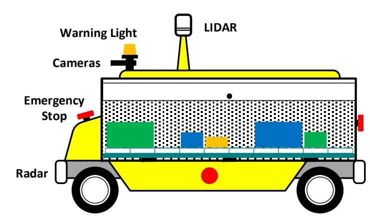
2. **Home delivery:**
   – Mechanism used to coordinate network of modular distribution centers and driverless delivery vehicles

Amazon Drone

Starship Delivery Robot

Nuro Delivery Vehicle

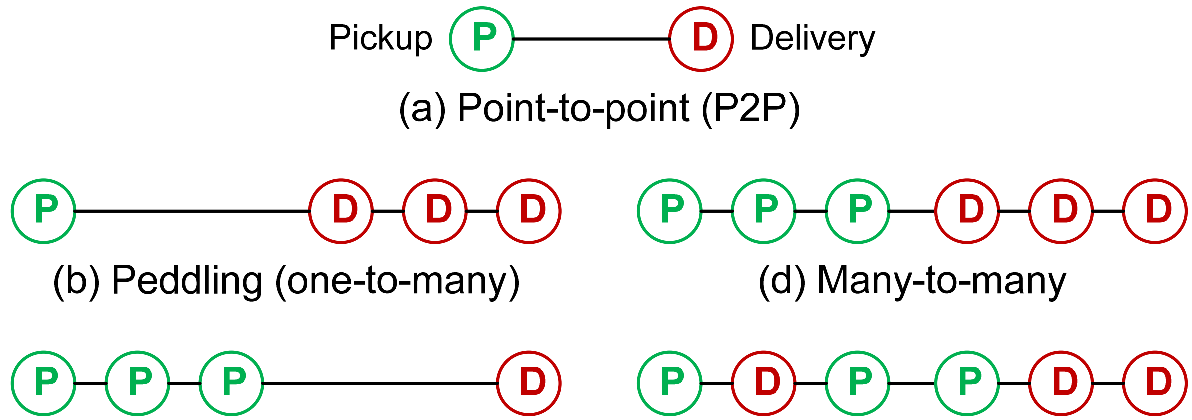
Delivery Vehicle with Auto Unloading



Example 1: Intercity Trucking

Intercity Trucking Operations

Truckload (TL) routing alternatives



(a) Point-to-point (P2P)

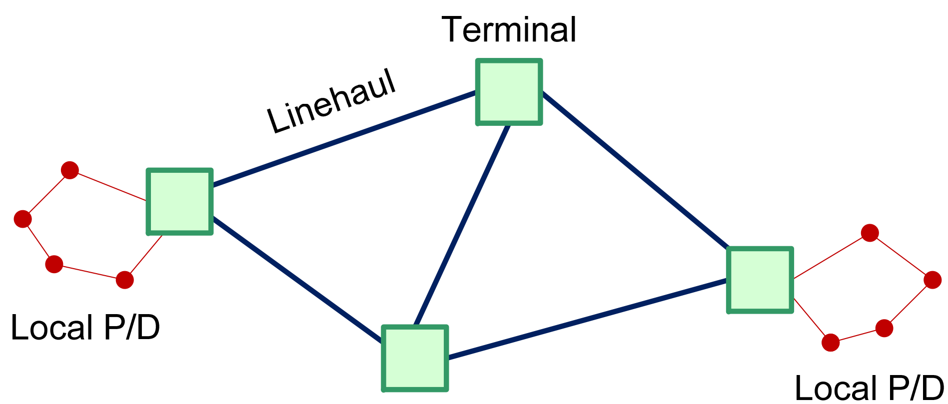
(b) Peddling (one-to-many)

(c) Collecting (many-to-one)

(d) Many-to-many

(e) Interleaved

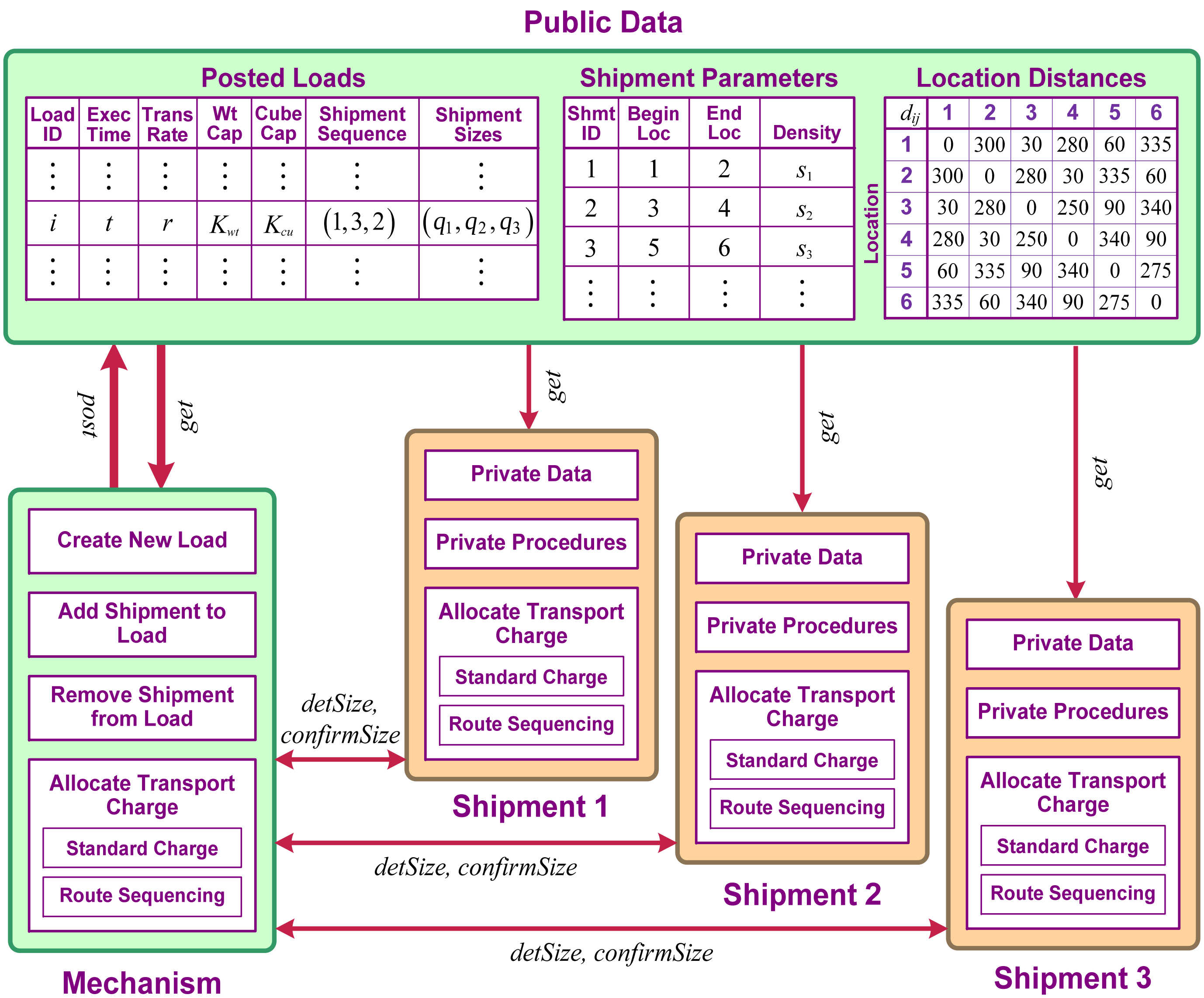
Logistics network used for less-than-truckload (LTL)



Coordination Mechanism

- Public information posted for each shipment
  - Size/weight
  - Density
  - Distance (based on origin/destination)
- Load formed by first shipment
  - Sets anchor transport rate
  - Sets its earliest pickup and latest delivery times
- Subsequent shipments that join load
  - Determine their cost using standard transport charge and online routing heuristic
  - Can veto later shipments wanting to join
- Route created using order shipments join load
- Shipments can join/leave multiple loads until load scheduled

Coordination Mechanism



Standard Transport Charge

- Charge based on
  - Shipment's public data
  - Anchor TL rate
  - Empirical LTL rate estimate

$$r = \text{ anchor TL rate (\$/mi, €/km)}$$

$$= \$2/\text{mi in } 2004$$

$$q = \text{ size/wt}, \quad s = \text{density}, \quad d = \text{ distance}$$

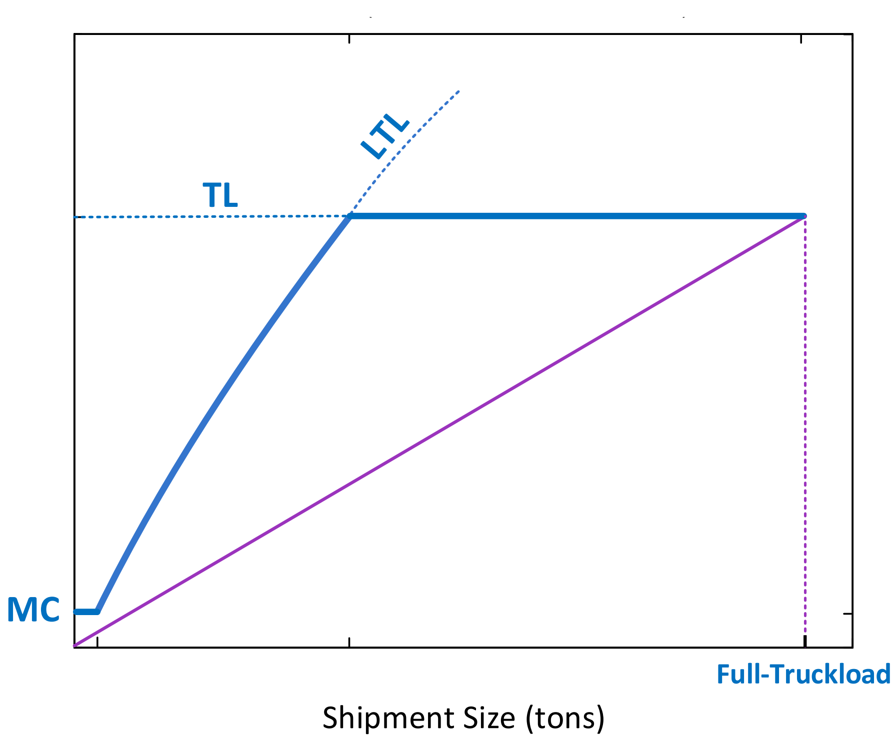
$$c = \max\left\{\min\left\{c_{TL}, c_{LTL}\right\}, MC\right\}$$

$$c_{TL} = rd = \text{TL transport charge}$$

$$c_{LTL} = \left(\frac{r}{2}\right) r_{LTL}\, qd = \text{LTL transport charge}$$

$$r_{LTL} = 104.2\left[\frac{\frac{s^2}{8}+14}{\left(q^{\frac{1}{7}} d^{\frac{15}{29}} - \frac{7}{2}\right)\left(s^2+2s+14\right)}\right]$$

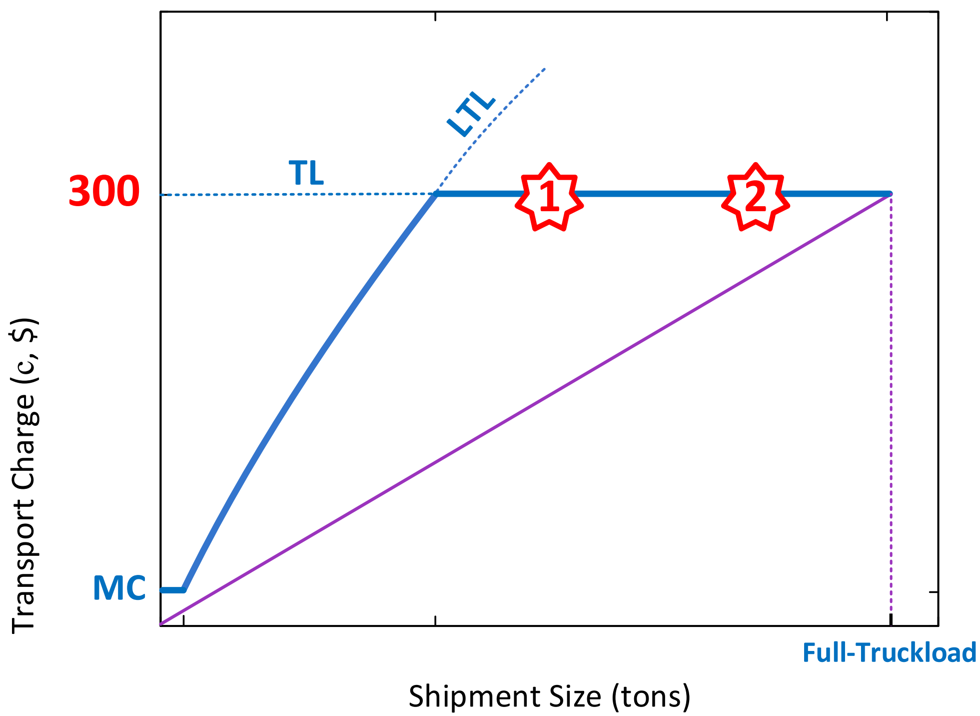
$$MC = \frac{r}{2}\left(45 + \frac{d^{\frac{28}{19}}}{1625}\right) = \text{ Minimum charge}$$



Example: TL + TL Same O/D

- Shipment 1
  - sets r = 1, d = 300, TL, max c = 300
- Shipment 2
  - same O/D, TL, max c = 300

$$c = \max\left\{\min\left\{c_{LTL}, c_{TL}\right\}, MC\right\}$$

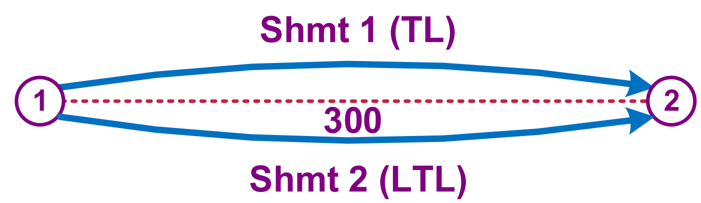


$$c = c_1 = 300$$

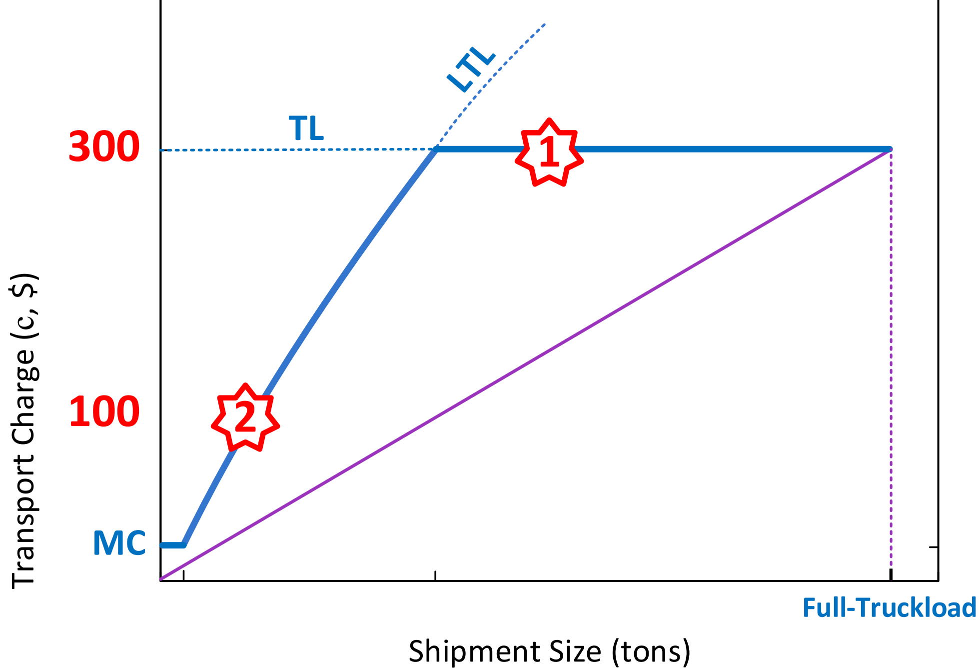
$$c = 300 = c_1 + c_2, \quad c_1 = c_2 = \frac{c}{2} = 150$$

Example: TL + LTL Same O/D

- Shipment 1
  - sets r = 1, d = 300, TL, max c = 300
- Shipment 2
  - same O/D, LTL, max c = 100



$$c = \max\left\{\min\left\{c_{LTL}, c_{TL}\right\}, MC\right\}$$



$$c = 300 = c_1 + c_2$$

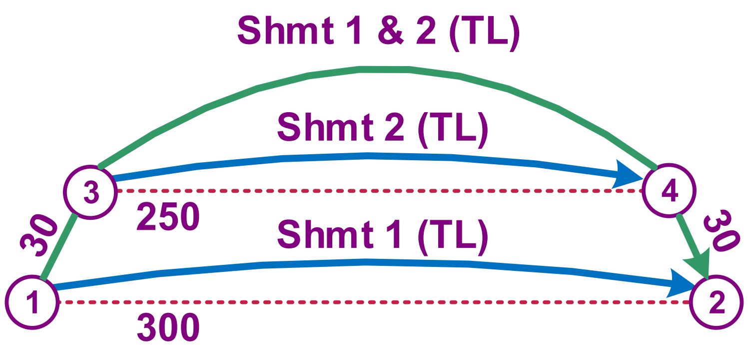
	1	2
1 2	300	0
2 1	200	100
	250	50

$$c_1 = 250, \quad c_2 = 50$$

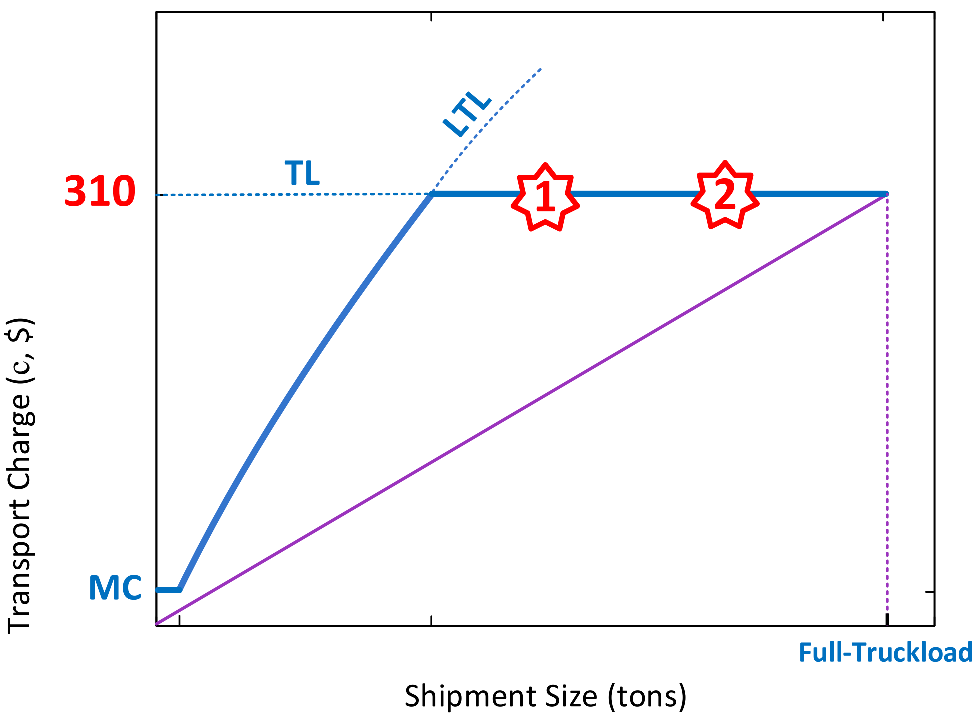
(Shapley value allocation)

Example: TL + TL Different O/D

- Shipment 1
  - sets r = 1, d = 300, TL, max c = 300
- Shipment 2
  - different O/D, TL, max c = 250



$$c = \max\{\min\{c_{LTL}, c_{TL}\}, MC\}$$



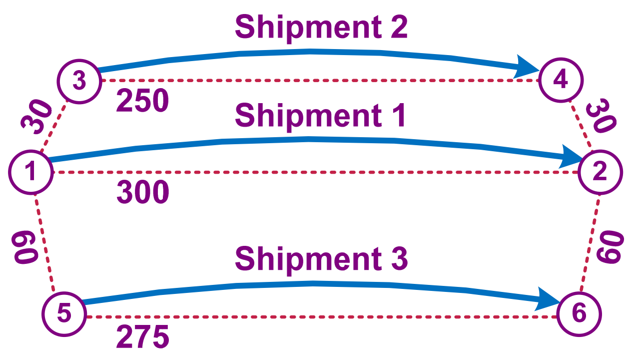
$$c = 310 = c_1 + c_2$$

	1	2
1 2	300	10
2 1	60	250
	180	130

$$c_1 = 180, \quad c_2 = 130$$

Multi-Stop Routing

- Each shipment might have a different origin and/or destination $\Rightarrow$ node/location sequence not adequate



$$L = (y_1, \ldots, y_n) = (1, 2, 3) \qquad n \text{ shipments}$$

$$R = (z_1, \ldots, z_{2n}) = (3, 1, 2, 2, 1, 3) \qquad 2n\text{-element route sequence}$$

$$X = (x_1, \ldots, x_{2n}) = (5, 1, 3, 4, 2, 6) \qquad 2n\text{-element location (node) sequence}$$

$$c_{ij} = \text{cost between locations } i \text{ and } j$$

$$c(R) = \sum_{i=1}^{2n-1} c_{x_i, x_{i+1}} = 60 + 30 + 250 + 30 + 60 = 430, \quad \text{total cost of route } R$$

Online Routing Heuristic

- To route each shipment added to load:
  - Minimum Cost Insertion
  - Two-opt improvement
- Different shipment sequences can result in different routes
  - Order shipment joins load important

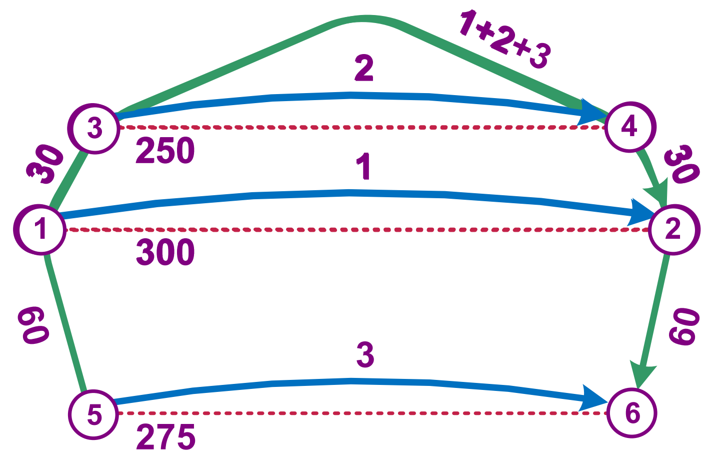
procedure *insertImprove*$(y_i \in L)$
$R = (y_1, y_1)$
for $i = 2, \ldots, |L|$
    $R = \text{minCostInsert}(y_i, R)$
    $R = \text{twoOpt}(R)$
endfor
return R

subprocedure *minCostInsert*$(y, z_i \in R)$
$c_R = c(R)$
for $i = 1, \ldots, |R|+1$, **for** $j = 1, \ldots, |R|+1$
    $R' = (z_1, \ldots, z_{i-1}, y, z_i, \ldots, z_{j-1}, y, z_j, \ldots, z_{|R|})$
    if $c(R') < c_R$, $c_R = c(R')$, $R = R'$, **endif**
endfor, **endfor**
return R

subprocedure *twoOpt*$(z_i \in R)$
$c_R = c(R)$
repeat
    $done = \text{true}$, $i = 1$, $j = 2$
    while $done$ and $i < |R|$
        while $done$ and $j < |R|+1$
            $R' = (z_1, \ldots, z_{i-1}, \text{reverseSequence}(z_i, \ldots, z_j), z_{j+1}, \ldots, z_{|R|})$
            if $c(R') < c_R$
                $c_R = c(R')$, $R = R'$, $done = \text{false}$
            endif
            $j = j + 1$
        endwhile
        $i = i + 1$, $j = i + 1$
    endwhile
until $done = \text{true}$
return R

Shapley Value Approximation

- Shapley value
  - Average additional cost shipment imposes by joining route
  - Exact value requires $n!$
  - Use n^2 pairwise savings approximation instead



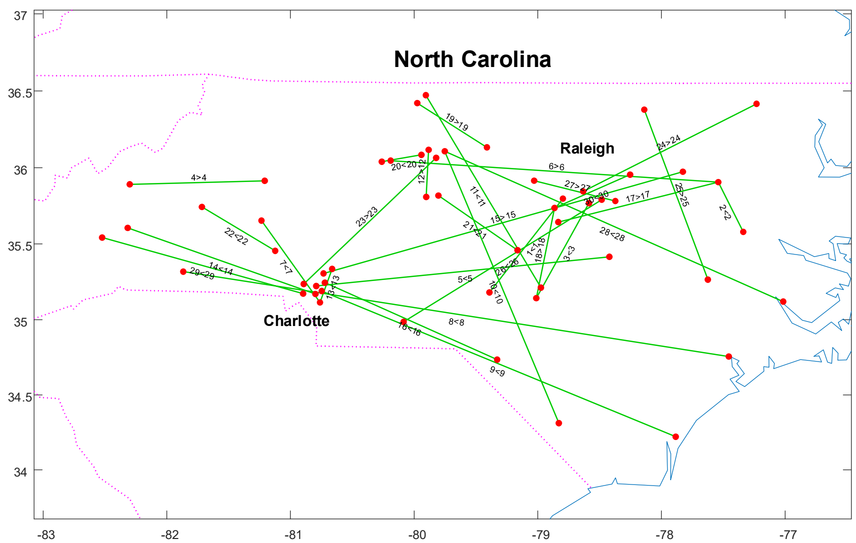
$$s_{ij} = \text{pairwise savings between } i \text{ and } j$$
$$= c_i + c_j - c_{ij}$$
$$s_{1,2} = 300 + 250 - 310$$
$$= 240$$

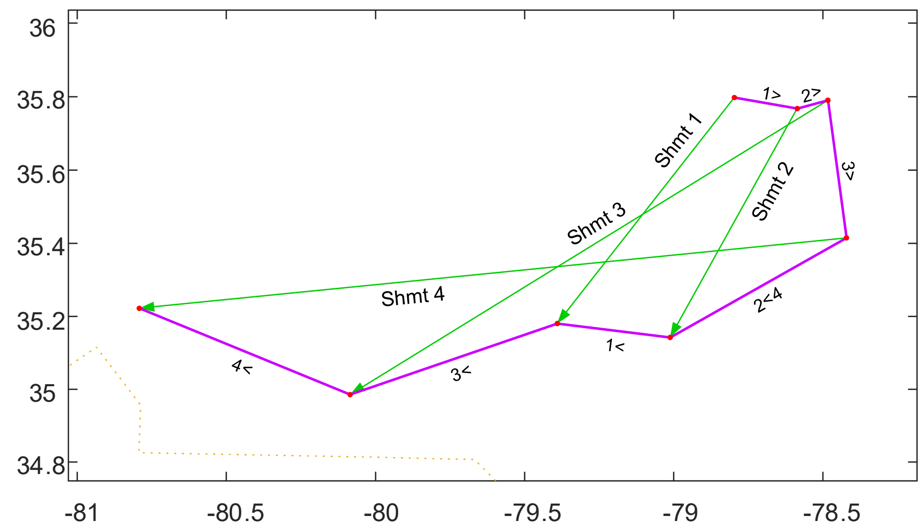
C:	1	2	3
123:	300	10	120
132:	300	35	95
213:	60	250	120
231:	0	250	180
312:	120	35	275
321:	0	155	275

:	c0	c_equal	c_eq_sav	c_Shap_exact	c_Shap_approx
1:	300	143.33	168.33	130.00	130.00
2:	250	143.33	118.33	122.50	122.50
3:	275	143.33	143.33	177.50	177.50
Total:	825	430.00	430.00	430.00	430.00
Avg:	275	143.33	143.33	143.33	143.33

Intercity Trucking Example

- 4 out 30 available shipments form consolidated load
  - Savings of 824.81 – 452.47 = 372.34 from consolidation
  - Pairwise approximation differs from exact Shapley value

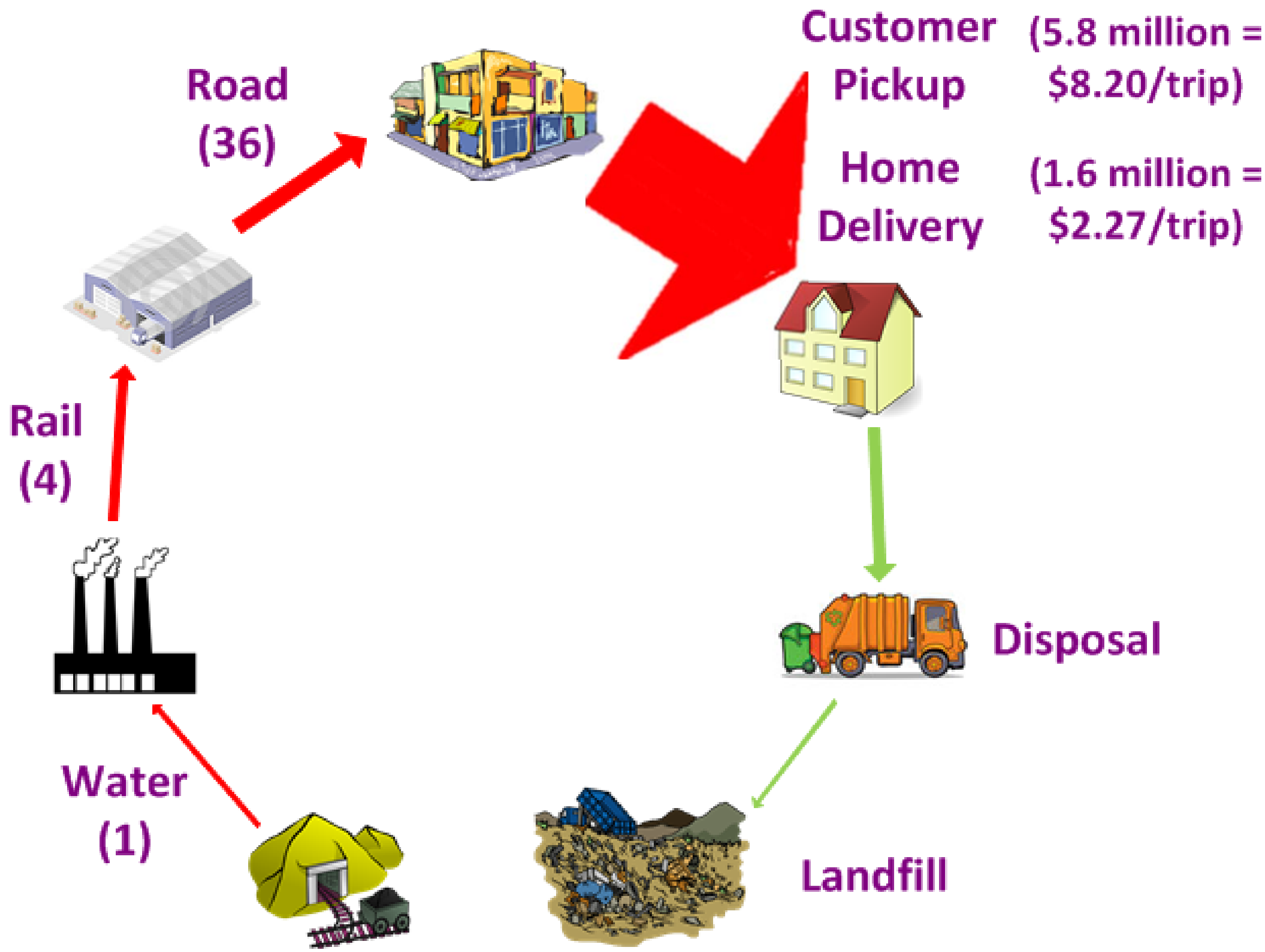




:	c0	c_equal	c_eq_sav	c_Shap_exact	c_Shap_approx
1:	129.94	113.12	36.86	62.34	52.10
2:	118.53	113.12	25.44	53.20	49.58
3:	254.20	113.12	161.12	117.12	123.34
4:	322.14	113.12	229.05	219.80	227.44
Total:	824.81	452.47	452.47	452.47	452.47

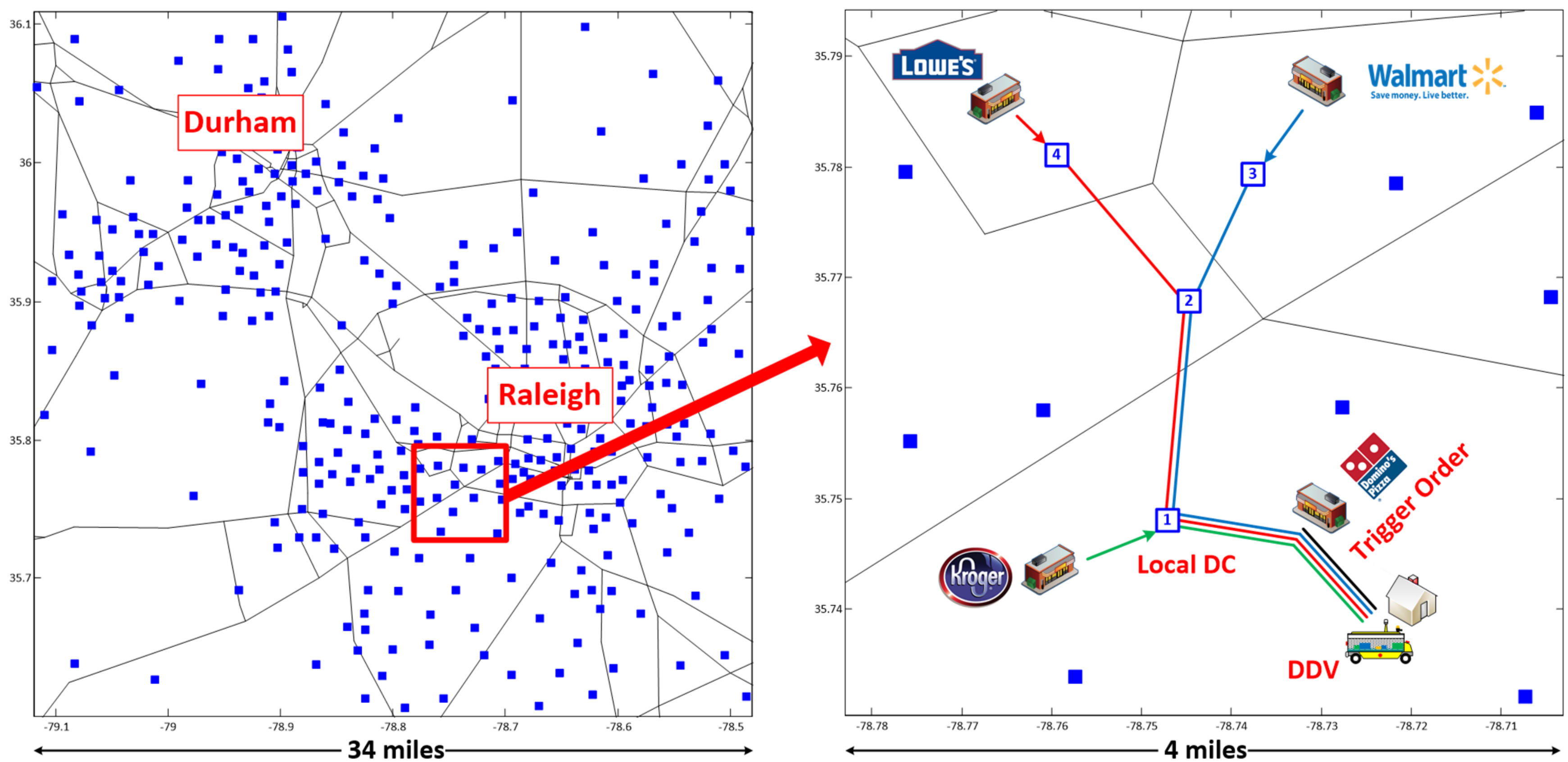
Example 2: Home Delivery

Dirt-to-Dirt Logistics Costs



($/ton-mi relative to water)

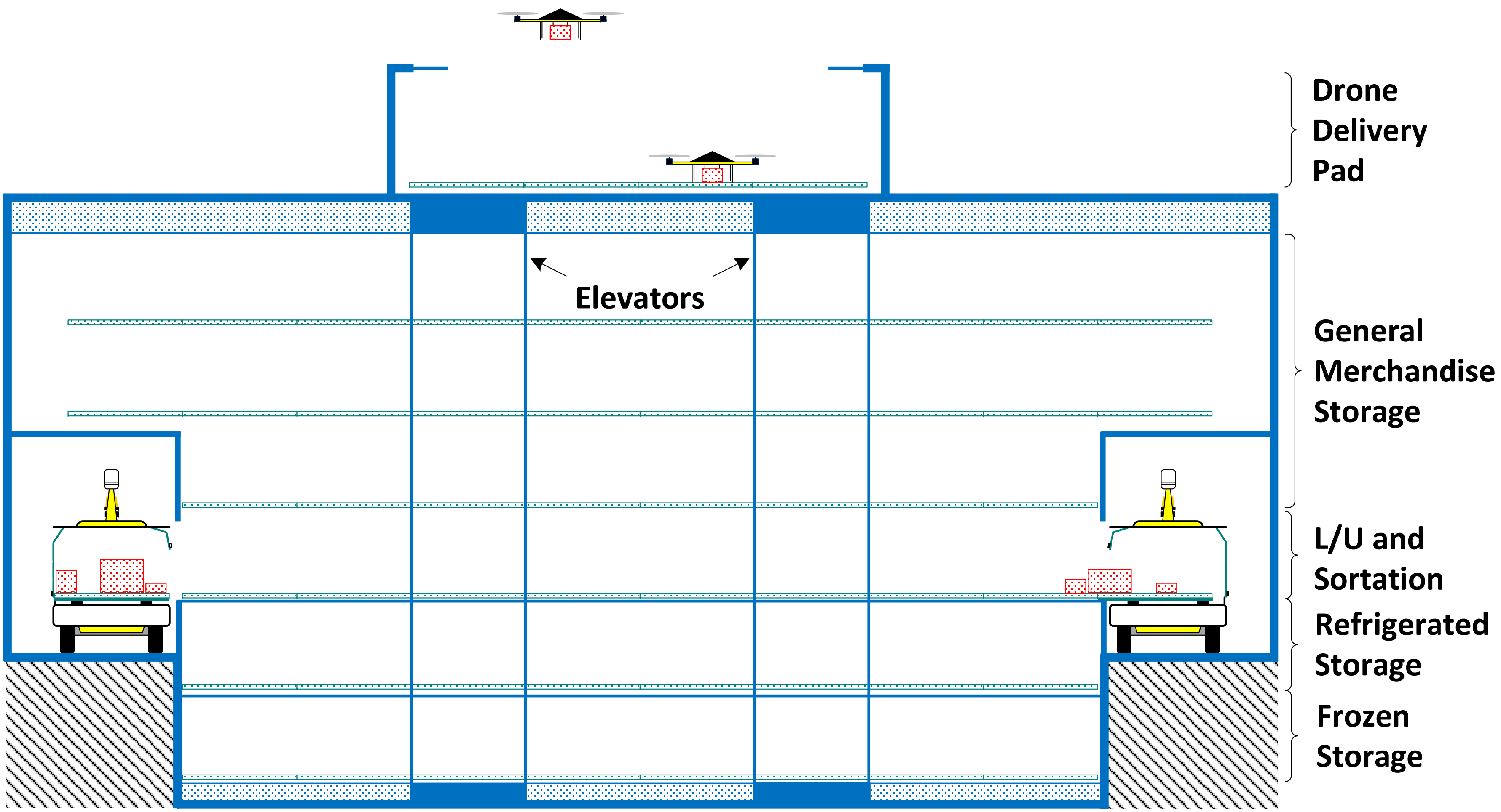
Home Delivery Logistics Network



(a) DCs covering Raleigh-Durham metro area.

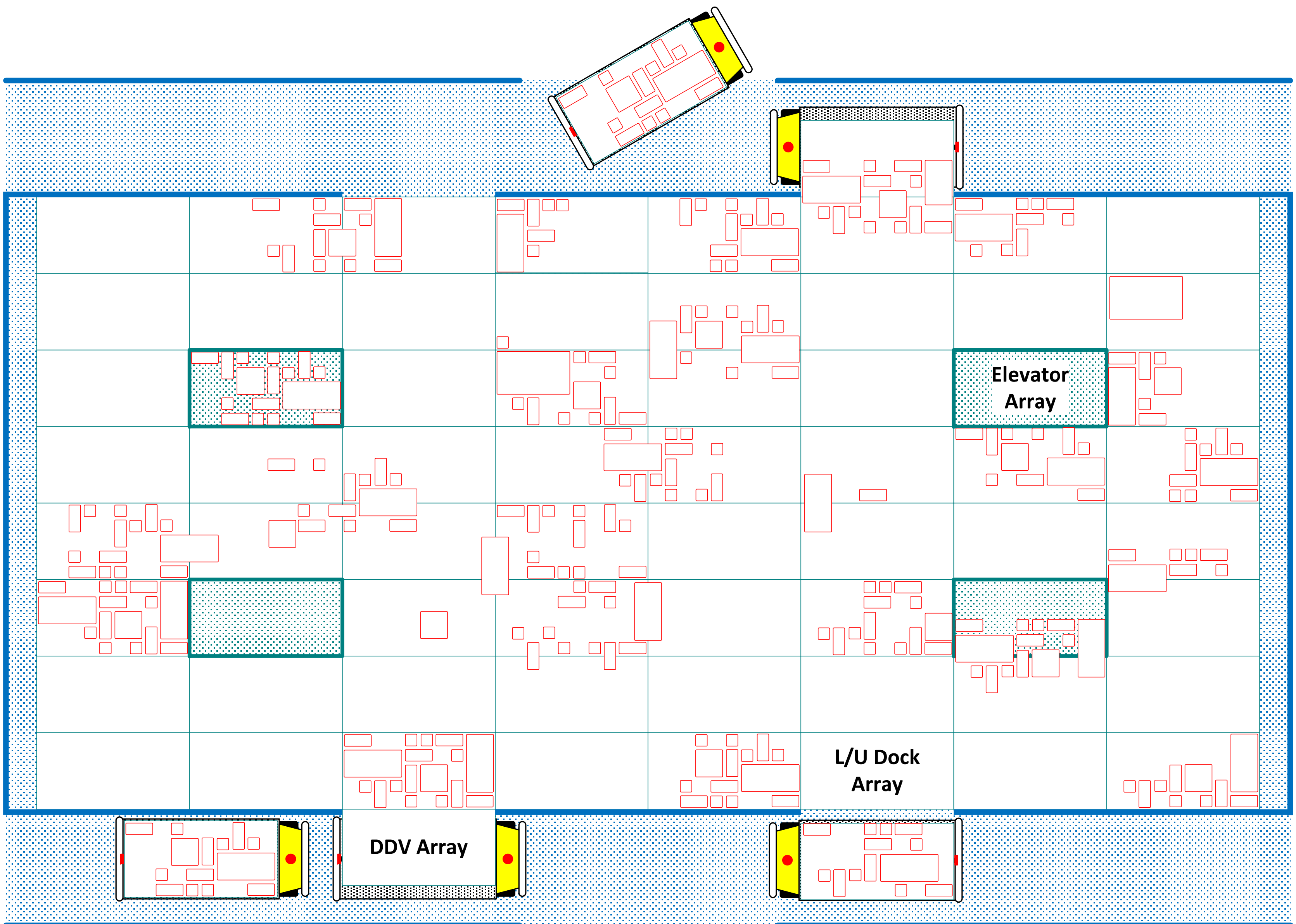
(b) Delivery of four orders to a home.

DC (side view)

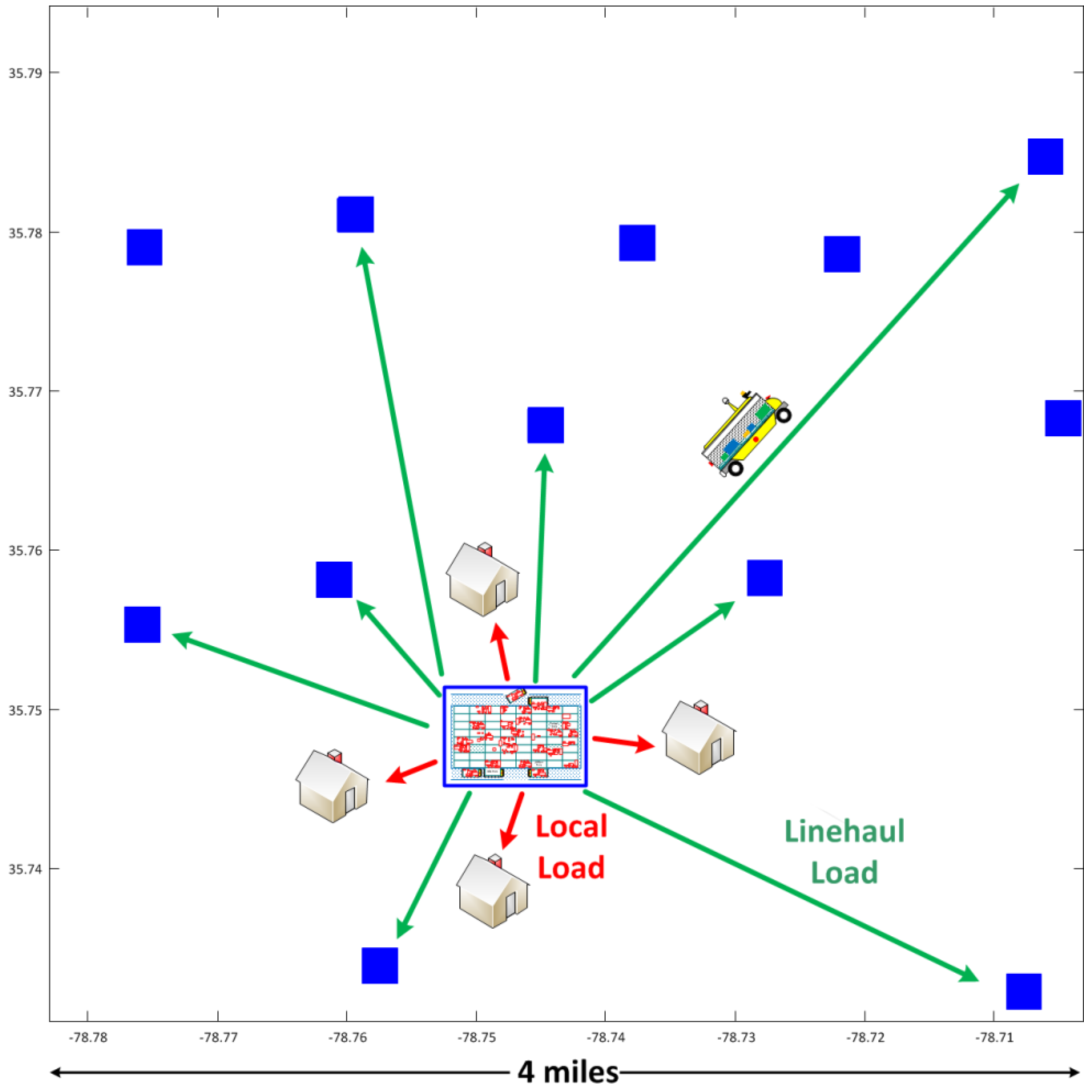


Elevators
Drone Delivery Pad
General Merchandise Storage
L/U and Sortation
Refrigerated Storage
Frozen Storage

DC (top view of one level)

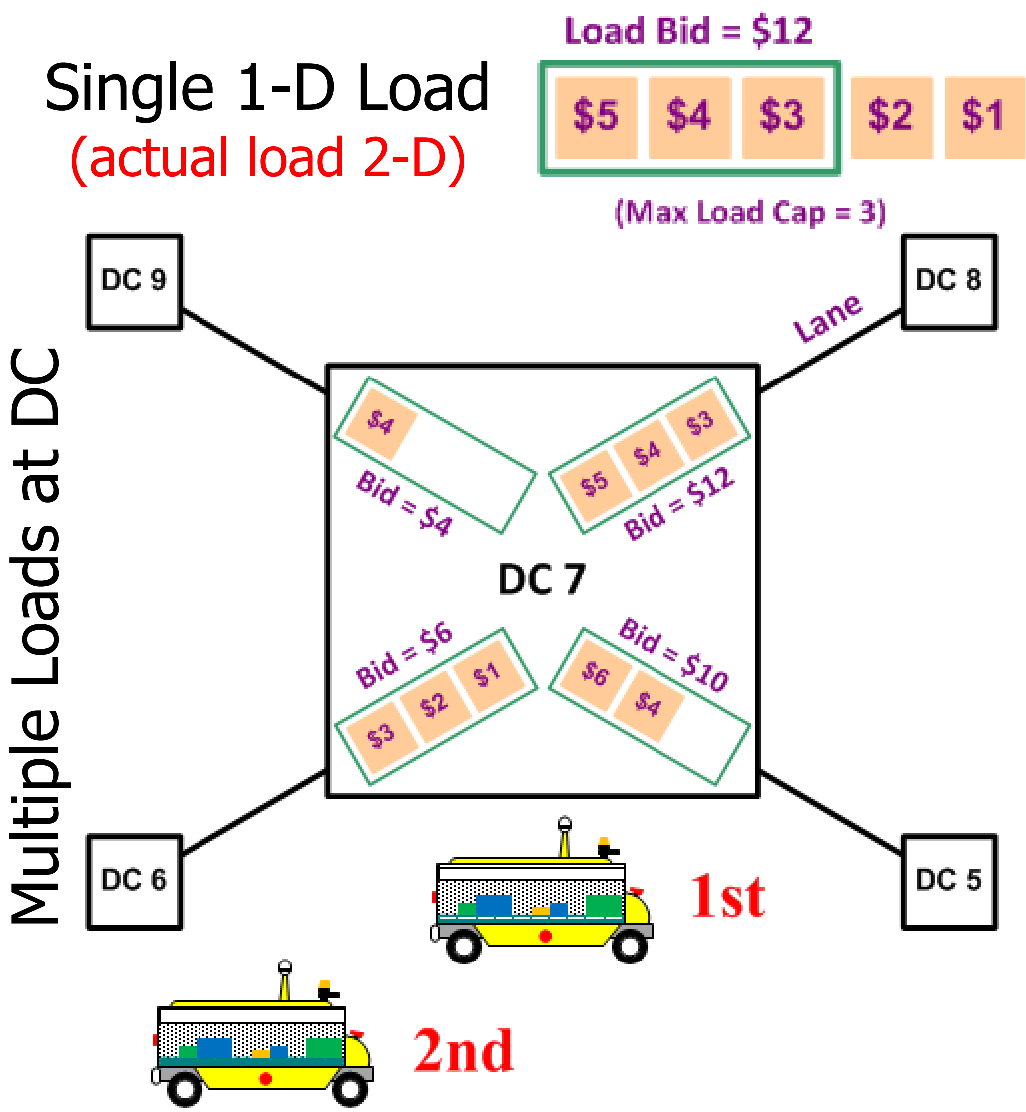


Coordination Mechanism



- Separate firm can own each DC and DDV → coordination more difficult than private network
- *Local load* is a single shipment
- Containers in *linehaul load* part of different shipments each owned by a separate firms
- Containers pay DC for storage time

Load Bids

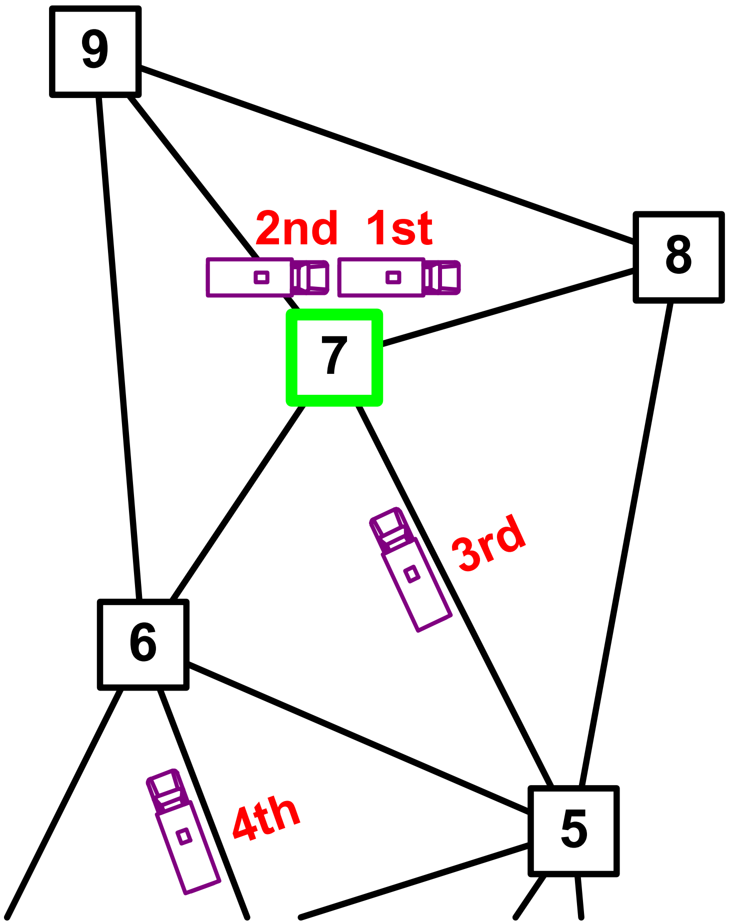


- *Load bid* is sum of container bids in load
- Loads in a lane ordered by decreasing bid
- Containers bid for services of the DDVs used for their transport
  - Containers going to same DC compete to be in next transported load
  - Loads to different DCs competing to be selected by a DDV
  - DDVs competing with each other to select loads

DDV Protocol

- Determines which DDV is used to transport what load at what DC
- Goal for DDV operation:
  - Try to match the load that values transport the highest with the DDV that can provide that transport service at the least cost
- Protocol:
  1. **Priority for Accepting Loads:** Opportunity to accept or reject load based on DDV's expected arrival time at DC
  2. **Reneging:** After reneging, DDV cannot again accept same load until all other DDVs have rejected it

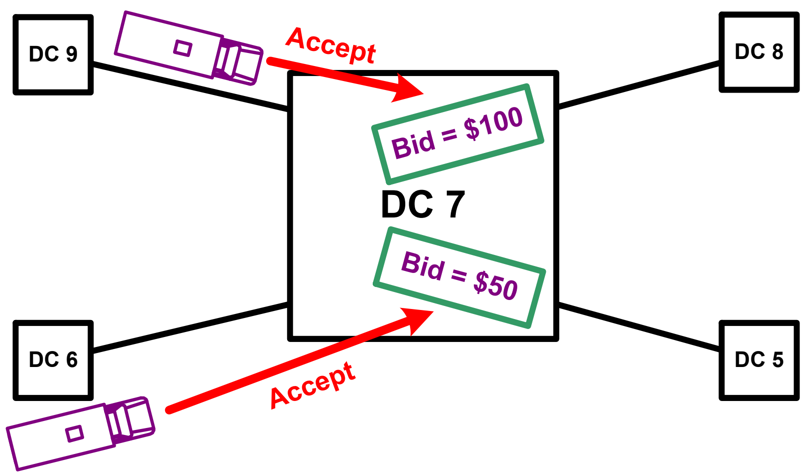
1. Priority for Accepting Loads



- Opportunity to accept or reject load based on DDV's arrival time at DC
- DDV's portion of load bid fixed after acceptance
- If all DDVs reject load, then it's posted at DC and available for any DDV to accept

Load at DC 7

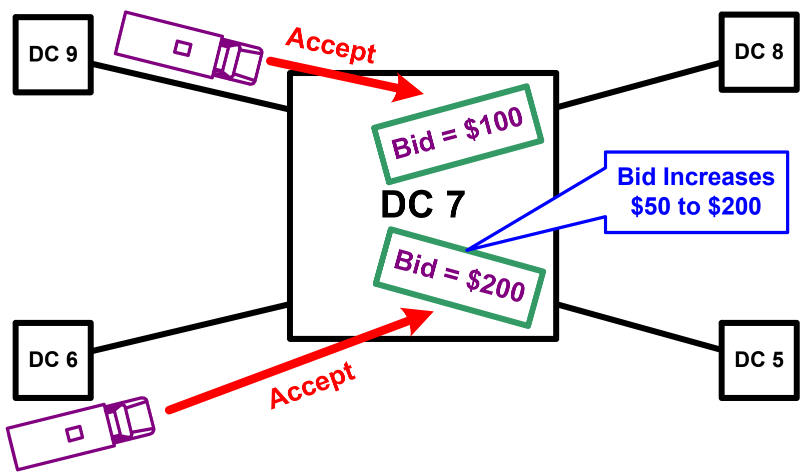
2. Reneging



- After reneging, DDV cannot again accept same load until all other DDVs have rejected it

Near and far DDV accept high and low bids, respectively

2. Reneging

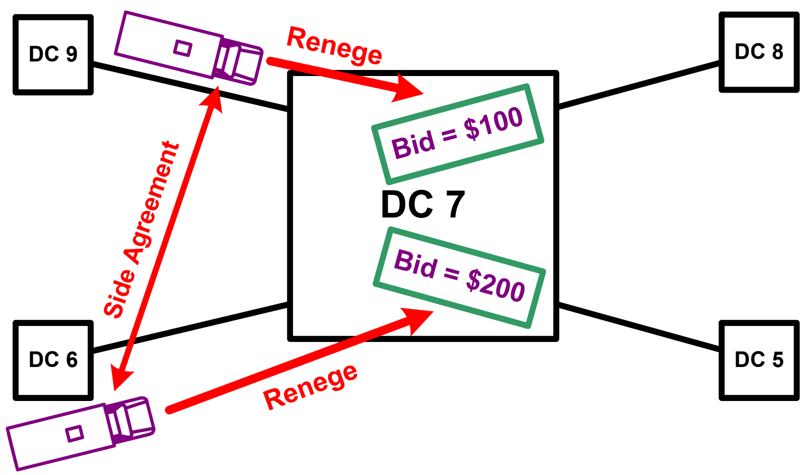


- After reneging, DDV cannot again accept same load until all other DDVs have rejected it

Near and far DDVs accept high and low bids, respectively

Low bid now increases beyond high bid

2. Reneging



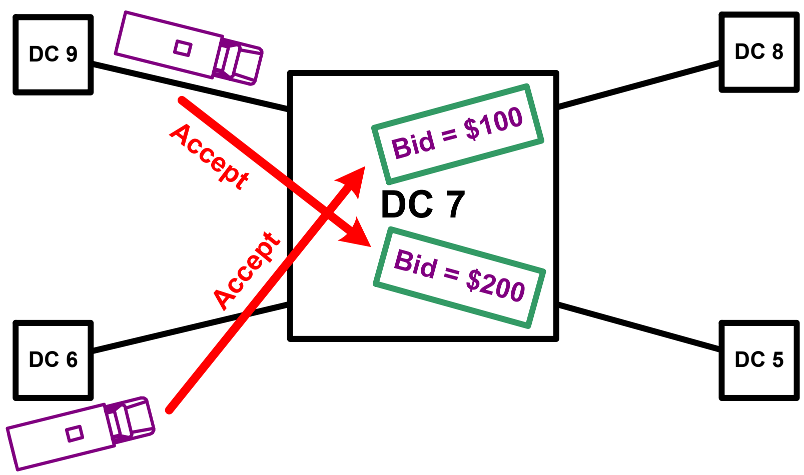
- After reneging, DDV cannot again accept same load until all other DDVs have rejected it

Near and far DDVs accept high and low bids, respectively

Low bid now increases beyond high bid

DDVs agree to renege (since far DDV's portion fixed at $50)

2. Reneging



- After reneging, DDV cannot again accept same load until all other DDVs have rejected it

Near and far DDVs accept high and low bids, respectively

Low bid now increases beyond high bid

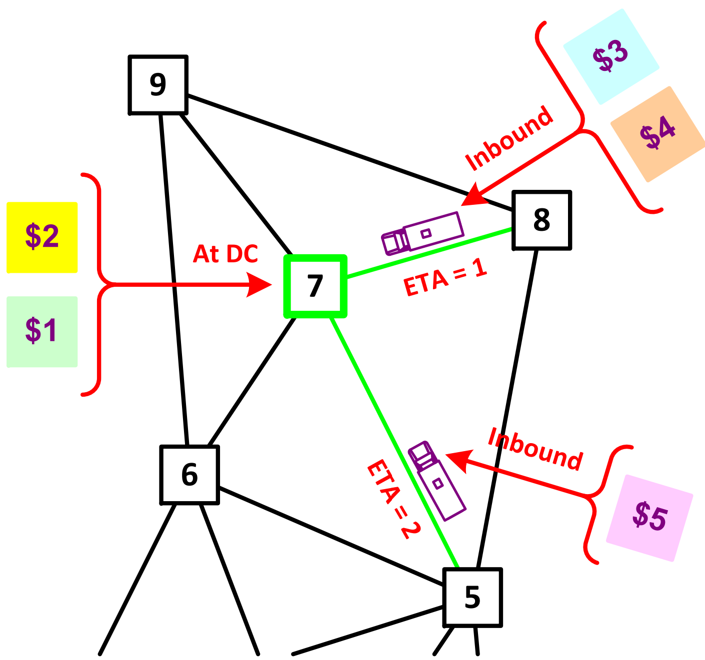
DDVs agree to renege (since far DDV's portion fixed at $50)

Near DDV accepts $200 bid and far DDV $100 bid

Container Protocol

- Determines which containers selected to join load
- Goal for container selection:
  - Encourage a container to submit a bid that represents its true value for transport as soon possible, thereby allowing DDVs to be more responsive and discouraging multiple-bid auction-like behavior
- Protocol:
  1. **Load Formation:** Bid per unit area of each container used by 2-D bin-packing heuristic to form loads
  2. **Allocation of Load Bid:** After acceptance, DDV's portion of load bid does not increase and bids of any subsequent containers joining load allocated to original containers
  3. **Withdrawal and Rebidding:** Containers that withdraw or rejoin load charged their previous bid amounts in addition to current bid

1. Load Formation



- Containers assigned to load that maximizes resulting load bid
- Containers can bid as soon as they are at or inbound to DC

Time Index	Load Bid	First Load	Load Bid	Second Load
0	$3	$2 $1		
1	$9	$4 $3 $2	$1	$1
2	$12	$5 $4 $3	$3	$2 $1

2. Allocation of Load Bid

- DDV’s portion of load bid fixed after acceptance
- Subsequent increases in bid allocated to container in load (and remain in load) at time of acceptance

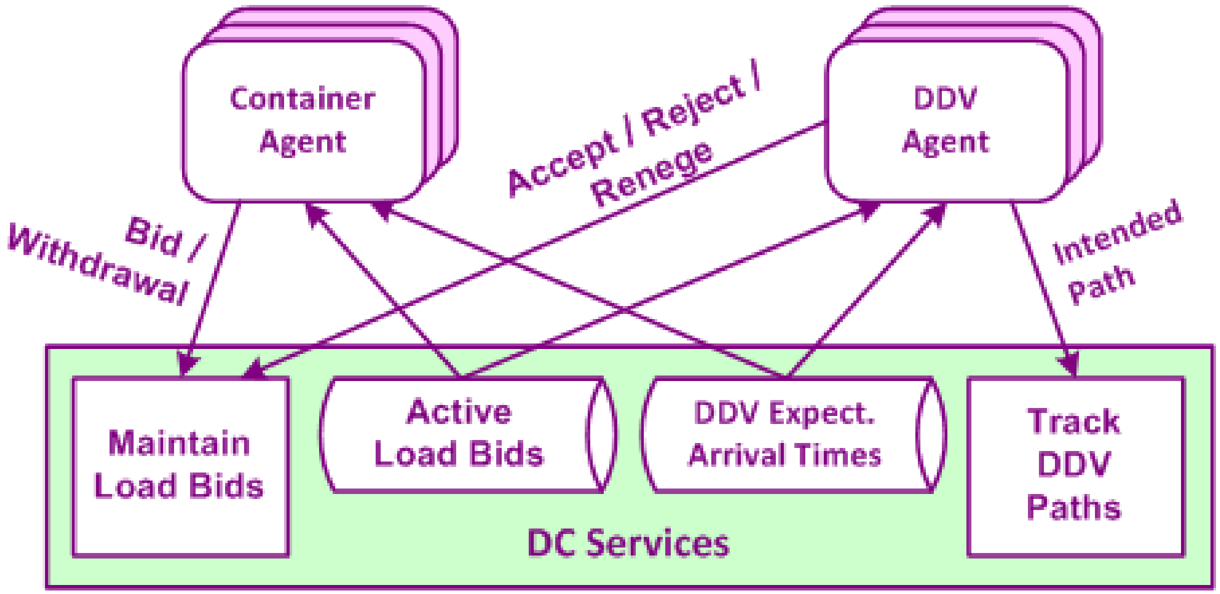
Container Event	DDV Response	Load Bid	DDV Portion	Allocated Portion	Load (Bid / Cost)
Bid & Join	Reject	8	8	0	8 / 8
Bid & Join	Accept	10	10	0	8 / 8, 2 / 2
Bid & Join	—	15	10	5	8 / 4, 5 / 5, 2 / 1
Bid, Join, & Drop	—	16	10	6	8 / 2, 5 / 5, 3 / 3, 2 / 0

3. Withdrawal and Rebidding

- Containers that withdraw or rejoin load are charged previous bid amounts

Container Event	DDV Response	Load Bid	DDV Portion	Allocated Portion	Load (Bid / Cost)			
Bid & Join	Reject	8	8	0	8 / 8			
Bid & Join	Accept	10	10	0	8 / 8	2 / 2		
Bid & Join	—	15	10	5	8 / 4	5 / 5	2 / 1	
Bid, Join, & Drop	—	16	10	6	8 / 2	5 / 5	3 / 3	2 / 0
Rebid, Rejoin, & Drop	—	19	10	9	8 /-1	5 / 5	4 / 6	3 / 0
Rebid, Rejoin, & Drop	—	24	10	14	8 /-6	6 / 9	5 / 5	4 / 2
Withdraw & Rejoin	—	28	10	18	8 /-10	6 / 9	4 / 6	0 / 5
—	Renege	28	28	0	8 / 8	6 / 9	4 / 6	0 / 5

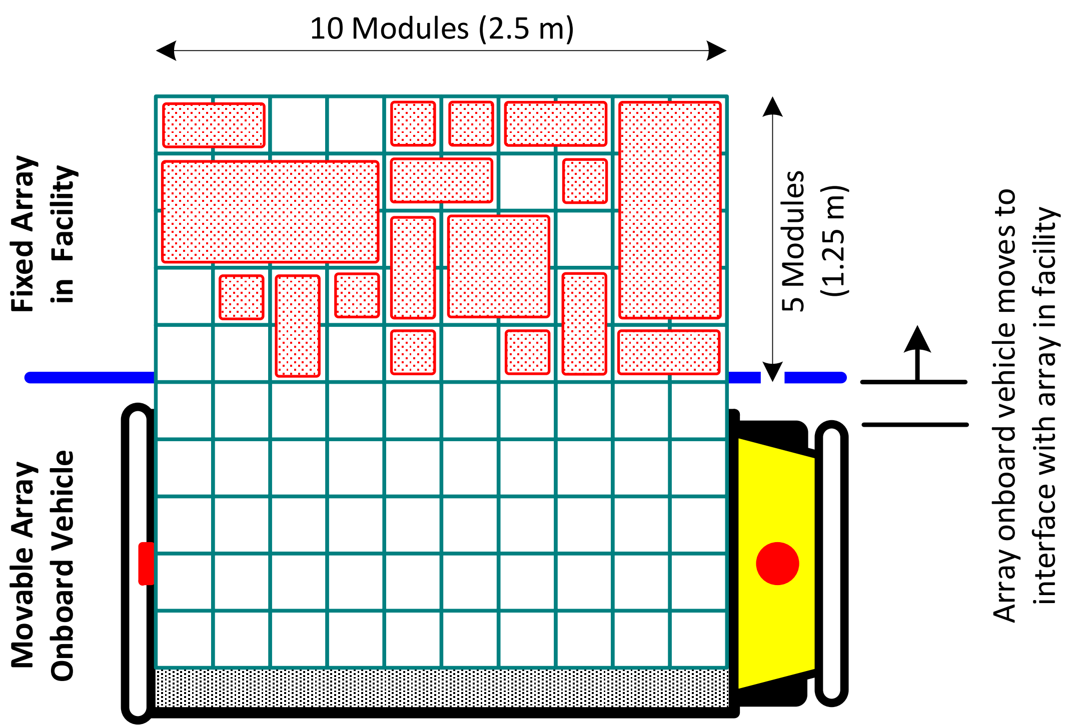
Agent-based Coordination



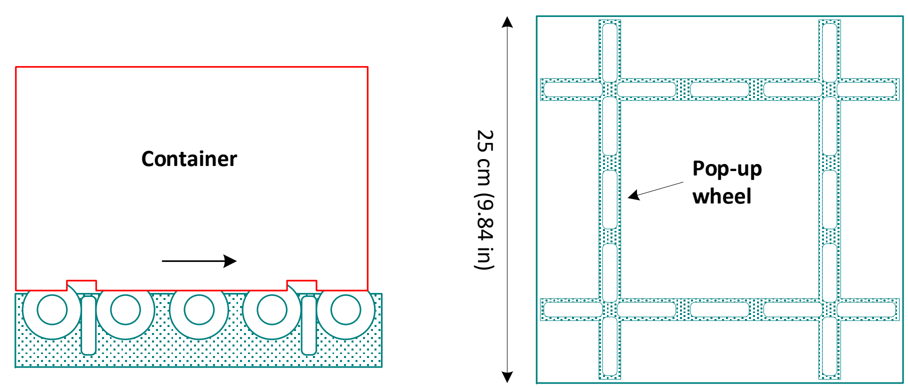
- Each container and each DDV controlled by a software agent
- Agents:
  - provided with all load bids at DC and all DDV locations
  - can make side payments with each other

2-D Load Formation

- Arrays of 50 modules
  - Used on DDV
  - Used in DC
- Enables automatic loading/unloading



Container on a module



2-D Load Formation: Select Containers

- Containers sorted based on decreasing per-unit bid value
- Selected until cumulative area = 50, capacity of module array

Cont.	Length	Width	Area	Cum. Area	Bid	Per Unit Bid
1	4	3	12	12	4.03	0.3361
2	2	3	6	18	1.99	0.3322
3	1	2	2	20	0.64	0.3195
4	2	2	4	24	1.27	0.3180
5	3	2	6	30	1.80	0.3000
6	2	1	2	32	0.56	0.2787
7	1	1	1	33	0.27	0.2737
8	1	2	2	35	0.54	0.2715
9	1	1	1	36	0.27	0.2650
10	1	1	1	37	0.26	0.2628
11	2	2	4	41	0.95	0.2379
12	3	1	3	44	0.55	0.1843
13	1	1	1	45	0.17	0.1750
14	1	2	2	47	0.35	0.1731
15	4	4	16		2.64	0.1651
16	1	1	1	48	0.15	0.1500
17	2	1	2	50	0.27	0.1366
18	1	1	1	51	0.12	0.1220

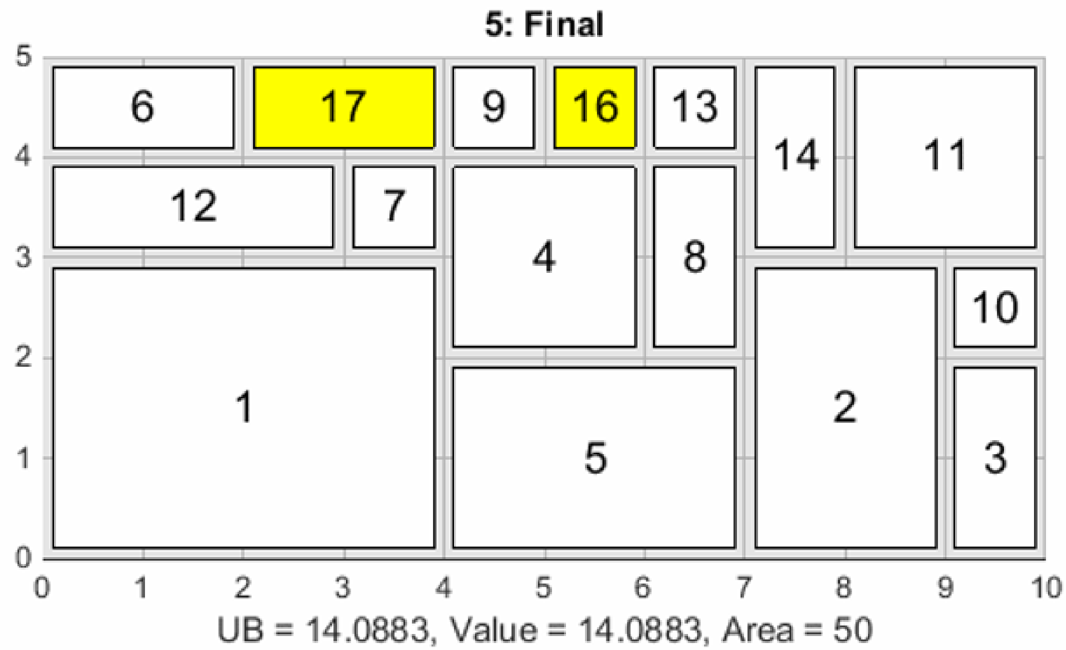
2-D Load Formation: Order Containers

- Order sequence determined based on:
  1. Length
  2. Width
  3. Bid
- Upper Bound (*UB*) = sum of bids of all containers
- May not be feasible to fit (pack) all containers into array (bin)

Cont.	Length	Width	Bid
1	4	3	4.03
5	3	2	1.80
12	3	1	0.55
2	2	3	1.99
4	2	2	1.27
11	2	2	0.95
6	2	1	0.56
17	2	1	0.27
3	1	2	0.64
8	1	2	0.54
14	1	2	0.35
7	1	1	0.27
9	1	1	0.27
10	1	1	0.26
13	1	1	0.17
16	1	1	0.15
18	1	1	0.12
		UB =	14.09

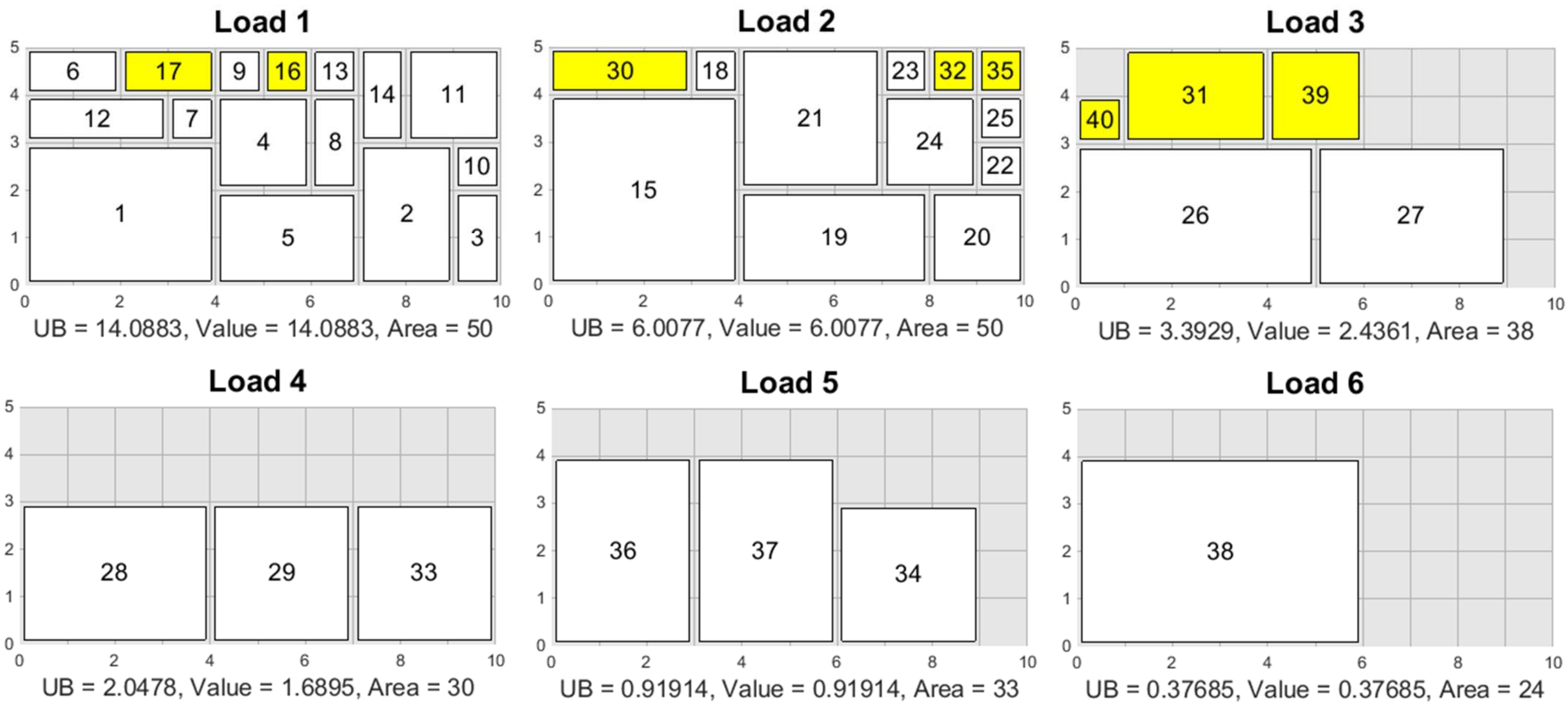
2-D Load Formation: Bin Packing

1. *Initial*: Add containers based on order sequence
2. *Re-check*: try adding any cont. left out of initial load
3. *Add more efficient*: replace if cont. with higher per-unit bid can be added
4. *Add extras*: insert cont. in any available space
5. *Final*



Diseconomies of Scale

Yellow containers spend/bid less on a per-unit basis to join a load that is leaving earlier due to their smaller size



(Containers 1-40 numbered in decreasing total bid; Loads 1-6 in increasing departure time)

Comparison

Intercity Trucking	Home Delivery
Separate firms own trucks, shipments	Separate firms own DDVs, containers, DCs
Multi-stop: different O/D each shipment	Point-to-point: DC-DC, DC-home
First shipment sets rate for load	Each container sets own bid
Can drop out of load *without* penalty until truck accepts	Can withdraw at any time *with* penalty (after DDV accepts, subsequent bids given back to initial containers in load)
Route heuristic, Shapley approximation	2-D bin packing heuristic
Within protocol: LTL rate option limits small shipment allocated charge	*Outside of protocol*: Drone delivery limits max bid of time-sensitive containers