Optimization Models for Block Re-design Problem

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Outline

➢ Motivation and Problem Definition
➢ Related Literature
➢ Model Formulation
➢ Solution Strategies
➢ Computational Results
➢ Conclusion
US Freight Railroads:

- 42% of total freight, more than any mode of transportation
- A typical Class I railroad:
  - 8000 new shipments/day
  - 1300 trains/day
  - 32,500 miles network
- Demand projected to increase by 88% in next 20 years
- 1% increase in service reliability can lead to an increase of 5% in revenue (Hallowell, 1998)

2. Surface Transportation Board Research Reports
Operations in Shipment Movement

- **Routing Policies**: Blocking Policies, Block-to-Train Assignments, Train Schedules
- **Train Capacities**: Multiple metrics of capacity, varying with segment
- **Block Switching Operations**: Yard operations, Classification
Railroad blocking is essentially a consolidation problem – similar to that encountered in postal service design.
When are Blocking Changes Required?

- **Relieving Congested Yards**
  - Changes in blocking plan to re-route traffic out of congested yard(s)
  - Blocking network may or may not change

- **Changes in Traffic Pattern**
  - Volume increases between origins and destinations
  - Blocking plan changes to better match Train Service Plan

- **Alternate Routing Plan for Restricted Traffic**
  - Restrictions based on material type or shipment characteristics
  - Traffic between same origin destination pair may follow different blocking plan

- **Directional Separation of Traffic**
  - Yard switching efficiency may increase depending on how traffic is blocked
Literature Review

- Algorithmic Blocking Model by Carl Van Dyke (1986, 1988)
- Keaton (1989, 1992)
- Newton, Barnhart, and Vance (1998)
- Barnhart and Vance (2000)
- Ahuja, Jha, and Liu (2007)
- Ahuja, Jha, and Sahin (2008)
- Fugenschuh et al. (2018)
Blocking Redesign: Problem Introduction

➢ Given
  ▪ Shipments to be transported during a planning horizon
  ▪ The current routes of the shipments (Current Blocking Plan)
  ▪ Set of congested yards and required volume changes at the congested yards
  ▪ Restriction on shipment routes

➢ Decision
  ▪ Modified Blocking Plan
  ▪ New Block Sequence for each rerouted shipment

➢ Constraints
  ▪ $\alpha\%$ volume reduction at congested yard
  ▪ $< \beta\%$ volume increase at other constrained yards
  ▪ Routing restrictions for hazardous, high-wide, and other restricted traffic

➢ Objective
  ▪ Minimize the total transportation cost: car miles + handling cost
Parameters and Definitions

Sets
- **T** = Planning horizon
- **W** = Set of shipments to be transported during planning horizon
- **K** = Set of unique OD pairs
- **B** = Set of candidate blocks
- **B_c** = Set of blocks in current blocking plan
- **N** = Set of nodes in network
- **S** = Set of locations where shipments can switch

Parameters
- **o_k** = Origin of commodity \( k \in K \)
- **d_k** = Destination of commodity \( k \in K \)
- **u_i** = Switching capacity of node \( i \in N \)
- **v_i** = Current switching volume of node \( i \in N \)
- **h_i** = Handling cost at node \( i \in N \)
- **g_i** = Maximum outdegree of node \( i \in N \)

Decision Variables
- **y_{ij}** = 1 if block \((i, j)\) is present in the modified blocking network
- **x_{ij}^k** = 1 if OD pair \( k \in K \) uses block \((i, j)\) in the modified blocking plan
Model Formulation

Objective

\[ Z = \min \sum_{k \in K} \sum_{(i,j) \in B} (d_{ij} v_k + h_i v_k) x_{ij}^k \]

Flow Conservation

\[ \sum_{(i,j) \in \delta^+(i)} x_{ij}^k - \sum_{(j,i) \in \delta^-(i)} x_{ji}^k = \begin{cases} 
1 & \text{if } i = o_k \\
0 & \text{if } i \neq o_k \text{ and } i \neq d_k \\
-1 & \text{if } i = d_k 
\end{cases} \quad \forall k \in K \]

Yard Switching Capacity

\[ \sum_{(j,i) \in \delta^-(i)} \sum_{k \in K, \; d_k \neq i} v_k x_{ji}^k \leq u_i \quad \forall i \in N \]

Yard Outdegree

\[ \sum_{(i,j) \in \delta^+(i)} y_{ij} \leq g_i \quad \forall i \in N \]

Forcing Constraints

\[ x_{ij}^k \leq y_{ij} \quad \forall (i,j) \in B, k \in K \]
Model Formulation (Contd.)

**Block Additions and Deletions**

\[
p_{ij} \geq y_{ij} - y_{ij}^0 \\
q_{ij} \geq y_{ij}^0 - y_{ij}
\]
\[∀ (i, j) ∈ B\]

**Block Changes Restrictions**

\[
\sum_{(i,j) ∈ A} p_{ij} + q_{ij} \leq C
\]

**Non – negativity**

\[
0 \leq X_{ij}^k \leq 1, \; Y_{ij} = 0 \text{ or } 1, \; p_{ij} \geq 0, \; q_{ij} \geq 0 \; ∀ (i, j) ∈ B, \; k ∈ K
\]
Algorithmic Enhancements & Heuristic Approaches

Problem Reduction Approaches:

- Node merging rules
- Deviation from Shortest Paths
- Directional Routing constraints

Heuristic Approaches:

- Iterative Shortest Path Approach
- Dual-Ascent based Heuristic
- Local Improvements based on Optimal Flow Solution
- Block Covering for Optimal Physical Path Flow
Algorithmic Enhancements & Heuristic Approaches

Problem Introduction  |  Related Literature | IP Formulation | Solution Approaches | Computational Results | Conclusion

**Problem Reduction Approaches**

- Node merging
- Deviation from Shortest Paths
- Directional Routing Restrictions

**Heuristic Approaches**

- Iterative Shortest Path
- Dual Ascent
- Optimal Flow based Local Improvements
- Optimal Physical Path based Blocks
Computational Results: Setup

Test cases
- Computational tests on 3 test instances
- Horizon Length: 28 days
- Number of blocks: 3182
- Number of shipments: ~253k

Computational Environment
- CPLEX 12.7 with Python 3.5
- TOSHIBA TECRA Z40-C laptop with 2.40 GHz Intel Core i5 and 8GB RAM
- Maximum allowed time limit: 1 hour
- Multi-thread (Parallel) Processing

Model Size

<table>
<thead>
<tr>
<th></th>
<th>Base Model</th>
<th>Reduced Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variables</td>
<td>3.99 million</td>
<td>1.02 million</td>
</tr>
<tr>
<td>Constraints</td>
<td>3.22 million</td>
<td>449k</td>
</tr>
</tbody>
</table>

Problem Introduction  | Related Literature  | IP Formulation  | Solution Approaches  | Computational Results  | Conclusion
### Computational Results: Setup

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Method</th>
<th>Variables</th>
<th>Constraints</th>
<th>Solution Time (in seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dataset 1</td>
<td>All Yards Uncapacitated</td>
<td>3,993,808</td>
<td>3,220,127</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Selective Yards Capacitated</td>
<td>3,993,808</td>
<td>3,220,134</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>All Yards Capacitated</td>
<td>3,993,808</td>
<td>3,220,397</td>
<td>31</td>
</tr>
<tr>
<td>Dataset 2</td>
<td>All Uncapacitated</td>
<td>14,138,688</td>
<td>11,399,737</td>
<td>158</td>
</tr>
<tr>
<td></td>
<td>Selective Capacitated</td>
<td>14,138,688</td>
<td>11,399,742</td>
<td>364</td>
</tr>
<tr>
<td></td>
<td>All Yards Capacitated</td>
<td>14,138,688</td>
<td>11,400,007</td>
<td>490</td>
</tr>
<tr>
<td>Dataset 3</td>
<td>All Uncapacitated</td>
<td>4,365,168</td>
<td>3,519,547</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>LP - few constraints</td>
<td>4,365,168</td>
<td>3,519,549</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>All Yards Capacitated</td>
<td>4,365,168</td>
<td>3,519,817</td>
<td>45</td>
</tr>
</tbody>
</table>

#### Solution times comparison (in seconds)

<table>
<thead>
<tr>
<th>Test Case</th>
<th>Without Reduction</th>
<th>With Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dataset 1</td>
<td>26</td>
<td>7 (107)</td>
</tr>
<tr>
<td>Dataset 2</td>
<td>22</td>
<td>-</td>
</tr>
<tr>
<td>Dataset 3</td>
<td>372</td>
<td>11 (180)</td>
</tr>
</tbody>
</table>

- Number of variables and constraints decreases by 70-90%
- Solution times decrease by 60-95%
- Preprocessing time is significant.
Conclusion & Future Work

➢ Developed optimization model to re-design a blocking plan while considering yard capacity constraints, shipment route restrictions, and other business constraints

➢ Developed problem reduction approaches to eliminate variables and constraints and optimization-based heuristic approaches to quickly obtain an upper-bound

➢ Tested developed models with three real-life datasets and showed efficacy of developed solution approaches