Improved Integer Programming-Based Neighborhood Search for LTL Load Plan Design

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What to remember

1. Load planning for LTL trucking, a problem of *service network design*, has grown in complexity
2. New tools needed for load planning
   - Faster transit times
   - Service requirements
3. Our approach
   - Detailed time-expanded network model
   - Very large path-selection IP with intree constraints
   - IP-based neighborhood search solution approach
4. Results
   - *Intree* neighborhood search: 3-5% $ savings
   - *New or old tree* neighborhood search: 35-40% $ savings

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- Transports shipments from multiple origins to destinations
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  - Trailer-to-trailer freight transfer: crossdocking
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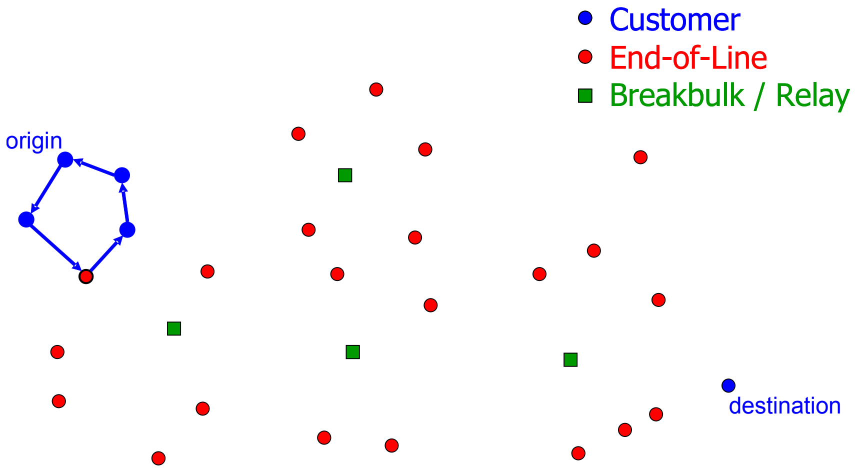
- High-volume operations
  - Each week, a large US carrier
    - Moves hundreds of millions lbs freight
    - Hauls trailers millions of miles
    - Spend millions of dollars on linehaul operation

LTL Operations

LTL Operations



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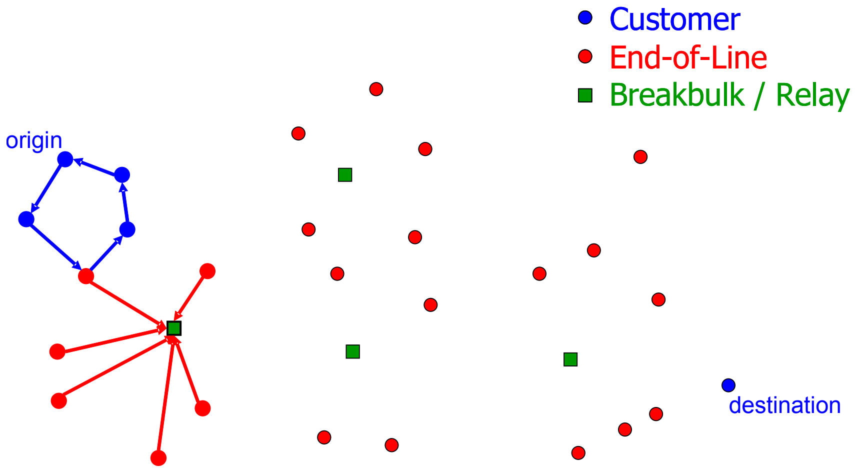

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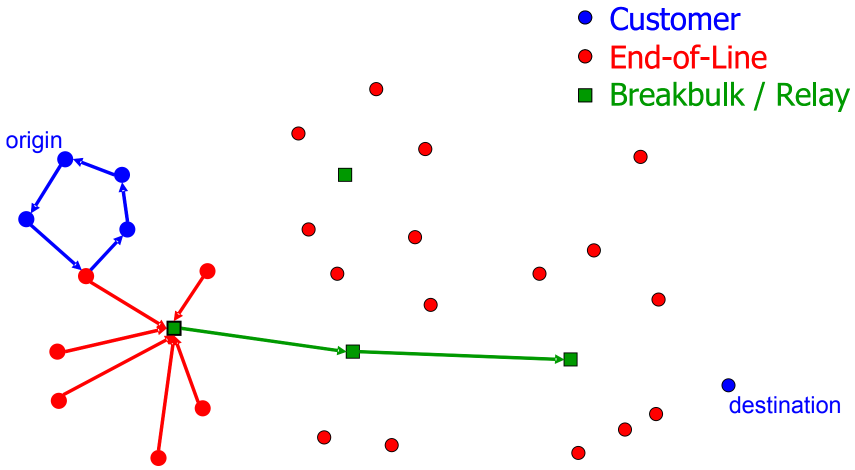

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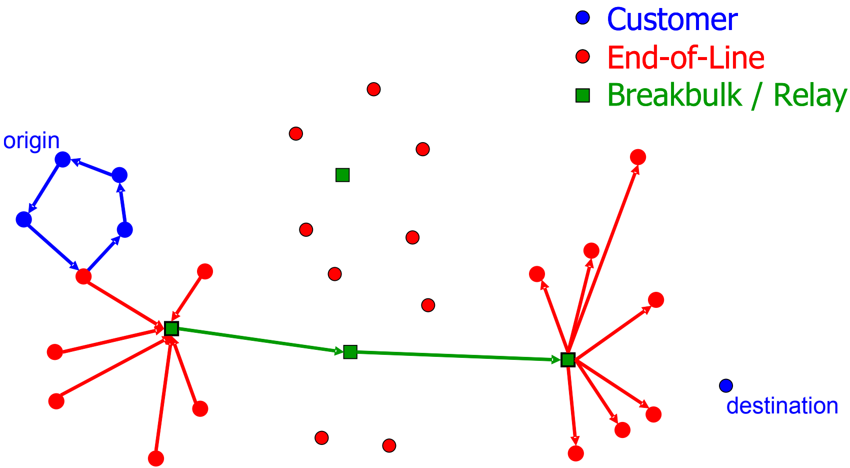

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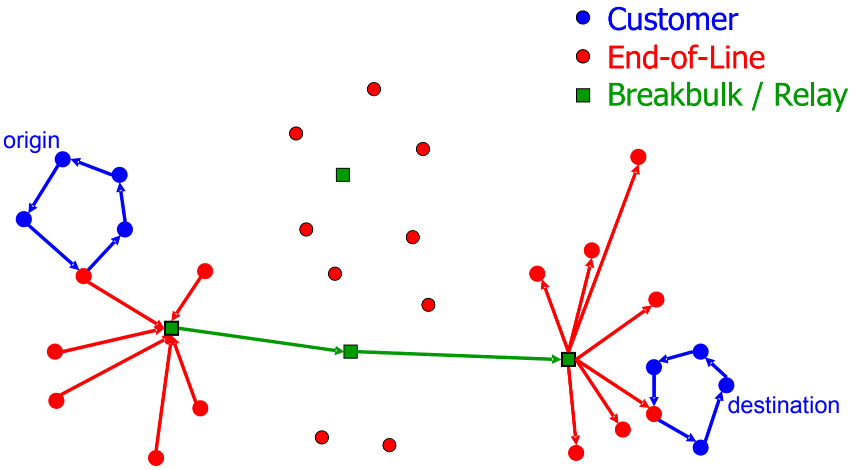

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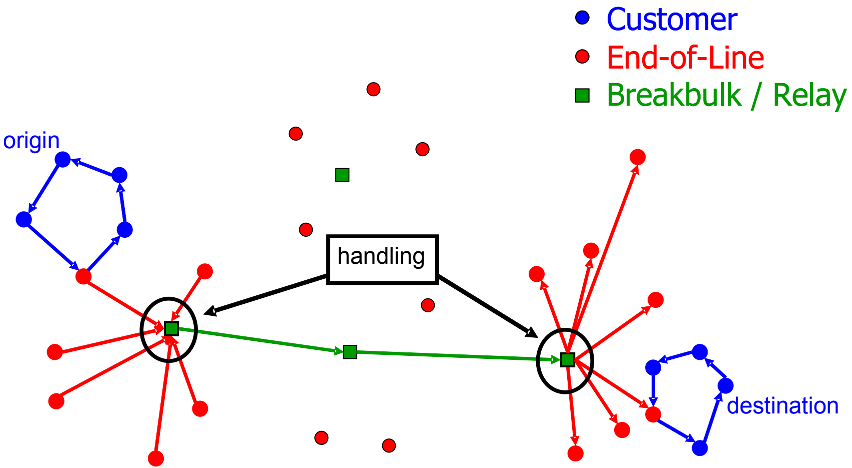

LTL linehaul service network design

Load planning

Given:

- Terminal locations
- Terminal types
- Transportation, handling cost structure

Determine:

- Unique freight transfer path for each (origin, destination) terminal pair

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Loosely-scheduled operations

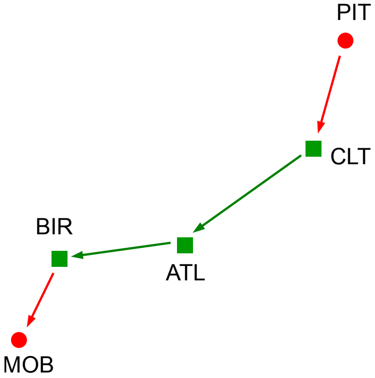
Given a load plan, freight arriving at terminals loaded into trailers, then dispatched using scheduled drivers, on-call “extra board” drivers, and third-party outsourcing (rail)

LTL load planning

Definition

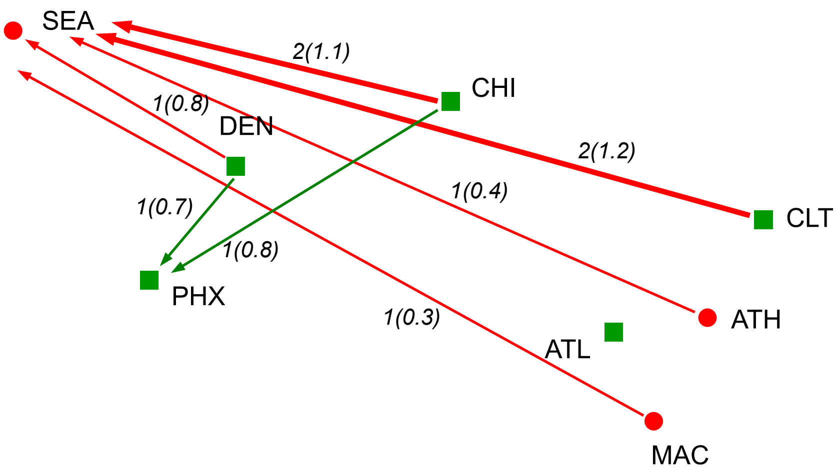
Freight transfer paths

- A freight path is a sequence of direct trailer moves (*directs*)
- Freight assigned to direct (A, D) is loaded into a trailer at A and unloaded for transfer at D



Overlapping freight paths and consolidation

Simple illustration



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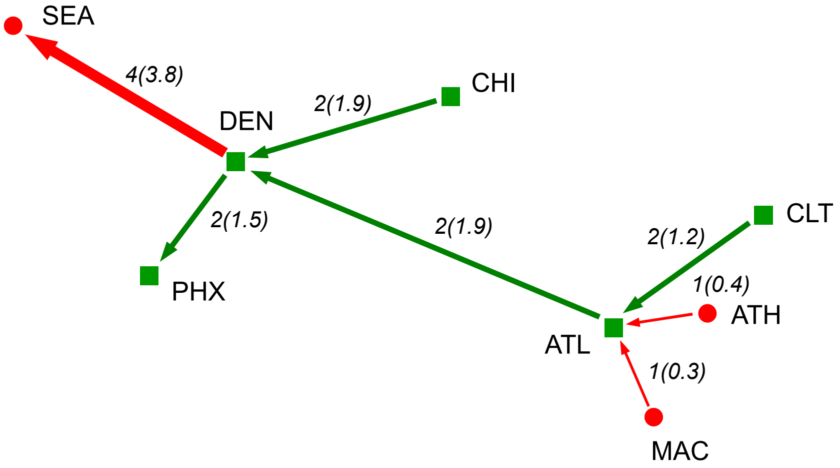
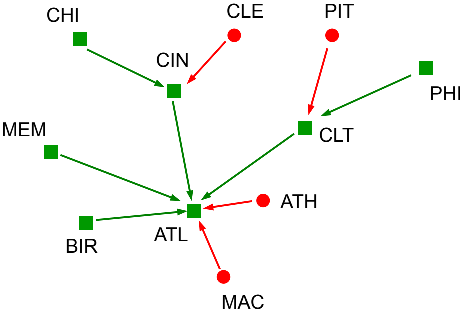


Load plan in-tree structure

- Set of directs forming freight paths to destination terminal d is directed intree
- Triples (i, d, j) for all i, d define load plan
  - All originating *and* transfer freight at i bound for final destination d is loaded into a trailer bound for next destination j



Models supporting LTL load planning

Deterministic tactical planning models

- Flat (static) network, sequential empties
  - Powell and Sheffi (1983, 1989), Powell (1986)
  - Powell and Koskosidis (1992)
- Dynamic network, sequential empties, no intree
  - Farvolden and Powell (1994)

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  - MIP heuristic with slope-scaling
  - Coarse time discretization: daily

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- **Detailed dynamic network, integrated empties**
  - Erera, Hewitt, Savelsbergh, Zhang (under review)
  - Erera, Lindsey, Savelsbergh (working paper)

Overview of our approach

One week wrapped dynamic network with overnight detail

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Why?

- More accurately model consolidation timing
- Input O-D freight volume to vary by day-of-week
- Properly represent scheduled outsourced transportation (rail)
- Model weekend operations

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Path-based freight transfer path selection IP

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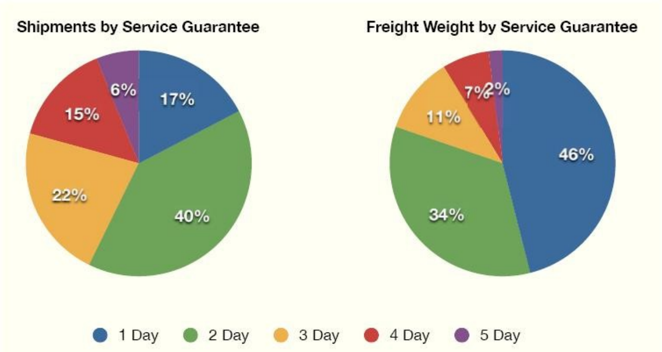

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Simultaneous determination of empty trailer movements

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- Input freight imbalance creates implicit empty movement “demand”
- Creates opportunities for low-cost transfer of backhaul freight

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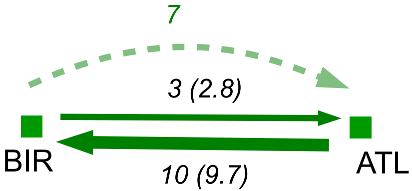
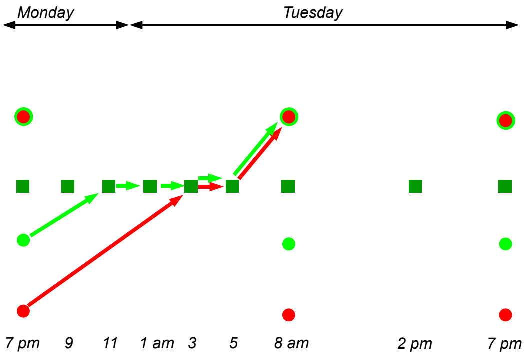


Dynamic Network and Freight Paths

Dynamic Network

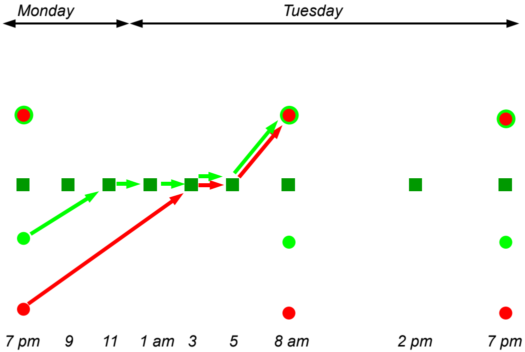
- Node: Terminal and time
- Arc: Freight direct or holding, or empty trailer move or holding
- Commodity: Freight demand from (o, t_1) to (d, t_2) each day



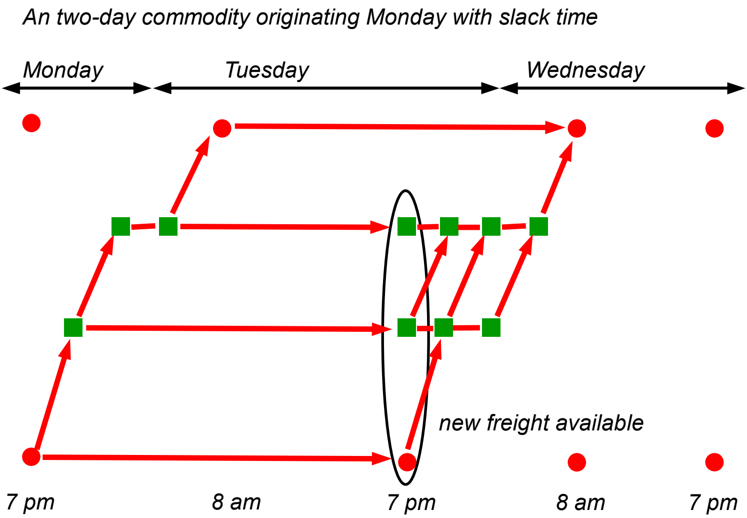
Dynamic Network and Freight Paths

Feasible Freight Path Generation

- *m* minimum cost flat network paths
- timed variants of each flat network path



Timed Freight Paths



Optimization Model

Linear multi-commodity flow IP with side constraints

Objective Function

Minimize sum of:

- Transportation costs (linear in integer trailer variables)
- Holding costs (linear in integer path variables)

Constraints

- Select one path for each commodity
- Ensure that a single outbound direct is selected from each terminal i for freight destined to d [or, one direct for each $i, wd(i)$]
- Only allow selection of paths if all component directs are selected
- Count required trailers for each direct
- Ensure trailer count balance at all nodes (empty repositioning)

Load Plan IP

$$\min \quad \sum_{a \in A} c_a \tau_a + \sum_{k \in K} \sum_{p \in P(k)} h_p q_k x_p^k$$

subject to

$$\sum_{p \in P(k)} x_p^k = 1 \qquad \forall k \in K$$

$$\sum_{\ell \in \delta^+(u)} y_\ell^d \leq 1 \qquad \forall u \in U, \ \forall d \in U$$

$$\sum_{p \in P(k): a \in p} x_p^k \leq y_{\ell(a)}^{d(k)} \qquad \forall k \in K, \forall a \in A$$

$$\sum_{k \in K} \sum_{p \in P(k): a \in p} q_k x_p^k \leq \tau_a \qquad \forall a \in A$$

$$\sum_{a \in \delta^+(v)} \tau_a - \sum_{a \in \delta^-(v)} \tau_a = 0 \qquad \forall v \in V$$

Gigantic Real-world instances

Saia, a large U.S. super-regional LTL carrier

- 93 EOLs
- 61 transfer terminals (BBs and smaller transfer points)
- Flat network directs $|L| = 15,658$
- Time-space nodes $|N| = 4,718$
- Time-space arcs $|A| = 502,946$

Instance	# Commodities $\|K\|$	# Paths $\sum_{k \in K} \|P(k)\|$
Mar09-W1	36,135	2,978,300
Mar09-W2	36,218	2,979,323
Mar09-W3	36,599	2,981,454
Mar09-W4	36,783	2,982,673

Integer Programming Based Local Search

IP-based LS Using Single Intree Neighborhood

Require: Current load plan solution $(\bar{y}, \bar{x}, \bar{\tau})$
while search time has not exceeded time limit T **do**
Choose a destination terminal d
Solve* Single Intree IP for d
if New solution has lower cost than current **then**
Update $(\bar{y}, \bar{x}, \bar{\tau})$
end if
end while

Searching Single Intree Neighborhood

Single Intree IP

Given single d and $K(d)$:

- Fix $y = \bar{y}$, $x = \bar{x}$ in Load Plan IP, except those involving d or $k \in K(d)$
- Compute arc freight flows f_a
- Create Load Plan IP with only variables for d and $K(d)$
- Add trailer bounds $\tau_a \geq \lceil f_a \rceil$

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Solving Single Intree IP

- CPLEX 11 (or Gurobi)
- MIPemphasis = *integer feasibility*
- Gap 0.1%, short time limit $T' << T$

Results and Ideas for Improvement

IP Based LS using Single Intree Neighborhood Results

- Initial load plan from carrier
- 6 hour solution time limit
- Cost savings of 3 to 5% found

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New ideas

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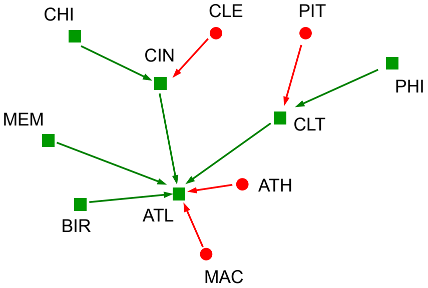
- Replace empty balance constraints with trailer flow bounds updated periodically within search

Multiple Destination Interactions

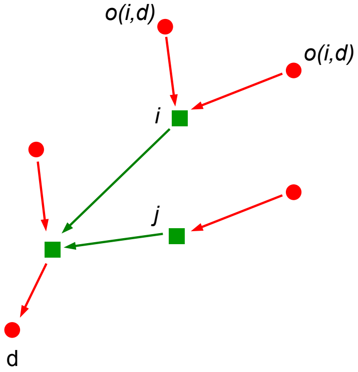


When changing freight paths into ATL, some paths into BIR should be simultaneously changed

New or Old Tree Neighborhood

Sets of Interacting O-D Pairs

- Two options
  - *Attract freight to direct* (i,j)
  - *Reduce freight from direct* (i,j)



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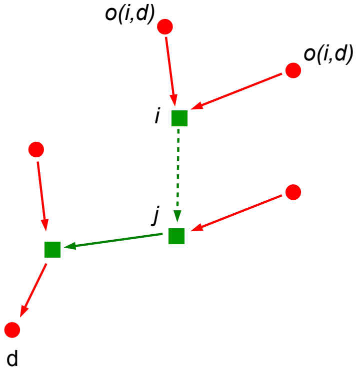

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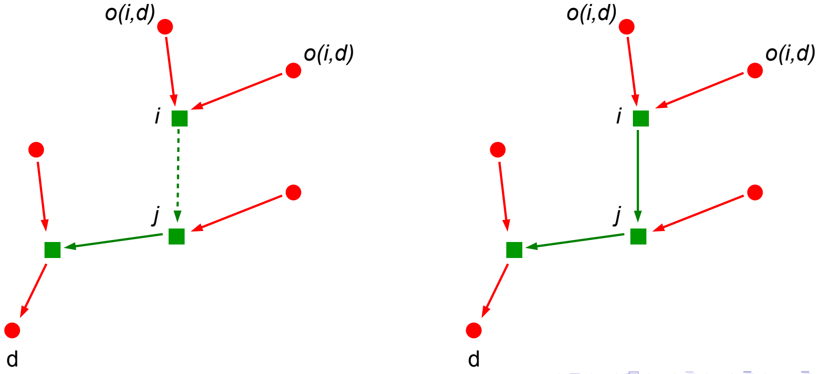

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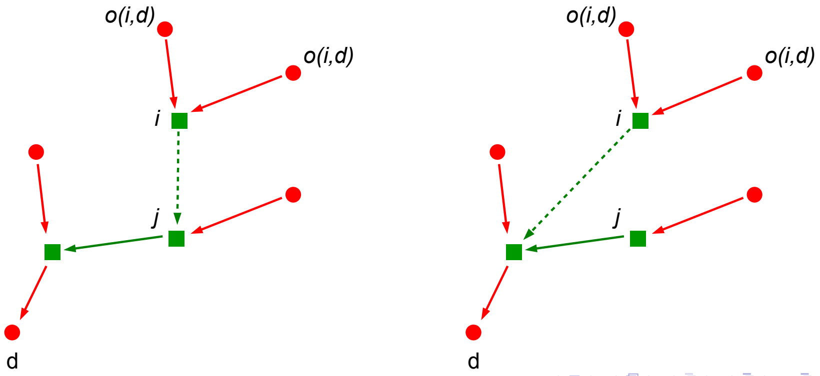

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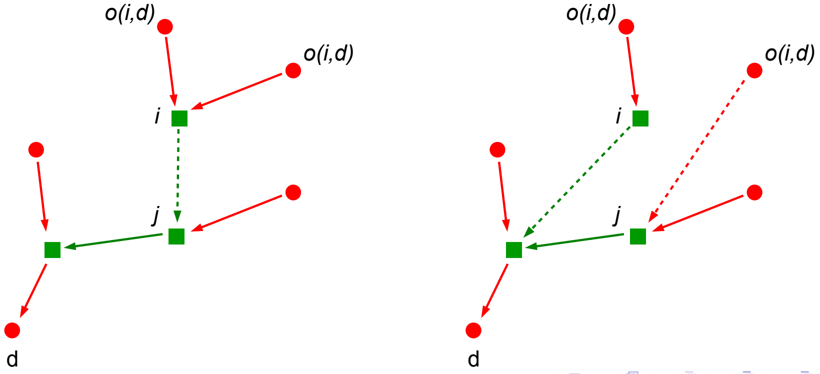

New or Old Tree IP

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subject to

$$\sum_{p \in P(k)} x_p^k = 1 \qquad \forall k \in K'$$

$$x_p^k \leq 1 - z_d \qquad \forall d \in D', k \in K'(d), p \in P(k, NewTree(d))$$

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$$\sum_{k \in K'} \sum_{p \in P(k)} q_k x_p^k + f_a \leq \tau_a \qquad \forall a \in A$$

$$x_p^k, \quad z_d \text{ binary}$$

$$\tau_a \geq Empties_a \text{ and integer}$$

Empty Balancing Outside of IP

Substantially reduce IP size within neighborhood search

Periodic Empty Balance

- Every k neighborhood search iterations, solve empty balance MCNF on time-space network
- Let $Empties_a$ be number of empty trailers moving on time-space arc a

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Require: Current load plan solution $(\bar{y}, \bar{x}, \bar{\tau})$ and $Empties_a$
  while search time has not exceeded time limit T **do**
    Choose whether to attract or reduce freight
    Choose a direct (i, j)
    Solve* New or Old Tree IP
    if New solution has lower cost than current **then**
      Update $(\bar{y}, \bar{x}, \bar{\tau})$
    end if
    if iterations since last empty balance exceeds threshold **then**
      Solve Empty Balance MCNF generating new $Empties_a$
    end if
  end while

New Results

1. Search IP Speed
   - *Intree*: 90s limit, 75% to optimality
   - *New Or Old Tree*: 30s limit, 97% to optimality

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		RO	AO	Rand(0.25)
Mar09-W1	$\Delta Cost$	20.41%	17.88%	24.07%
Mar09-W2	$\Delta Cost$	19.28%	16.76%	22.45%
Mar09-W3	$\Delta Cost$	18.16%	17.38%	22.24%
Mar09-W4	$\Delta Cost$	20.75%	16.44%	22.24%

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Mar09-W3	$\Delta Cost$	18.16%	17.38%	22.24%
Mar09-W4	$\Delta Cost$	20.75%	16.44%	22.24%

3. Cost Reduction from Base Plan: 6 hours

		RO	AO	Rand(0.25)
Mar09-W1	$\Delta Cost$	28.96%	24.47%	38.79%
Mar09-W2	$\Delta Cost$	29.14%	24.76%	38.60%
Mar09-W3	$\Delta Cost$	28.44%	24.80%	38.16%
Mar09-W4	$\Delta Cost$	28.47%	23.13%	38.48%

LTL Service Network Design Tools

1. Weekly Tactical Planner
    - *Intree* or New Or Old Tree IP Neighborhood Search

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    - Build dispatches and driver tours
    - More accurate cost estimator for load plan

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   - *Intree* or New Or Old Tree IP Neighborhood Search
2. Weekly Operation Scheduler and Cost Estimator
   - Build dispatches and driver tours
   - More accurate cost estimator for load plan
3. Daily Load Plan Adjuster
   - Multiple daily updates for load plans given freight pickups
   - GRASP

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