Co-Simulation Based Optimization for Container Pickup and Delivery

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Outline

1. **Background**
2. Literature Review
3. Mathematical Model
4. Methodology
5. Experimental Analysis
6. Conclusion

- **Background**

Increasing Demand in Sea Transportation

- In 2021, Ports of Los Angeles and Long Beach handled about 20 million TEUs.

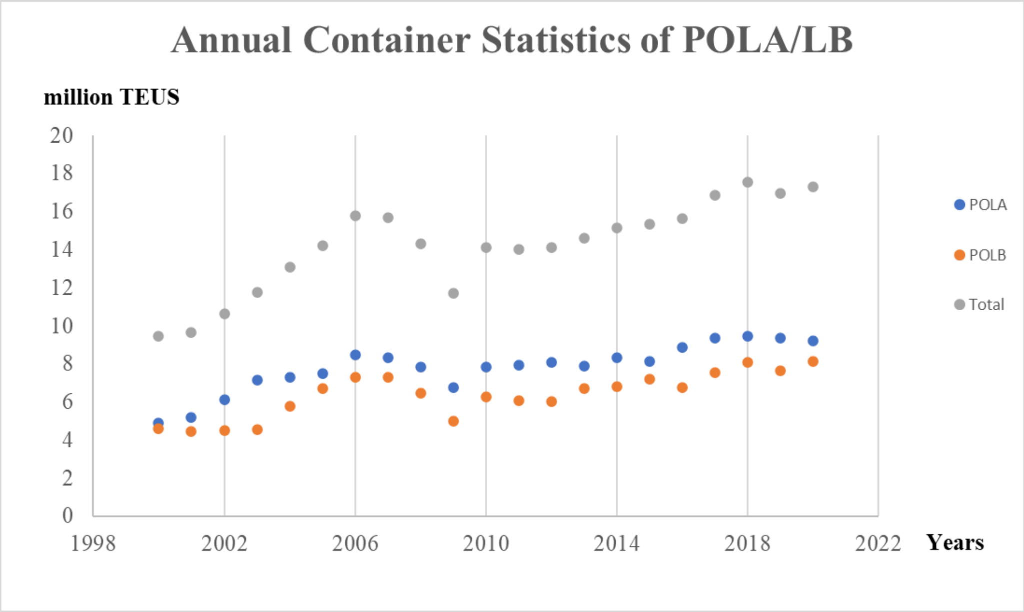

Figure 1. San Pedro Bay Area Container Statistics

- **Background**

Suppose 40% of the containers were carried by rail; there are still about 10 thousand units of containers that needs to be transported daily in San Pedro Bay area, causing traffic congestion and air pollution.

Therefore, how to manage freight traffic efficiently in urban centers is an urgent issue.

Figure 2. Traffic Congestions on I-710 and I-5

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- **Literature Review**

This study focuses on the regional container pickup and delivery problem with predetermined supply and demand on a flow-dependent dynamic transportation network.

Topics related to freight operation problems:

1. Multi-Commodity Network Flow
   Dorneles et al., 2017; Fakhri and Ghatee, 2014; Kuiteing et al., 2018; Letchford and Salazar-González, 2015; Masri et al., 2015; Moradi et al., 2015
2. System Optimal Dynamic Traffic Assignemnt
   Peeta and Mahmassani, 1995; Shen et al., 2006 Zhang and Qian, 2020
3. Simulation Models
   Mahmassani, 2001; Mahmassani et al., 2007; Zhou et al., 2008
4. Load-Balancing Approachs
   Abadi et al., 2016; Zhao et al., 2018; Chen et al., 2021

Research Gap & Contribution

1. Introduce traffic simulator into traditional optimization loop to better approximate network dynamics caused by traffic flows.
2. Enable truck reuse by extending load-balancing approach with touring

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- **Mathematical Model**

Model Assumptions

The problem is defined on a transportation network $G = (N, A)$.

The demand ($d_{i,j}$) from location i to j is predetermined, which needs to be satisfied by the end of the day.

All the trucks start from the depot (with the location index 0) and return to the depot by the end of the day.

The study horizon is discretized into $|K|$ intervals.

Terminologies:

(1) *trip* is defined as a truck going from one location to another;

(2) *truck routing* represents the routing decision (which roads to travel on) for a trip;

(3) *truck touring* represents the sequence of trips for trucks in the study horizon;

(4) *delivery flows* are the aggregated truck trips carrying containers;

(5) *pickup flows* are the aggregated truck trips without carrying containers.

- **Mathematical Model**

Notation

a The index of the arcs set, $a \in A$;

k The index of the time interval, $k \in K$;

$d_{i,j}$ The demand from location i to location j in number of containers, $i, j \in N$;

$R_{i,j}$ The candidate route set for location i to j with index r;

$x^r_{i,j,k}$ The delivery flow from location i to location j using route r leaving at time k;

$y^r_{i,j,k}$ The pickup flow from location i to location j using route r leaving at time k;

$c^r_{i,j,k}$ The travel cost from location i to j using route r leaving at time k, $r \in R_{i,j}$;

λ The weighting factor for the travel cost and the truck cost;

$p_{i,k}$ The delivery flow leaving location i at time k;

$q_{j,k}$ The cumulative delivery flow that has arrived at location j by time k;

- # Mathematical Model

Pickup and Delivery Problem with Dynamic Transportation Network (PDPDTN)

$$\underset{x^r_{i,j,k}, y^r_{j,i,k}}{\text{minimize}}\ \lambda \sum_{i\in N}\sum_{k\in K}\sum_{r\in R_{0,i}} y^r_{0,i,k} + \sum_{i\in N}\sum_{j\in N}\sum_{k\in K}\sum_{r\in R_{i,j}} x^r_{i,j,k}\cdot c^r_{i,j,k} + \sum_{j\in N}\sum_{i\in N}\sum_{k\in K}\sum_{r\in R_{j,i}} y^r_{j,i,k}\cdot c^r_{j,i,k} \quad (1)$$

Truck employment costs + travel costs

Subject to

$$d_{i,j} = \sum_{k\in K}\sum_{r\in R_{i,j}} x^r_{i,j,k} \qquad \forall i\in N, j\in N \quad (2)$$

Demand constraint

$$p_{i,k} = \sum_{j\in N}\sum_{r\in R_{i,j}} x^r_{i,j,k} \qquad \forall i\in N\backslash\{0\}, k\in K \quad (3)$$

$$q_{j,k} = \sum_{i\in N}\sum_{r\in R_{i,j}}\sum_{\tau\le k} x^r_{i,j,\tau}\cdot \phi^r_{i,j,\tau,k} \qquad \forall j\in N\backslash\{0\}, k\in K \quad (4)$$

$$q_{j,k} \ge \sum_{\tau\le k}\sum_{i\in N}\sum_{r\in R_{j,i}} y^r_{j,i,\tau} \qquad \forall j\in N\backslash\{0\}, k\in K \quad (5)$$

$$\sum_{\tau\le k} p_{i,\tau} \le \sum_{j\in N}\sum_{r\in R_{j,i}}\sum_{\tau\le k} y^r_{j,i,\tau}\cdot \bar{\phi}^r_{j,i,\tau,k} \qquad \forall i\in N\backslash\{0\}, k\in K \quad (6)$$

$$\sum_{j\in N\backslash\{0\}}\sum_{k\in K}\sum_{r\in R_{j,0}} y^r_{j,0,k} = \sum_{i\in N\backslash\{0\}}\sum_{k\in K}\sum_{r\in R_{0,i}} y^r_{0,i,k} \quad (7)$$

Flow conservation constraints

$$x^r_{i,j,k}\in Z^{0+} \qquad \forall i\in N, j\in N, k\in K, r\in R_{i,j} \quad (8)$$

$$y^r_{i,j,k}\in Z^{0+} \qquad \forall i\in N, j\in N, k\in K, r\in R_{i,j} \quad (9)$$

Domain constraints

- ## Mathematical Model

Due to the complexity of the transportation network and the nonlinear relationship between the traffic flows and the network conditions, it is hard to explicitly express the binary indicators $\phi^r_{i,j,\tau,k}$ and $\bar{\phi}^{\,r}_{j,i,\tau,k}$. Therefore, instead of using analytical expressions for these functions, we use simulation models to approximate transportation network states.

Remark:
$\phi^r_{i,j,\tau,k} = 1$ if and only if the delivery flow from i to j leaving at time τ with route r is available for another delivery task at time k.
$\bar{\phi}^{\,r}_{j,i,\tau,k} = 1$ if and only if the pickup flow from i to j leaving at time τ with route r is available for another delivery task at time k.

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- **Methodology**

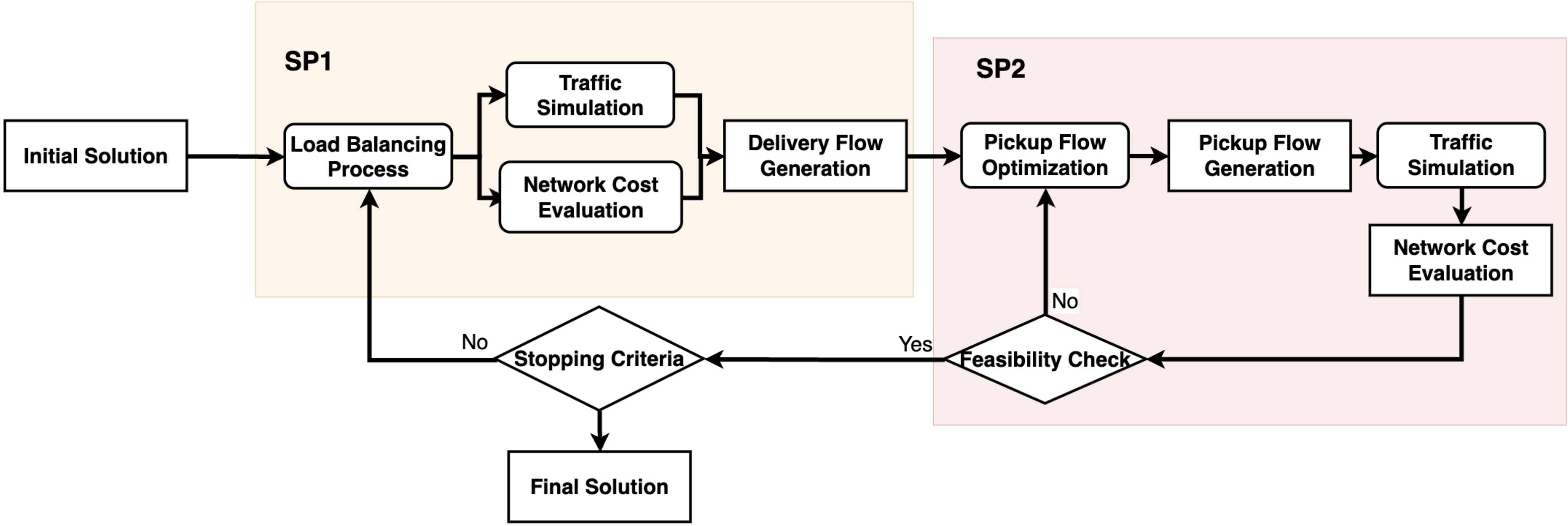
Problem Decomposition:

PDPDTN

- SP1
  finding the least-cost flows for a DTA problem
  - We only solve the delivery flows ($x^{r}_{i,j,k}$) in the dynamic transportation network.
- SP2
  finding the minimum cost pickup flows for current delivery flows
  - Based on the delivery flow solution, we find the best pickup flow solution ($y^{r}_{i,j,k}$) that can support the delivery flow solution.

- **Methodology**

Solution Framework

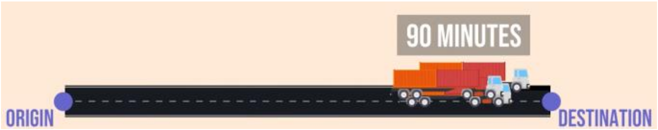


- **Methodology**

Load Balancing Process

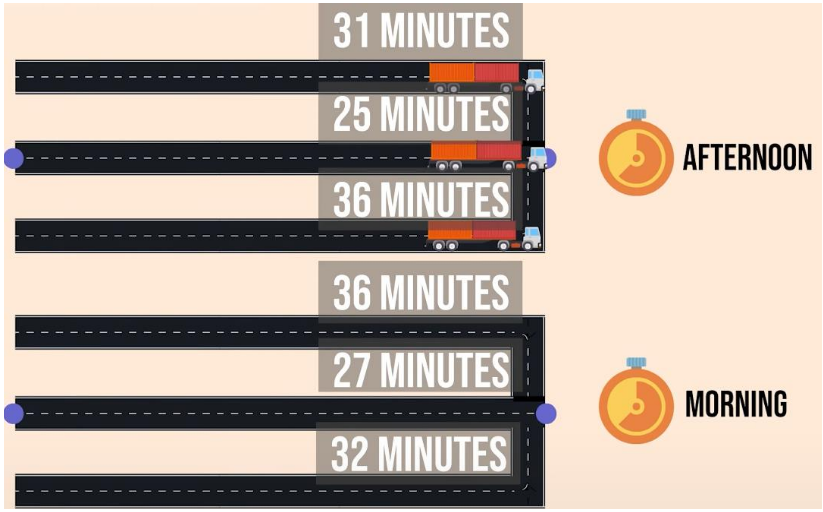
The intuition for the Load Balancing Process is to distribute demand across the transportation network over the study horizon, ensuring no single set of paths bears too much demand.

Single Path



Multiple Paths

Multiple Paths & Time Interval



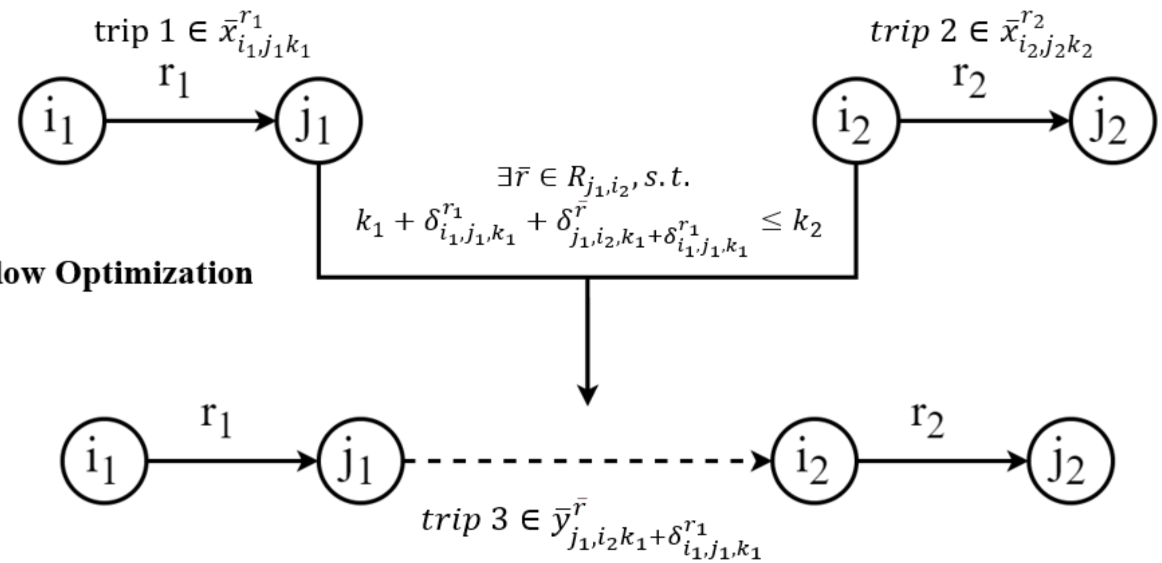
- **Methodology**

Pickup Flow Optimization

The intuition for the Pickup Flow Optimization is the following:

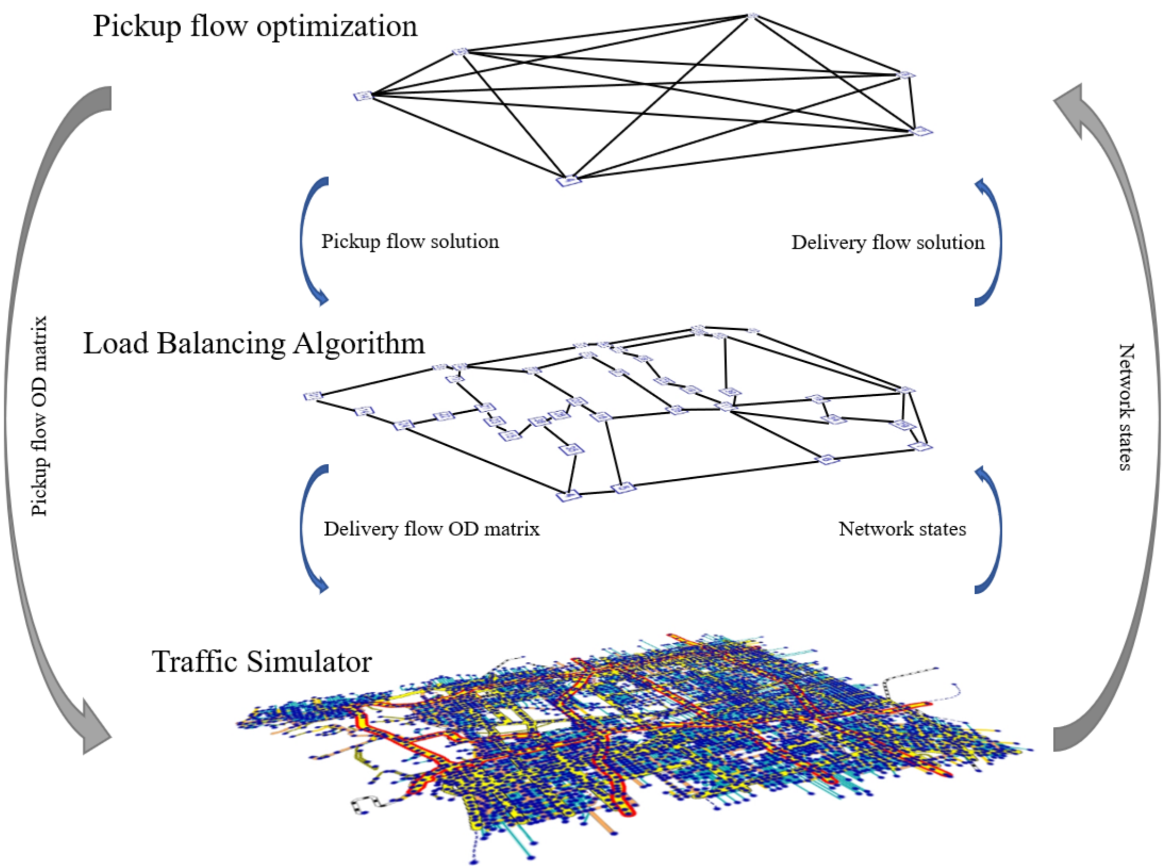
Phase 1: Load Balancing Process

Phase 2: Pickup Flow Optimization



- **Methodology**

Data Flow in the Framework



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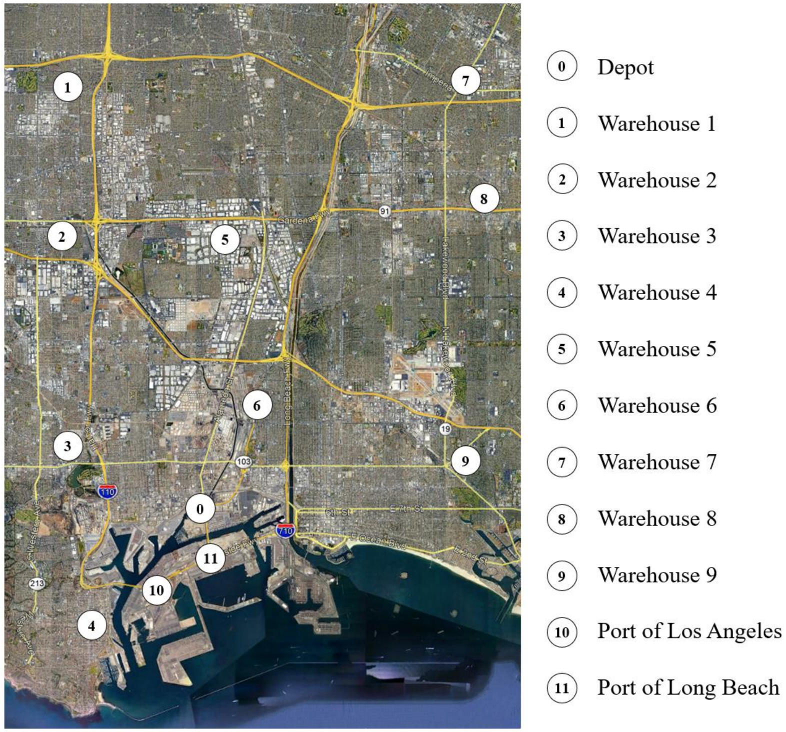
• Experimental Analysis

Study Area



Parameters

Parameter name	Parameter value
Daily horizon	10 hours
Time interval	15 minutes
Ports' service time	1 hour
Warehouses' service time	30 minutes
Weighting factor λ	\$50/truck
Stopping threshold ϵ	\$100
Maximum running time T_{cap}	8 hours

Most of the parameters are learned from Zhao et al., (2018) and adjusted based on our dataset from Giuliano et al., (2021).

Stopping Criteria:

(1) the maximum running time (T_{cap}) is reached;

(2) the difference of the system costs between two iterations is smaller than a threshold (ϵ).

- **Experimental Analysis**

Testing Platform

(1) Traffic simulator:
Visum 17

(2) Programming Language
Python 3.6

(3) Solver
Gurobi 9.1.2

(4) Hardware
a virtual machine with 8-core 3.70 GHz CPU and 16 GB of memory

Solution Approaches:

Approach 1: Only use Load Balancing Process to solve the problem;

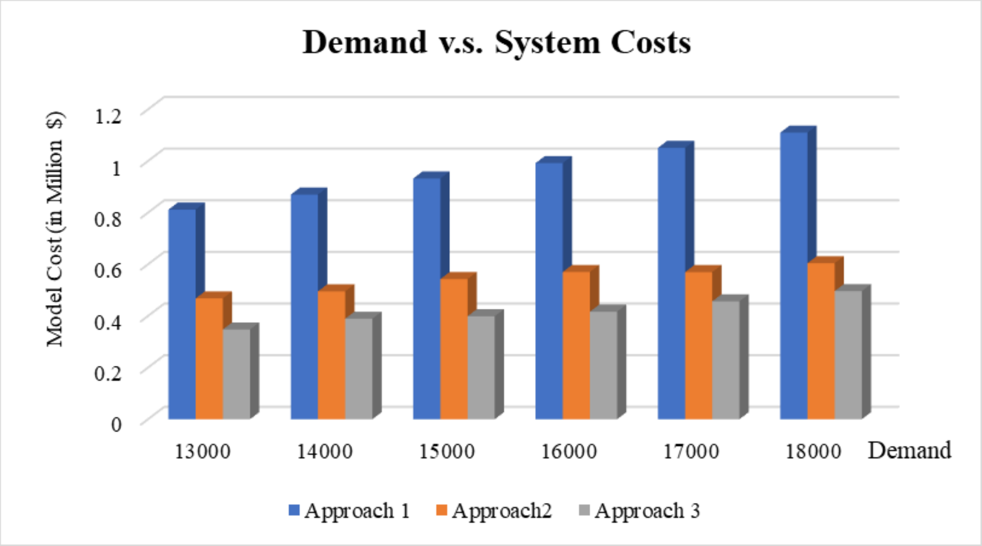
Approach 2: Optimize Pickup flow once after getting solution from the Load Balancing Process;

Approach 3: Iteratively solve the problem using the framework.

- ## Experimental Analysis

Numerical Results

Demand	Approach 1			Approach 2			Approach 3		
	Number of Trips Leaving the Depot	Truck Travel Distance (mi)	Truck Travel Time (hr)	Number of Trips Leaving the Depot	Truck Travel Distance (mi)	Truck Travel Time (hr)	Number of Trips Leaving the Depot	Truck Travel Distance (mi)	Truck Travel Time (hr)
13000	13000	294739	6464	6022	282380	6664	4022	265217	5853
14000	14000	307711	6796	6447	284632	6914	4446	284037	6671
15000	15000	322203	7278	7062	308658	7576	4324	306701	7307
16000	16000	338802	7666	7493	311892	7815	4572	311125	7516
17000	17000	356554	8028	7408	322741	7966	5308	321333	7645
18000	18000	371415	8389	7804	333261	8553	5858	332797	8121



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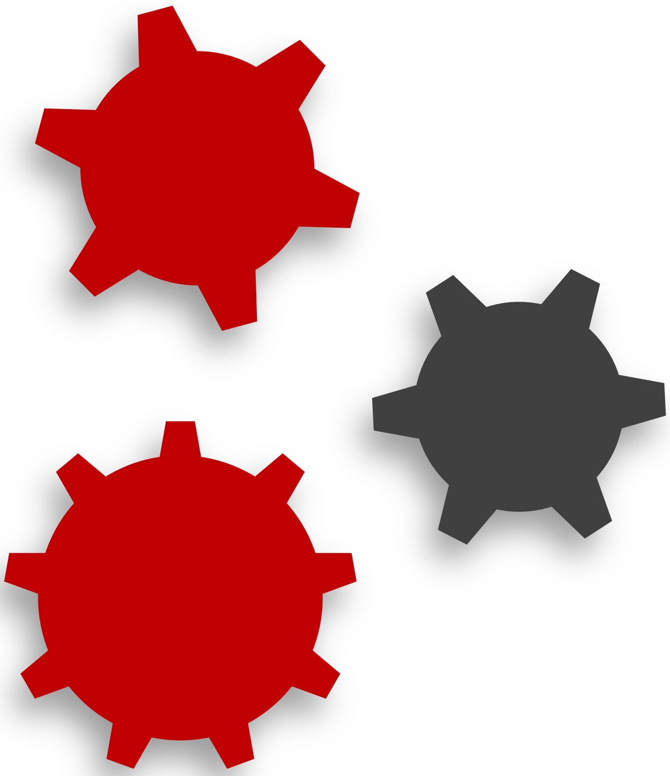

- By performing pickup flow optimization once, the system cost can be reduced by 41 to 46%.

- By iteratively optimizing delivery flow and pickup flow, the system cost can be further decreased by about 20%.

- Experimental analysis on actual data shows the effectiveness of the proposed approach in reducing the system costs compared to other approaches.

Thank you for listening & watching!