A Hierarchical Co-Simulation Optimization Control System for Multimodal Freight Routing

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Introduction

- Multimodal Network Freight Routing
  - High concentration of passenger and freight traffic
    - Non-homogeneous traffic and complex interactions
  - Incidents, accidents, disruptions
    - Capacity shortage, load imbalances, environment

- COSMO (CO-SiMulation Optimization) Approach Application

Los Angeles/Long Beach Ports

Service Graph
Problem Formulation

- Service Graph and Traffic Network
  - Hard freight vehicle availability constraints
  - Bi-level optimization
Problem Formulation

Problem Formulation in Service Graph

\[
\min TC(X) = \sum_{k \in K} \sum_{i \in I} \sum_{j \in J} S^r_{i,j}(k) X^r_{i,j}(k)
\]

\[
= \sum_{k \in K} \sum_{i \in I} \sum_{j \in J} \sum_{e \in \mathcal{E}_{i,j}} (C^r_{i,j}(k) + \kappa_k T^r_{i,j}(k)) X^r_{i,j}(k)
\]

subject to

\[
\sum_{k \in K} X^r_{i,j}(k) = d_{i,j}, \quad \text{for } \forall i \in I, \forall j \in J
\]

\[
\sum_{i \in I} \sum_{j \in J} \sum_{k \in K} X^r_{i,j}(k) \delta_{l,r,r,k} = x_l(k), \quad \text{for } \forall l \in L, \forall k \in K
\]

\[0 \leq x_l(k) \leq u_l(k) v_l(k) \quad \text{for } \forall l \in L^k, \forall k \in K\]

\[X^r_{i,j}(k) \geq 0\]
Problem Formulation in Traffic Network

\[ \min \sum_{k \in K} \sum_{l \in L} \sum_{p \in P_l} (c^p_l(k) + \eta^p_l t^p_l(k)) y^p_l(k) \]

subject to

\[ z_a(k+1) = f_a(z_a(k), q_a(k), Y(k), k), \text{ for } \forall a \in A, \forall k \in K \]

\[ W(k) = g(Z(k), k), \text{ for } \forall k \in K \]

\[ t^p_l(k) = \sum_{n_p=1}^{N_p} w_{a_p,n_p} e_{a_p,n_p}(k) \]

\[ \sum_{p \in P_l} y^p_l(k) = x_l(k), \text{ for } \forall l \in L, \forall k \in K \]

\[ y^p_l(k) \geq 0 \text{ for } \forall l \in L, \forall p \in P_l, \forall k \in K \]

given \( X \)

- \( y^p_l(k) \) – Decision Variable, The freight demand using vehicle path \( p \) with a departure time \( k \);
- \( c^p_l(k) \) - Non-travel time cost of vehicle setup & usage
- \( t^p_l(k) \) - Travel time of vehicle path \( p \)
- \( \eta^p_l \) - Value of time of vehicle path \( p \)

Traffic volume dynamical function
Travel time dynamical function
Path travel time
Assign service link demand to available vehicle paths

Traffic Network

Road Node
Road Arc
Rail Node
Rail Arc
Problem Formulation in Traffic Network

\[
\min \sum_{k \in K} \sum_{l \in L} \sum_{p \in P_l} (c^p_l(k) + \eta^p_l t^p_l(k)) y^p_l(k)
\]

subject to

\[
z_a(k+1) = f_a(z_a(k), q_a(k), Y(k), k), \quad \text{for } \forall a \in A, \forall k \in K
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\[
W(k) = g(Z(k), k), \quad \text{for } \forall k \in K
\]

\[
t^p_l(k) = \sum_{n_p=1}^{N_p} w_{a_p,n_p} \left(e_{a_p,n_p}(k)\right)
\]

\[
\sum_{p \in P_l} y^p_l(k) = x_l(k), \quad \text{for } \forall l \in L, \forall k \in K
\]

\[
y^p_l(k) \geq 0 \quad \text{for } \forall l \in L, \forall p \in P_l, \forall k \in K
\]

given \(X\)

Traffic volume dynamical function

Travel time dynamical function

Path travel time

Assign service link demand to available vehicle paths
Solving with COSMO

Incremental Penalty Method

\[ \min J(X) = TC + \sum_{k \in K} \sum_{l \in L^R} \sigma_l \phi_l(x_l(k), u_l(k), v_l(k)) \]

\[ \sum_{k \in K} \sum_{l \in L^R} X_{i,j}^l(k) = d_{i,j}, \quad \text{for} \, \forall i \in I, \forall j \in J \]

\[ \sum_{l \in L^R} \sum_{(i,j) \in E} X_{i,j}^l(\tau) \delta_{i,j,\tau} = x_l(k), \quad \text{for} \, \forall \tau \in T, \forall k \in K \]

\[ 0 \leq x_l(k) \leq u_l(k)v_l(k), \quad \text{for} \, \forall l \in L, \forall k \in K \]

\[ X_{i,j}^l(k) \geq 0 \]

given \( d_{i,j} \), \( u_l(k), v_l(k) \), for \( \forall i \in I, j \in J, l \in L, k \in K \)

- Set initial penalty factors;
- Solve relaxed problem with given penalty factors;
- Update penalty factors until algorithm terminates.
Solving with COSMO

Incremental Penalty Method

\[ \min J(X) = TC + \sum_{k \in K} \sum_{l \in L^R} \sigma_l \phi_l \left( x_l(k), u_l(k), v_l(k) \right) \]

- Step 1: Set initial solution;
- Step 2: Update link costs with simulation models;
- Step 3: Find routes with min marginal cost;
- Step 4: Check for convergence;
- Step 5: Load balancing with new found routes
Load Balancing with new found minimum routes
- Formulate an auxiliary solution $X^{(m)}_{Aux}$ in $m$th iteration
- Generate a new solution $X^{(m+1)} = X^{(m)} + \alpha^{(m)} \left( X^{(m)}_{Aux} - X^{(m)} \right)$

Step Size Selection
- Enumeration method – very slow
- MSA (Moving successive average)
  $$\alpha^{(m)} = \frac{1}{m}$$
- Optimal step size
  $$\alpha^{(m)} = \arg \min_{\alpha^{(m)} \in [0,1]} J\left( X^{(m)} + \alpha^{(m)} \left( X^{(m)}_{Aux} - X^{(m)} \right) \right)$$
- Step sizes for all OD demand are same
- May generate new load imbalances
Step Size Selection with Priority

\[
\alpha_{i,j}^{(m)} = \min \left\{ \alpha_{\text{max}}, \sum_{(i,j)} \alpha^{(m)} \frac{\text{std}(d_{i,j})}{\sum_{(i,j)} \text{std}(d_{i,j})} \right\}
\]

\(\text{std}(d_{i,j})\): is the standard deviation of the marginal cost of all the used routes by demand \(d_{i,j}\).

- Reduce unnecessary load imbalance
- Speed-up overall optimization process
Experimental Analysis

- **Physical Network**
  
  About 80 square miles near the Port of LA/LB
  
  Road network with 12824 links and 4747 nodes
  
  Rail network with 5 stations

- **Simulation Testbed**
  
  Road Model with VISUM + Dynamic Assignment
  
  Rail Model with Arena + Deadlock-free Dispatching
**Evaluation Scenario**

Origin and Baseline Supply:
3 terminals A (1020), B(1020), C(1020)

Destinations and Baseline Demand:
D1 (350), D2(450), D3(400), D4(600), D5(700), D6(560)

Train Availability:
A->TS1: 6; B->TS1: 2; C->TS1: 4; TS1->TS2: 10.

Three Step Size Methods:
1. MSA with Priority
2. Optimal Step Size
3. Optimal Step Size with Priority

A Cost Decreasing Example of Fixed Penalty Factors in COSMO
Experimental Analysis

<table>
<thead>
<tr>
<th>Traffic Condition</th>
<th>MSA with Priority</th>
<th>Optimal Step</th>
<th>Optimal Step with Priority</th>
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A hierarchical Co-Simulation Optimization control system is proposed to solve the regional freight flow routing problem considering hard vehicle availability constraints;

A load balancing algorithm based on novel step size selection method considering supplier priority is presented to speed up the optimization convergence;

A multimodal transport testbed adjacent to the Los Angeles/Long Beach Ports is developed to demonstrate the performance of the proposed methodologies.
Thank you
Find Minimum Cost Routes with Simulation Outputs

\[ MCP_{l'}^{p'} (k') = \frac{\partial TC}{\partial y_{l'}^{p'} (k')} = \frac{\partial \sum_{k \in K} \sum_{l \in L} \sum_{p \in P_l} (c_{l'}^{p'} (k) + \eta_{l'}^{p'} t_{l'}^{p'} (k)) y_{l'}^{p'} (k)}{\partial y_{l'}^{p'} (k')} \]

\[ = c_{l'}^{p'} (k') + \eta_{l'}^{p'} t_{l'}^{p'} (k') + \sum_{k \in K} \sum_{l \in L} \sum_{p \in P_l} \eta_{l'}^{p'} y_{l'}^{p'} (k) \frac{\partial t_{l'}^{p'} (k)}{\partial y_{l'}^{p'} (k')} \]

\[ MCP_{l'}^{p'} (k') \approx c_{l'}^{p'} (k') + \eta_{l'}^{p'} t_{l'}^{p'} (k') + \]

\[ \sum_{n_{p'}=1}^{N_{p'}} \left( \eta_{l'}^{p'} y_{l'}^{p'} \left( e_{a_{p'},n_{p'}} (k') \right) \right) \frac{1}{\nu_{l'} \left( e_{a_{p'},n_{p'}} (k') \right) \Delta t} \frac{\partial w_{a_{p'},n_{p'}}}{\partial z_{a_{p'},n_{p'}}} \left( e_{a_{p'},n_{p'}} (k') \right) \]

for \( \forall l' \in L, \forall p' \in P_{l'}, \forall k' \in K \)

Shortest route problem with marginal link cost