Public Logistics Networks for Home Delivery

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Research

- Goal:
  - To eliminate the need for all non-recreational shopping by making it possible to have a hot pizza and a vehicle-load of other stuff delivered to your home, exactly when you want, for the price of what you would have tipped the pizza delivery guy
- Activity:
  - Provide tools for expanded role of public logistics networks in intercity trucking and urban logistics
  - Particular focus: home delivery using autonomous vehicles
  - Tools include design methodologies, performance analysis, and protocol/mechanism specifications

Challenges

- Home delivery has increased during the pandemic
- Just increasing scale of current driver-based delivery not sustainable:
  - Multiple vans each make separate deliveries of a few small items in non-reusable packaging
  - Leads to congestion and mountains of packaging requiring disposal
- Autonomous vehicles and drones can’t just directly replace driver-based delivery
  - Autonomous vehicles can’t unload a package at a home
  - Drones limited to high value urban home delivery due to cost and noise, most useful for rural home delivery

Opportunities

- Delivery via autonomous vehicle much easier than passenger transport
  - less "edge cases" due to slow travel and can avoid bad weather
- Major tech bottleneck:
  - Person needed to unload autonomous vehicle at home
- Solution:
  - Consolidate all items to deliver when customer at home
  - Requires rethinking type of logistics network that can best support home delivery (P2P instead of Multi-stop)
  - P2P delivery ⇒ Automated DCs located close to customer
- P2P ⇒ Backhaul available from home to DC ⇒
  - Empty containers can be returned on same vehicle
  - Feasible means of implementing reuse instead of recycle
- Long term ⇒ Need to travel to store reduced/eliminated
  - Low cost means of allowing elderly/disabled to remain at home

Public vs Private Logistics Networks

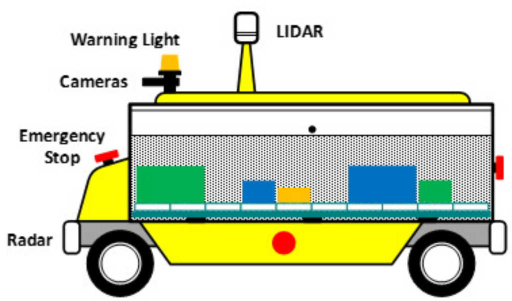
Public Network	Private Network
Each vehicle and facility can be operated by *different* firm	*Single* firm (UPS, Amazon) coordinates network, owning all critical resources
Each vehicle/facility has access to potentially all of network's demand $\Rightarrow$ *scale economies* and *dense* network	Each 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

Vehicles for Home Delivery

(a) Delivery van ($1.58/del)

(b) Nuro delivery vehicle ($?/del)



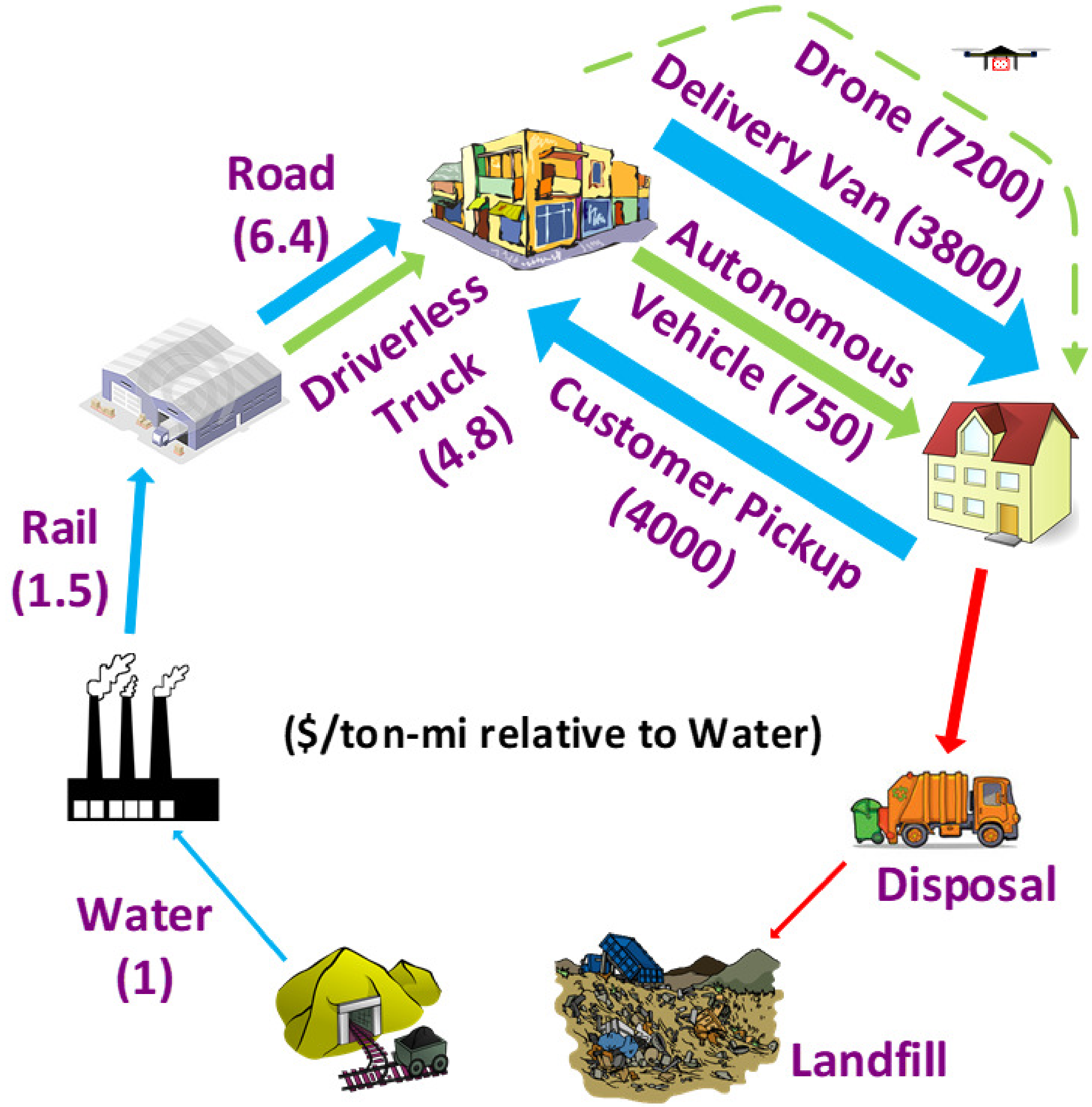
(c) Autonomous vehicle ($2.27/del)

(d) Starship delivery robot ($1.89/del)

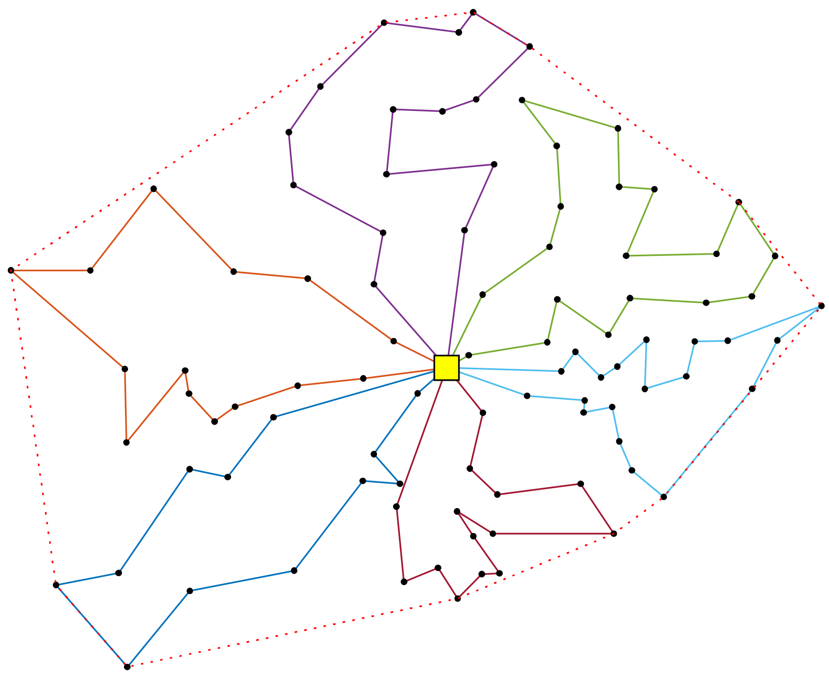
(e) Drone ($0.80/del)

(f) Customer pickup at store ($11.94/trip)

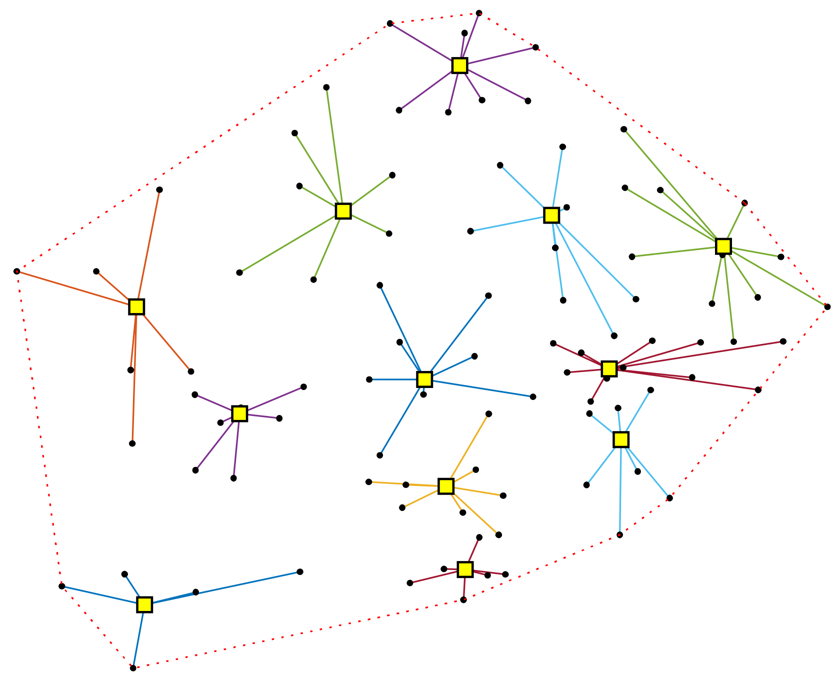
Relative Cost of Transportation Alternatives



Multi-stop versus Point-to-Point Delivery

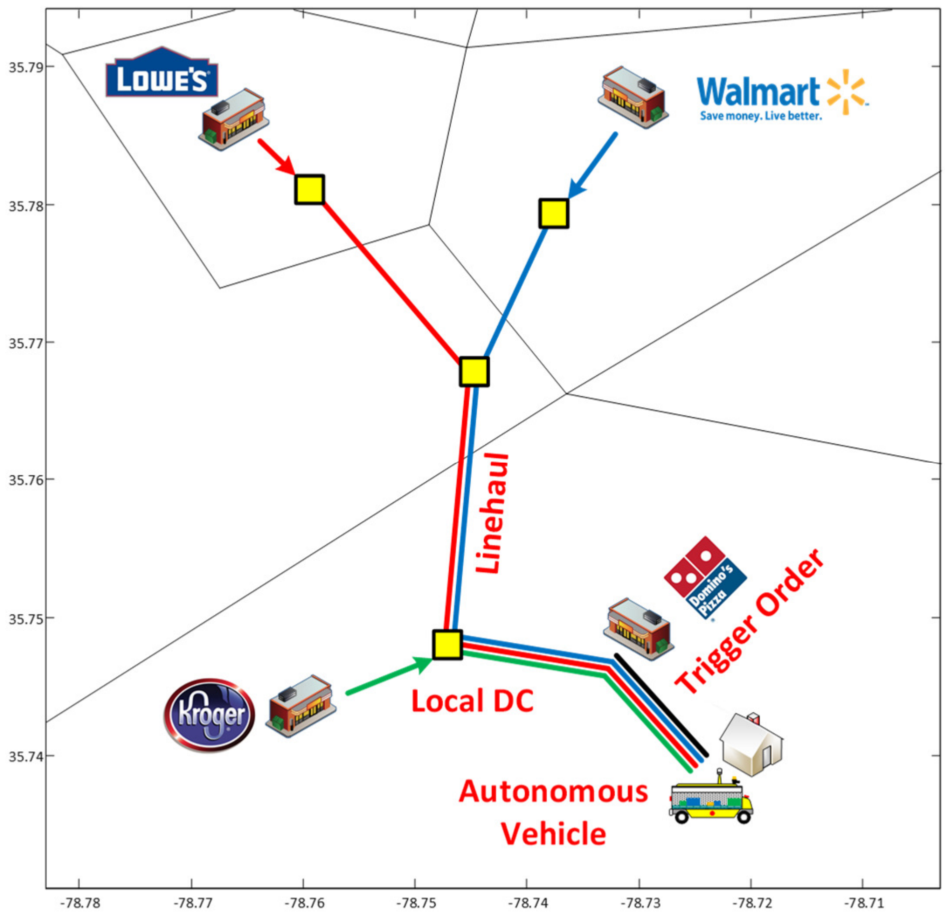


(a) Multi-stop deliveries from a single DC.

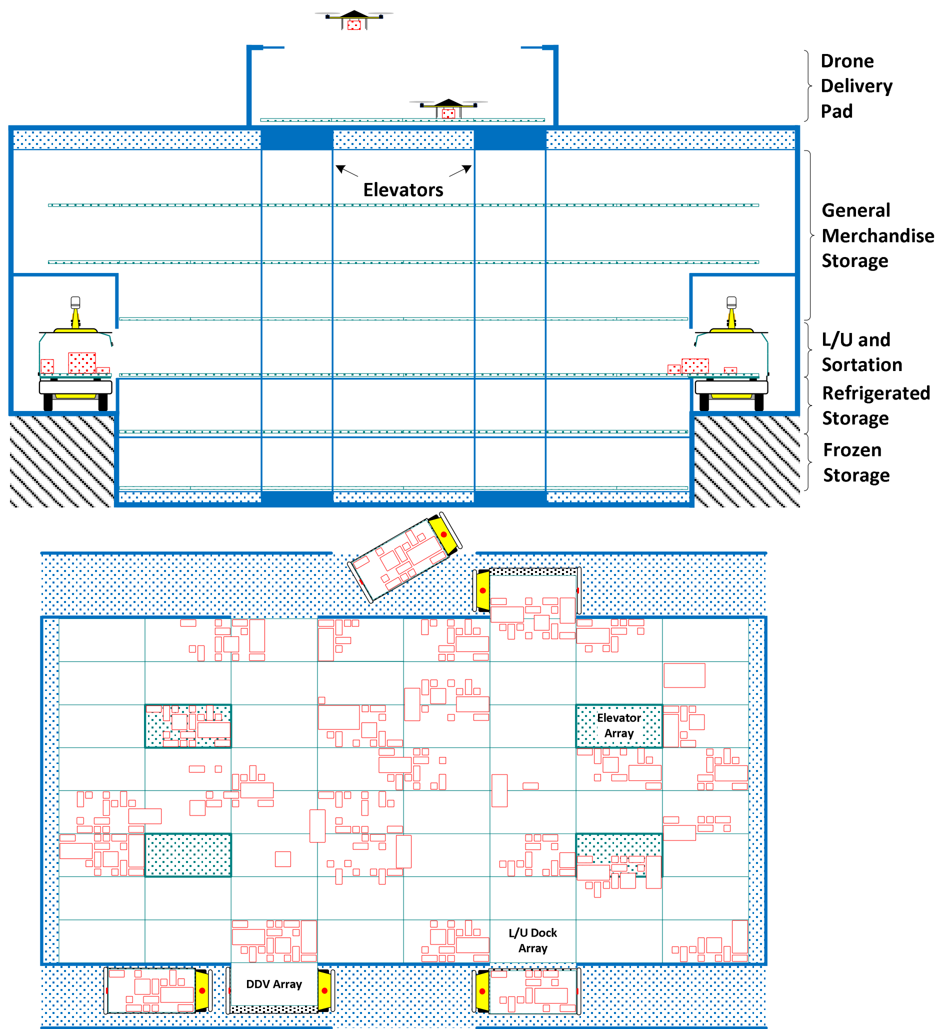


(b) Point-to-point deliveries from several DCs.

Consolidated On-demand Home Delivery



DC with Automatic Loading/Unloading Capability



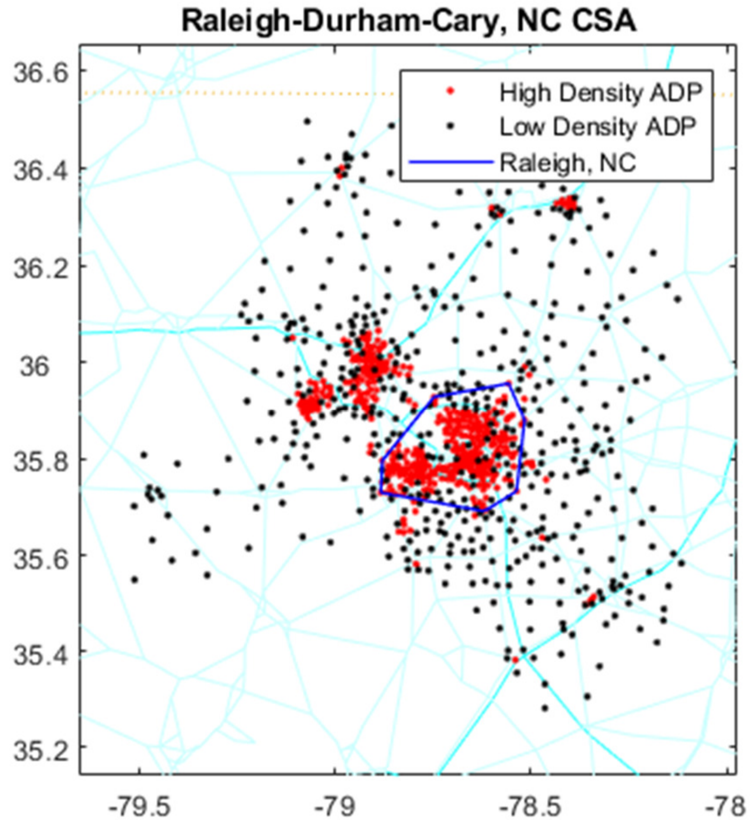
Home Delivery Alternatives

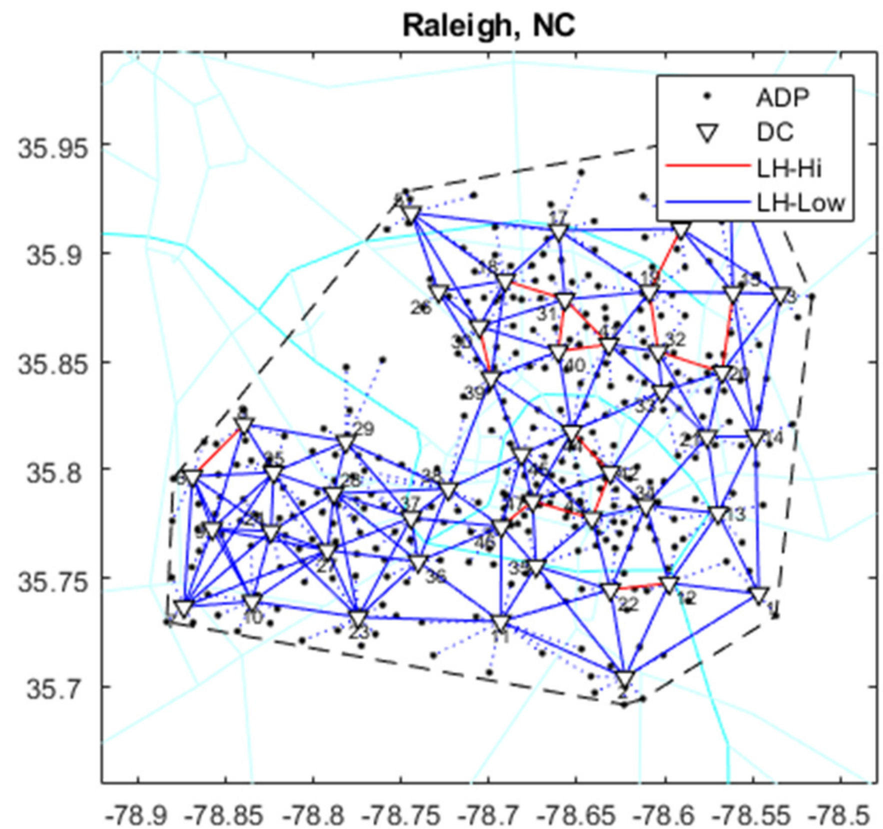
Unloading at Home	Point-to-Point On-Demand Delivery	Multi-stop Delivery Window
Customer Supervised	• Time-sensitive driver-based (groceries, pizza) • Autonomous vehicle (manual home unloading)	• Bulk-item driver-based (furniture, appliances)
Unattended (packaged/container)	• Drone	• Time-insensitive driver-based (UPS, USPS, FedEx) • Autonomous vehicle (auto home unloading)

Current Research Areas

1. **Network Design**
   – Develop network design procedure to determine the number and location of DCs for a metro area
2. **Storage System Control**
   – Unload, store, and load each container in a DC
3. **Coordination Mechanism**
   – Develop mechanism to coordinate the operation of each container, vehicle, and DC in the network
4. **Performance Analysis**
   – Estimate delivery times and associated cost for given logistic network

1. Network Design





Network Design Procedure

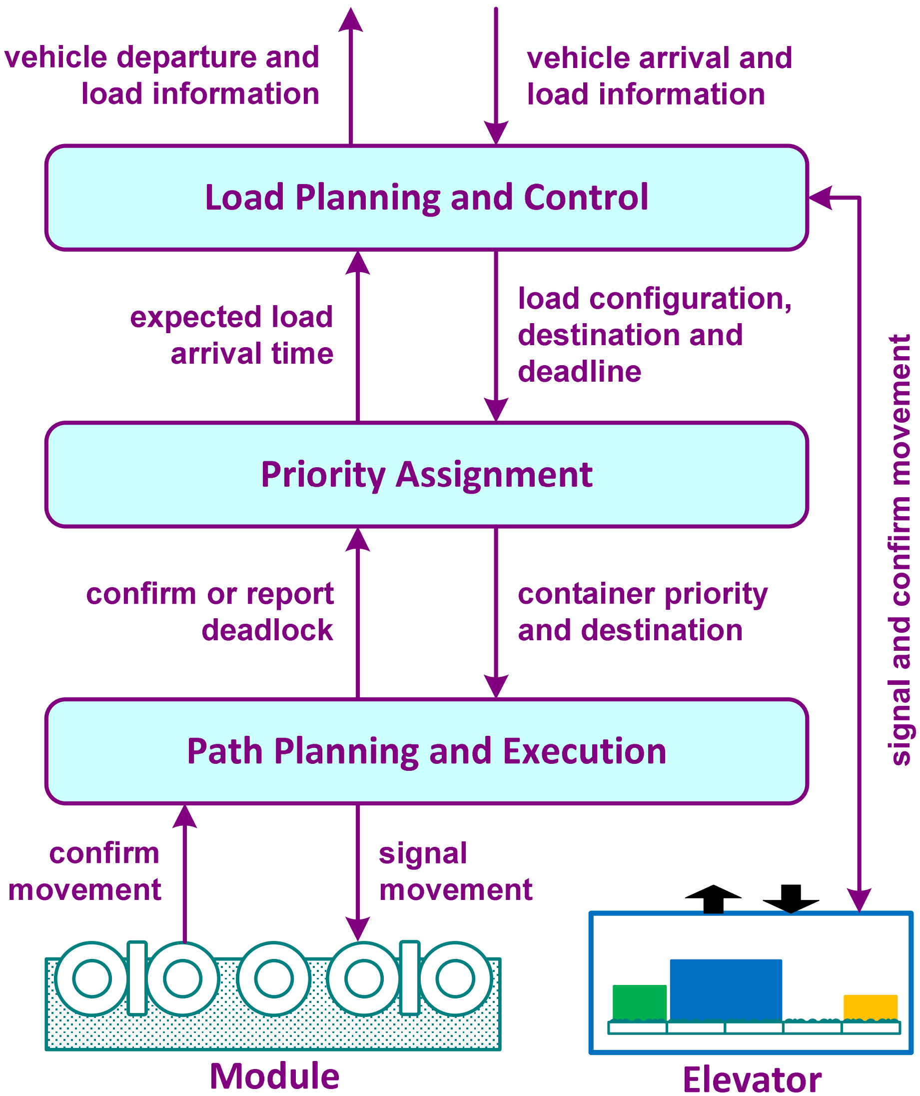
Design Parameters:

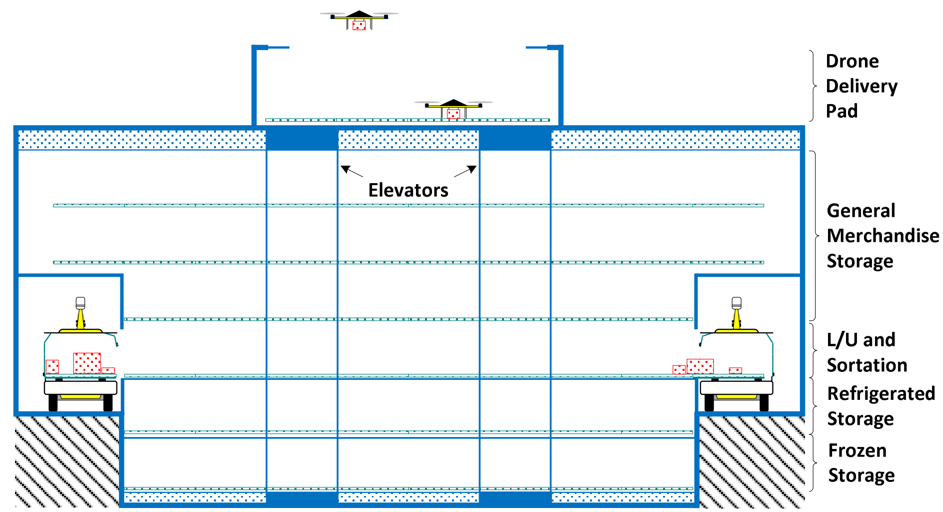
1. Number of people served by a grocery store
   - LB for avg trip distance
2. Average DC loads per hour
   - Network capacity
3. Average packages delivered per week per person
   - Network demand
4. Average vehicle speed
5. Average packages trans-ported by vehicle
   - Determines number of vehicles required

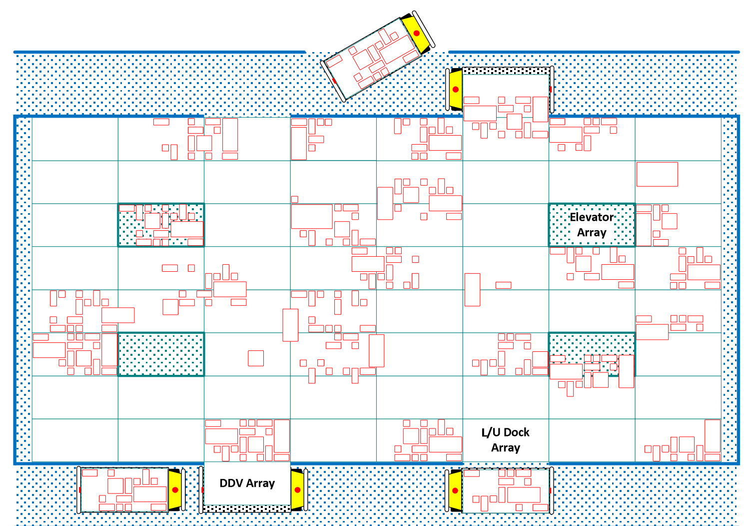
Algorithm 1 Design Logistics Network

```
procedure DesignNetwork(m, X_p, q_p, a_p)              ▷ Given data for m ADPs
    f_p ← InitialLoadDemand(q_p)                        ▷ Initial ADP loads
    W_p ← DemandWeight(X_p, q_p, a_p)                   ▷ ADP demand weights
    repeat
        n, X, F ← LocateDC(f_p, X_p, a_p)               ▷ Returns location of n DCs
        for i ← 1, n do
            for j ← 1, m do
                A(i, j) ← F(i, j) / f_p(j)              ▷ Allocation matrix
            end for
        end for
        for i ← 1, n do
            for j ← 1, n do
                W(i, j) ← Σ_{k=1}^{m} [ Σ_{l=1}^{m} A(i, l) W_p(l, k) ] A(j, k)   ▷ ADP to DC
            end for
        end for
        f_L ← LocalLoadDemand(q_p, W)                   ▷ DC local loads
        for i ← 1, n do
            a(i) ← Σ_{j=1}^{m} a_p(j) A(i, j)           ▷ ADP to DC area
        end for
        f_H ← LinehaulLoadDemand(q_p, W, X, a)          ▷ DC linehaul loads
        done ← TRUE
        for i ← 1, n do
            u(i) ← (f_L(i) + f_H(i)) / FMAX             ▷ Load factor
            if |u(i) − 1| > ε then
                done ← FALSE
            end if
        end for
        for j ← 1, m do
            f'_p(j) ← Σ_{i=1}^{n} u(i) A(i, j) f_p(j)   ▷ Adjusted ADP demand
            f_p(j) ← (1 − α) f_p(j) + α f'_p(j)         ▷ Update ADP demand
        end for
    until done = TRUE
end procedure
```

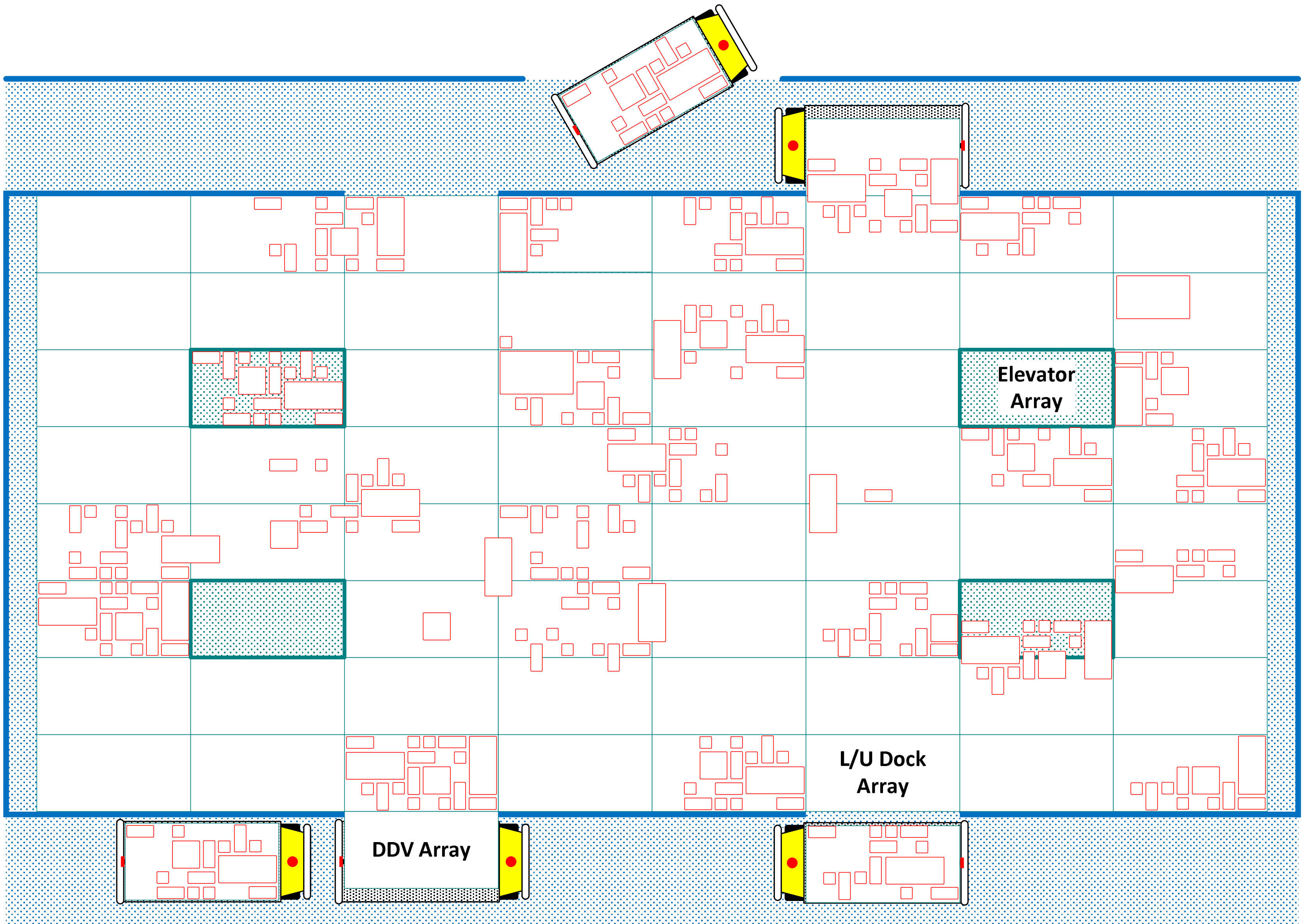
2. Storage System Control







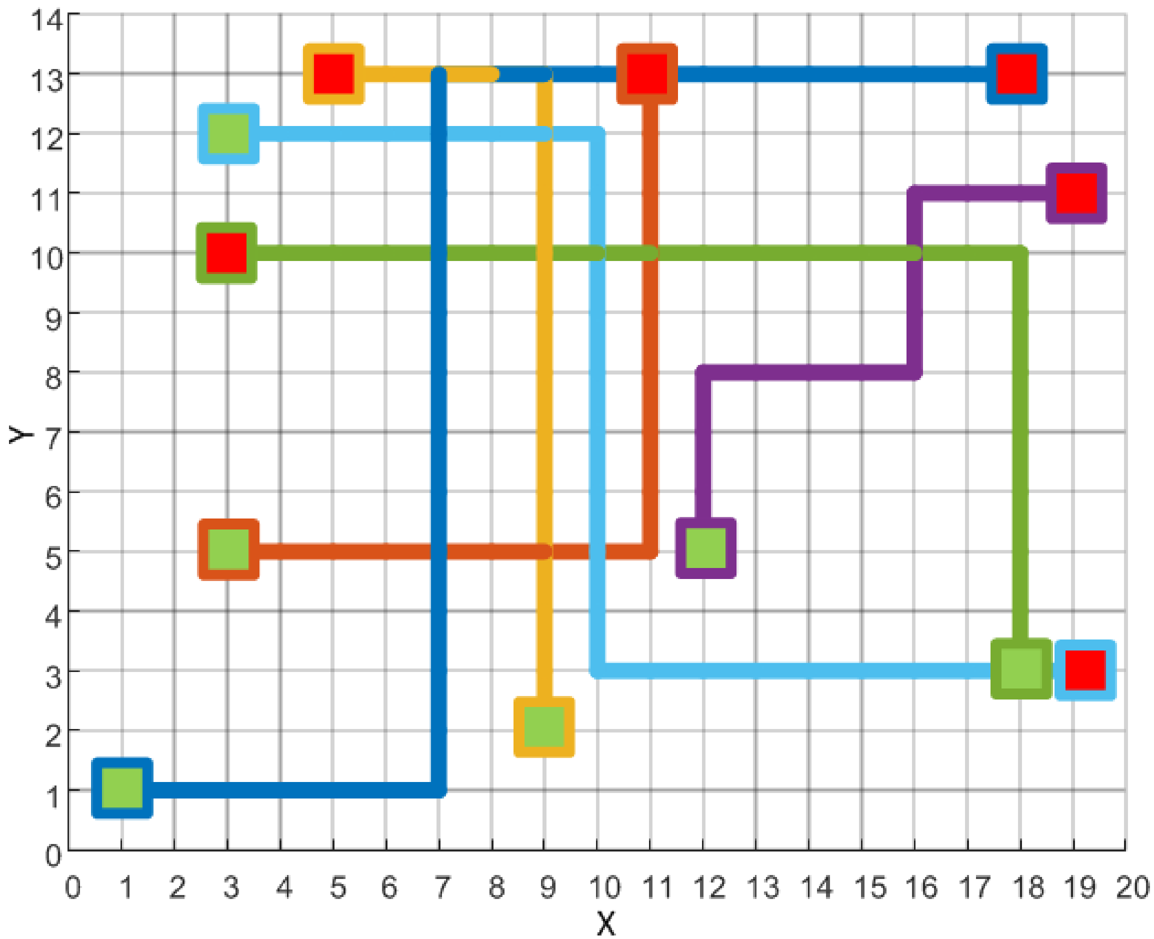
DC (top view of one level)



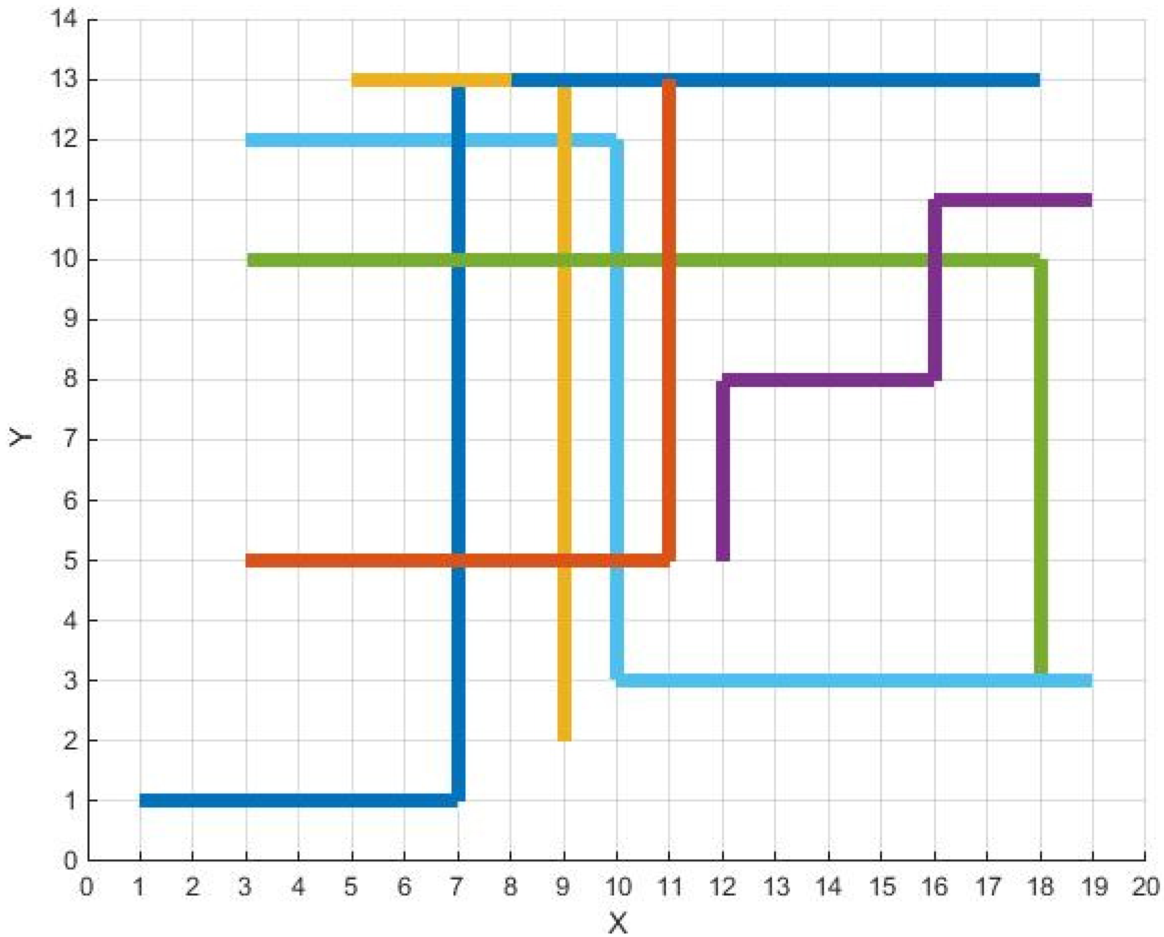
Path Planning and Execution

- *Module* ≤ *Container* ≤ *Shipment* ≤ *Load*
- 3-D (x,y,t) A* used for planning path of each container
- Each container assigned unique priority that determines planning sequence
  - Paths of higher-priority containers become obstacles for subsequent containers
  - First-in-last-out loading/unloading → must change container priority from when it is unloaded to when it is loaded
- Adaptive priority adjustment to correct for:
  - Delay along planned path
  - Deadlock detection
- Destination of containers in long-term storage is maxmin distance to other containers

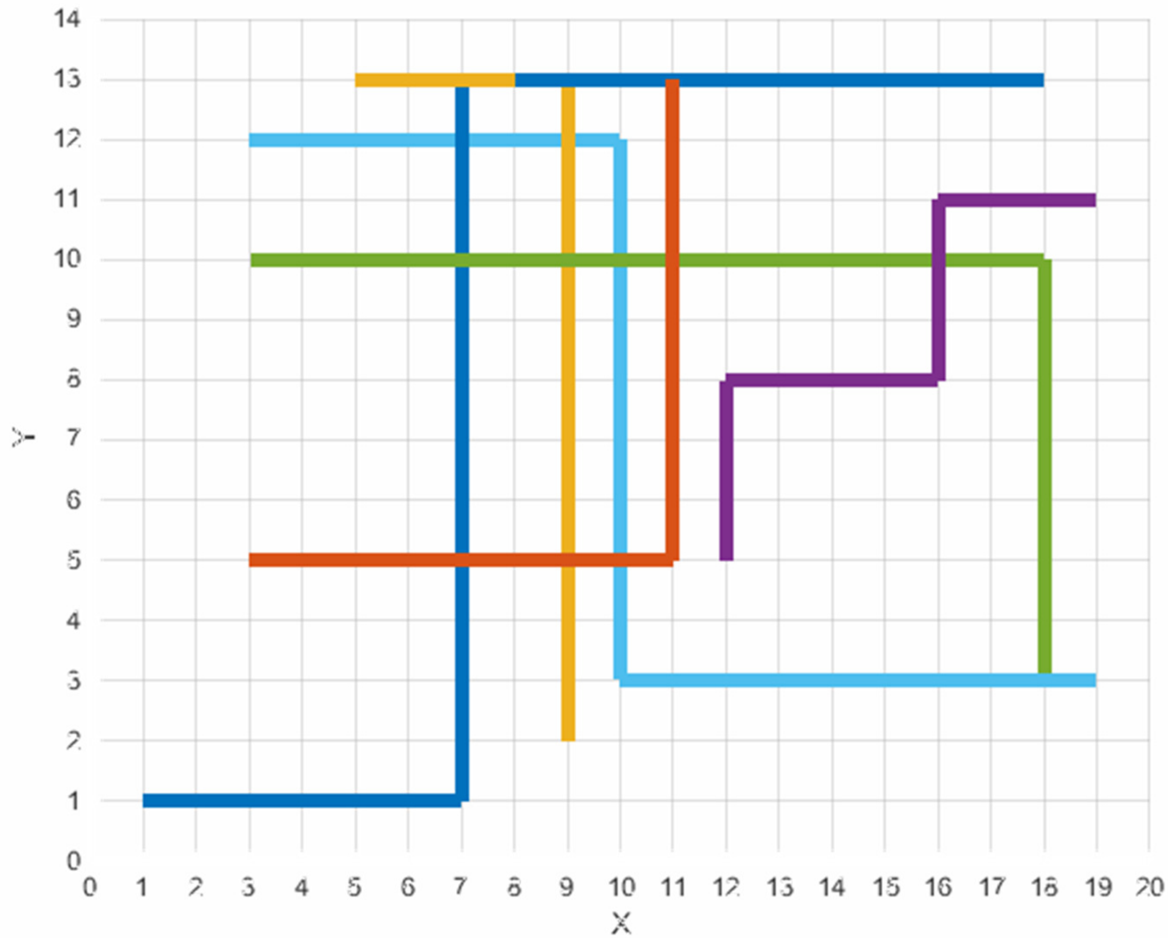
2-D Paths



2-D Paths



3-D Paths



14
13
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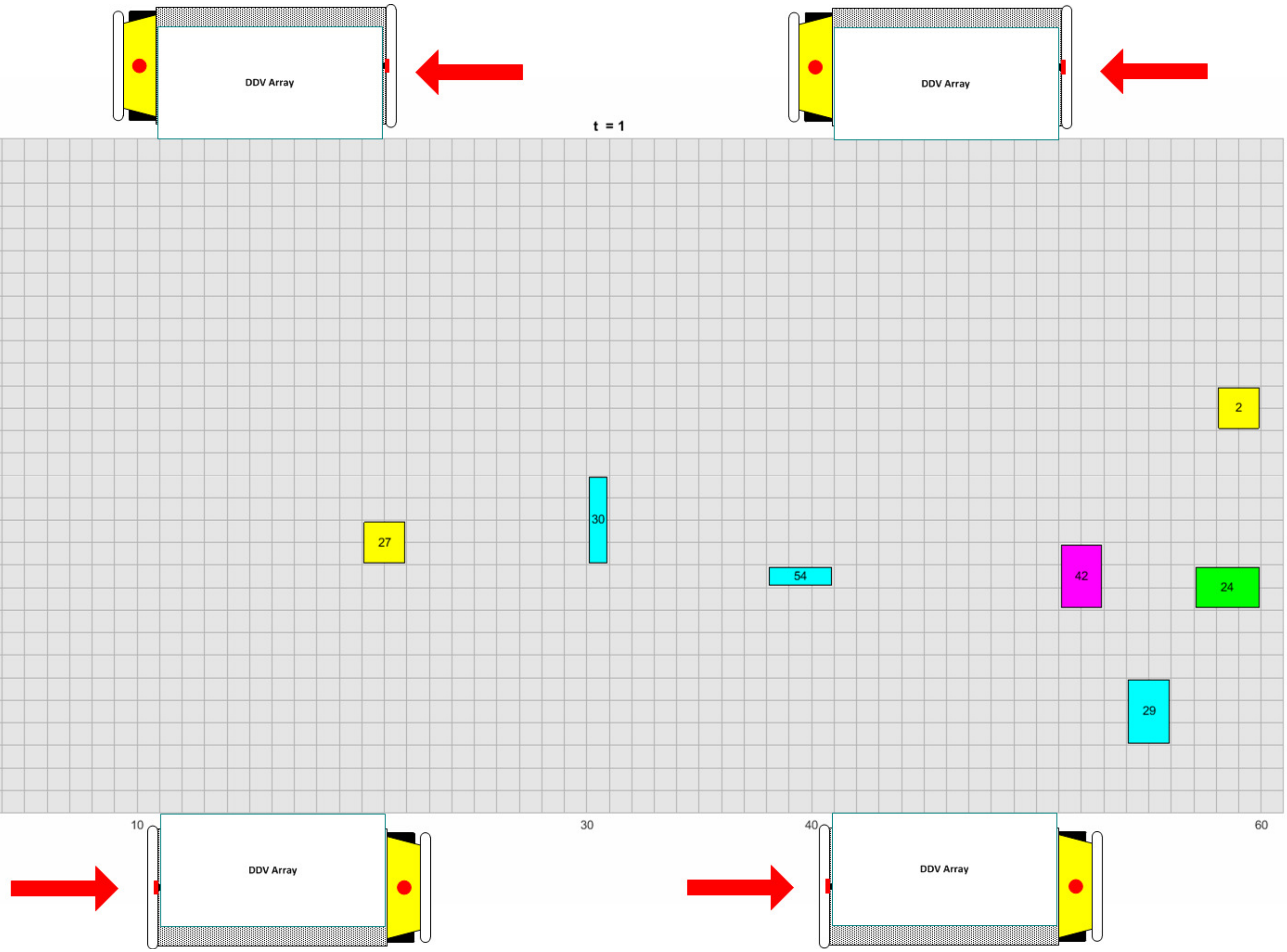
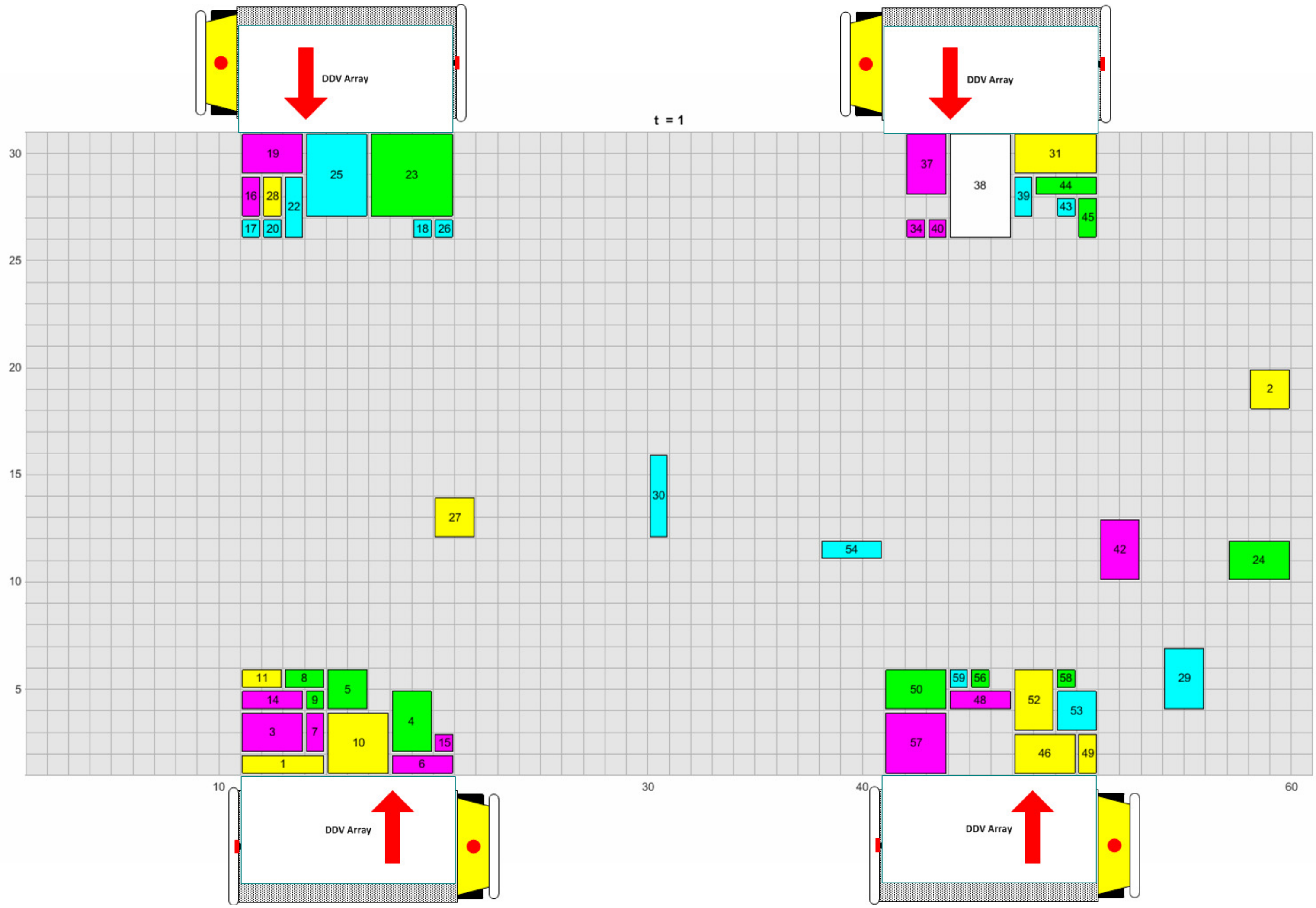
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
X

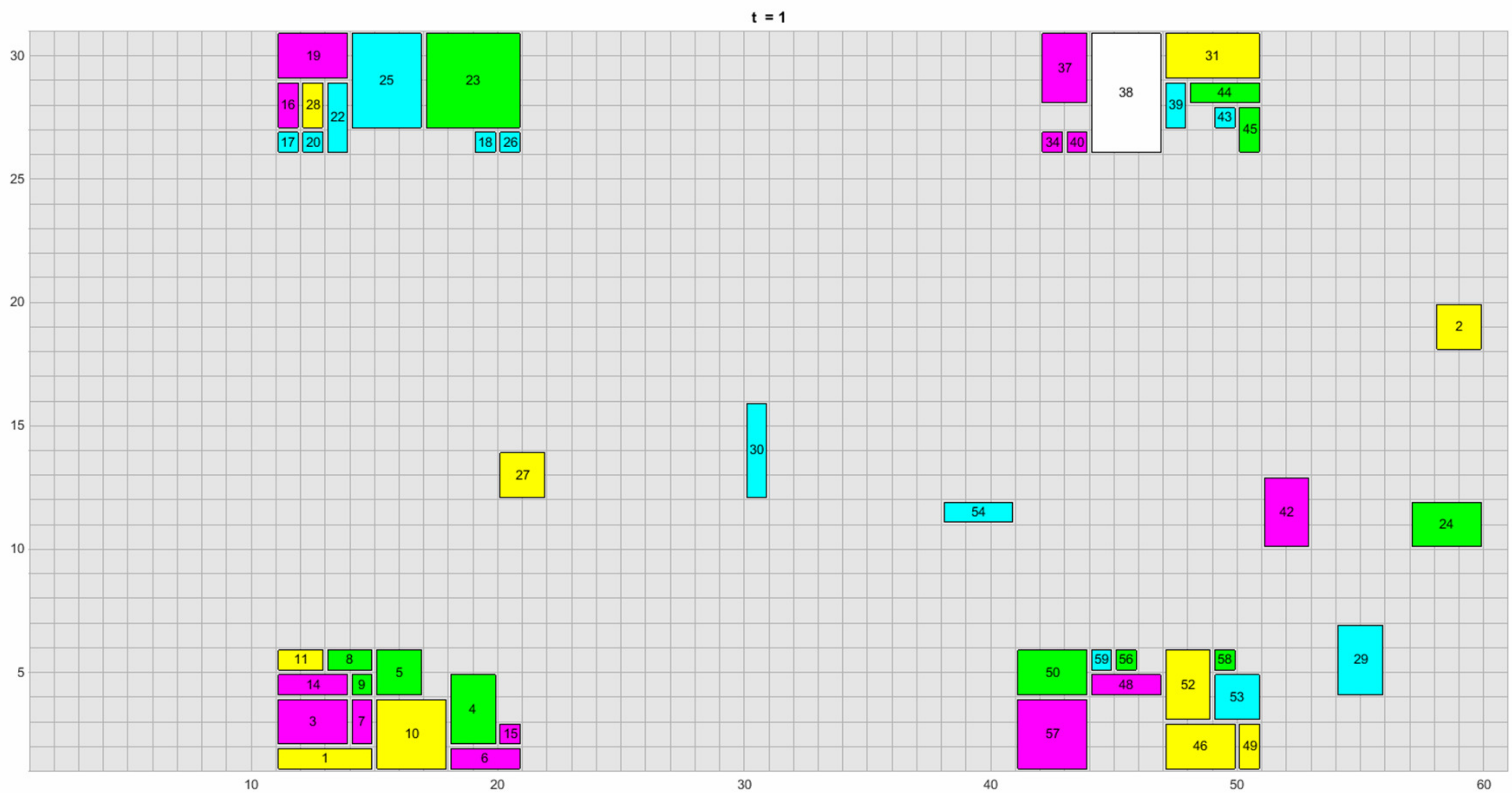
Example: Loads on DDVs Arrive to DC



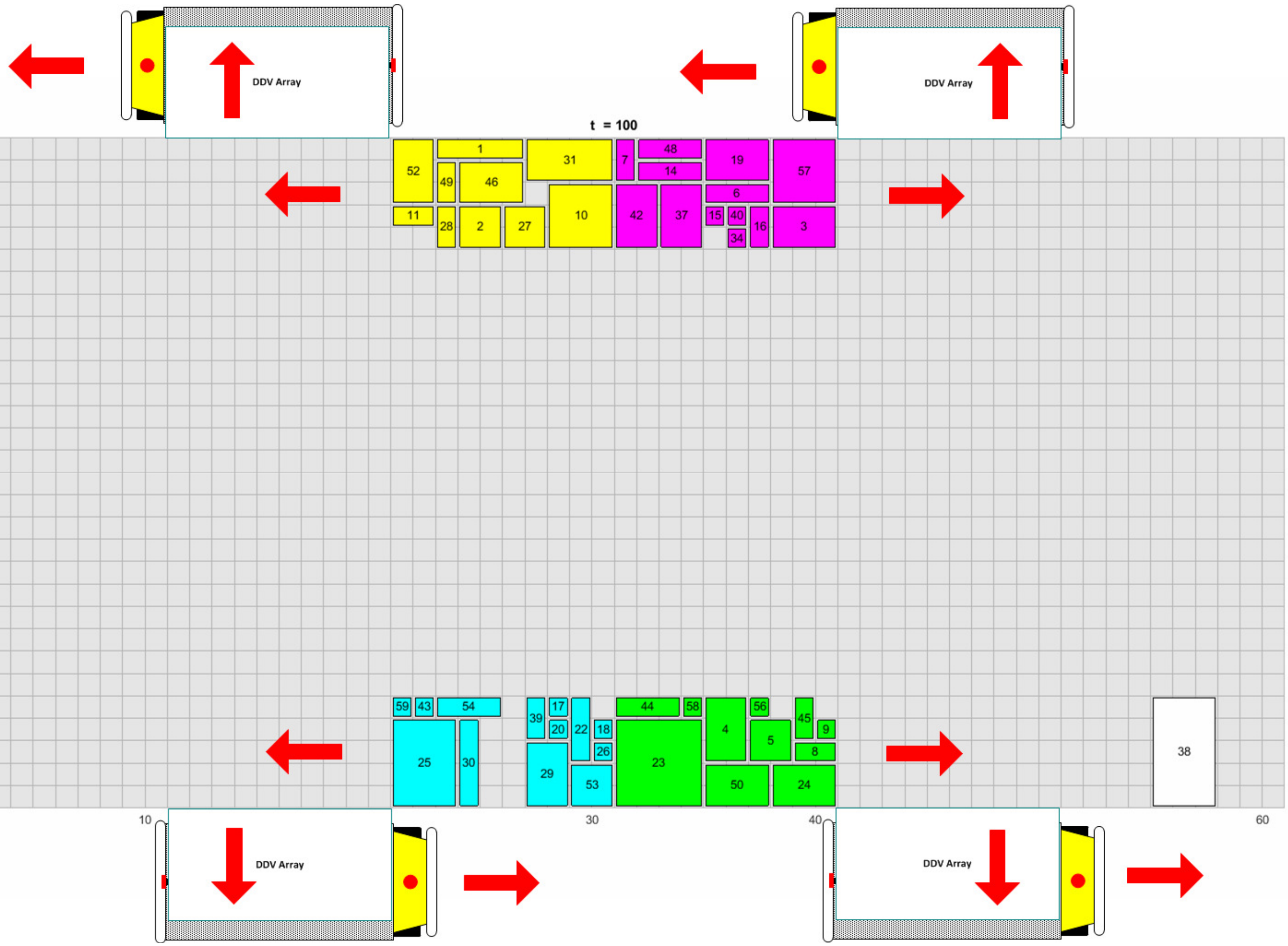
Example: Loads Unloaded into DC



Example: Containers Move to Staging



Example: Containers Loaded on DDVs



3. Coordination Mechanism

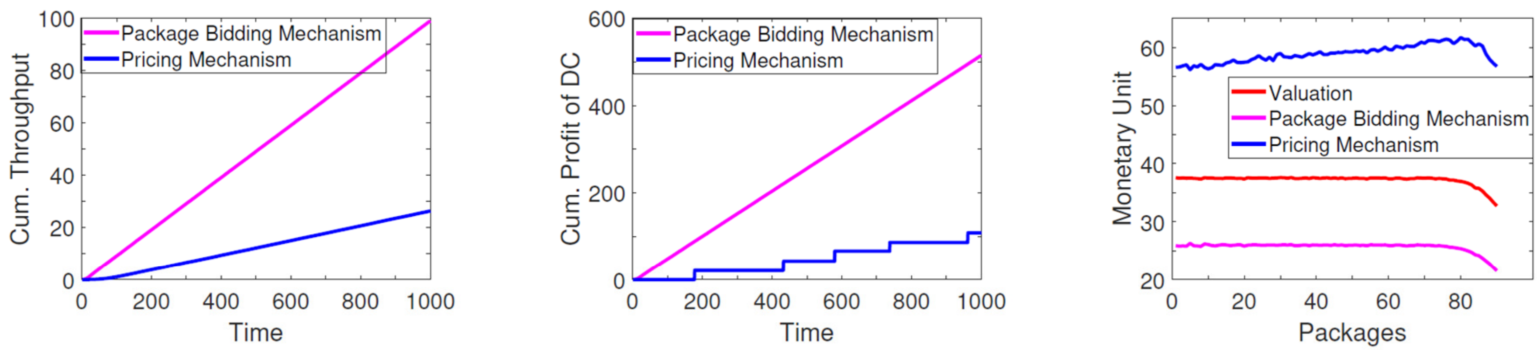
- Mechanism determines:
  – Which shipments form a load
  – How cost paid to carrier (vehicle) to transport load is allocated to shipments
- Mechanism tries to match shipments that value transport the highest with vehicles that can provide it at least cost:
  – Shipment(s) bid for transport (reverse 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

Package Bidding vs. Platform Pricing

- Exploratory analysis of participation incentives for on-demand service platform for packages:
  - Packages bid for transportation service through auction mechanisms
  - Trucks offer transportation services
  - DCs match demand and supply

Table 1: Package waiting times and trucks' earnings.

Mechanism	Average Number of Active Trucks	Average Earnings	Average Waiting Time of Packages
Platform Pricing	5.34	87.16	233 (± 119.46)
Package Bidding	22.143	93.0157	18.619 (± 18.977)

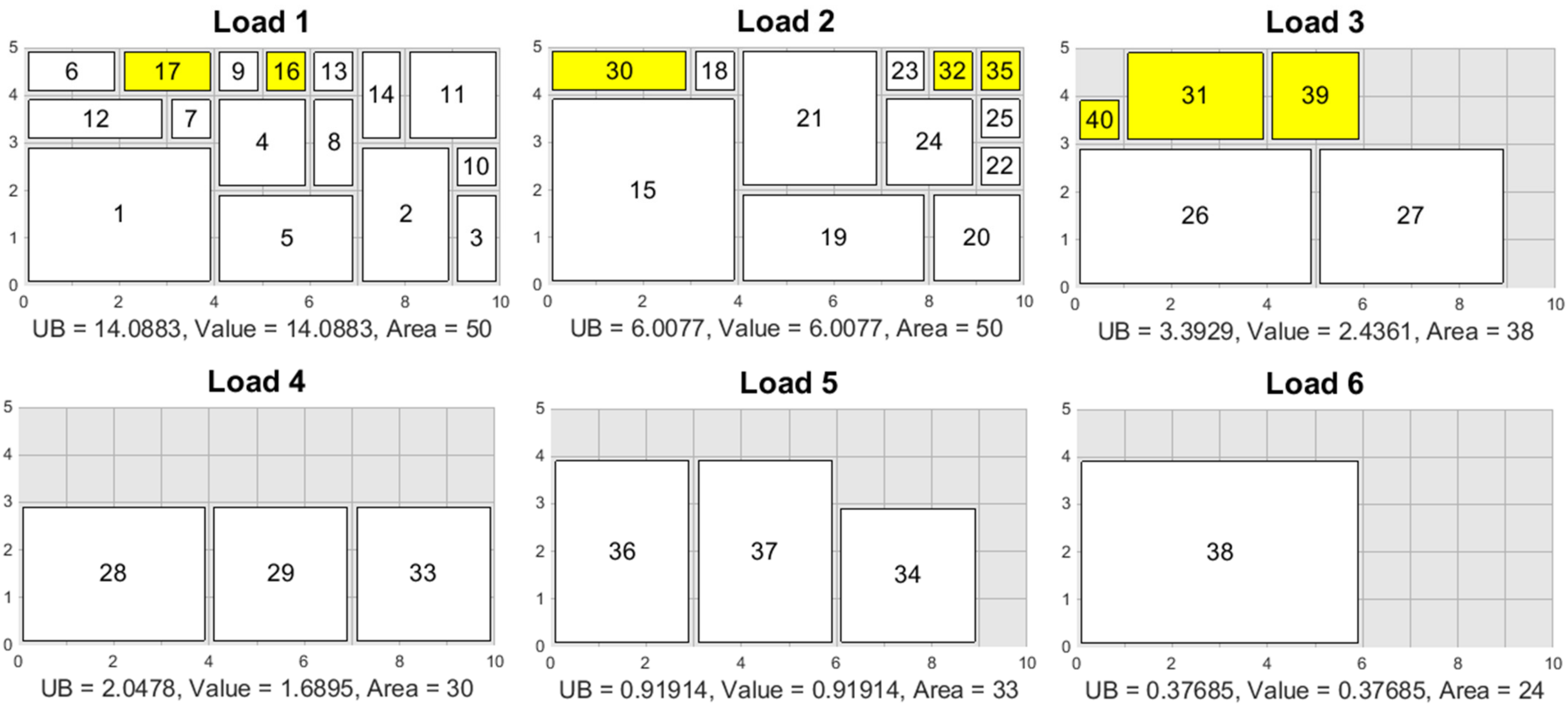


(a) (b) (c)

Figure 2: Package bid mechanism vs. platform pricing: (a) cumulative throughput at DC, (b) cumulative profit of DC, and (c) amount paid by the customer.

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)

4. Performance Analysis

Home Delivery Cost Estimate

Module Cost	L/U Time (min)	DC Space Util.	Household Demand (trips/week)															
			2								4							
			Modules per Trip								Modules per Trip							
			10				20				10				20			
				DC	**Trip**	**Mod**		**DC**	**Trip**	**Mod**		**DC**	**Trip**	**Mod**		**DC**	**Trip**	**Mod**
50	5	0.6	*1*	1.46	2.27	0.23	*9*	2.27	3.19	0.16	*17*	0.73	1.54	0.15	*25*	1.14	2.05	0.10
50	5	0.8	*2*	1.29	2.10	0.21	*10*	1.93	2.84	0.14	*18*	0.64	1.45	0.15	*26*	0.96	1.88	0.09
50	10	0.6	*3*	1.46	2.27	0.23	*11*	2.27	3.19	0.16	*19*	1.32	2.13	0.21	*27*	1.64	2.56	0.13
50	10	0.8	*4*	1.29	2.10	0.21	*12*	1.93	2.84	0.14	*20*	1.32	2.13	0.21	*28*	1.64	2.56	0.13
100	5	0.6	*5*	2.51	3.39	0.34	*13*	4.01	5.02	0.25	*21*	1.25	2.14	0.21	*29*	2.01	3.01	0.15
100	5	0.8	*6*	2.16	3.05	0.30	*14*	3.32	4.32	0.22	*22*	1.08	1.97	0.20	*30*	1.66	2.66	0.13
100	10	0.6	*7*	2.51	3.39	0.34	*15*	4.01	5.02	0.25	*23*	2.12	3.01	0.30	*31*	2.71	3.71	0.19
100	10	0.8	*8*	2.16	3.05	0.30	*16*	3.32	4.32	0.22	*24*	2.12	3.01	0.30	*32*	2.71	3.71	0.19

(DC cost in $, DC + vehicle cost = Trip cost in $, Mod = cost per module delivered in $)

Conclusion

- Biggest impact of this research is likely to result from availability of “free” backhauls from the home:
  - Recycling
  - Reusable containers
  - Presentation stock delivered to home
  - Home manufacturing

Student Researchers

- Ajithkumar Parlikad
- Ashish Jain
- Amogh Bansal
- Ling Xiang
- Peerapol Sittivijan
- Manish Tripathy
- Ekin Yalvac