Optimal Scheduling of Railroad Track Inspection Activities and Production Teams

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The William W. Hay Railroad Engineering Seminar Series
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Importance of Track Maintenance

• U.S. Class I railroads operated 160,781 miles of track (2009)
• 42.7% of the U.S. freight revenue ton-miles were carried by railroad (2007)
• Track maintenance
  – Identify and repair track defects
  – Critically important to railroad performance and safety
Costs Related to Track Maintenance

- **Track maintenance costs**
  - $7.52 billion by Class I railroads in 2008
- **Train accident costs**
  - Track defects have become the leading cause of train accidents in U.S. since 2009
  - 658 of 1,890 (34.8%) train accidents were caused by track defects in 2009, which incurred a $108.7 million loss
- **Train delay costs**
  - Track maintenance activities may delay trains
  - Estimated $200-$300 per hour per train (excluding shipment delay costs)
- **Other costs** (locomotive and car maintenance costs, etc.)
Importance of Optimizing Track Maintenance Process

- A small percentage of cost reduction implies a significant saving
- Cost reduction can be achieved by optimizing track maintenance processes
  - Activity schedule
  - Machinery movement
  - Material transportation
Optimization Problems on Track Maintenance in CSX

- Track Inspection Scheduling
- Rail Inspection Scheduling
- Geometry Inspection Scheduling
- Tie Inspection Scheduling

- Capital Track Maintenance Scheduling
  - Defect-to-Job Clustering
  - Job-to-Project Clustering
  - Production Team Scheduling

- Routine Track Maintenance Scheduling
  - Ballast Cleaning Scheduling
  - Surfacing Scheduling
  - Rail Grinding Scheduling

- Track Maintenance Logistics
  - Relay Rail Sourcing
  - New Rail and Tie Sourcing
  - Ballast Sourcing
  - Work Train Scheduling
Track Inspection Scheduling

- Track Inspection Scheduling
- Rail Inspection Scheduling
- Geometry Inspection Scheduling
- Tie Inspection Scheduling

- Capital Track Maintenance Scheduling
- Production Team Scheduling
- Cleaning Scheduling
- Grinding Scheduling

- Track Maintenance Logistics
- Work Train Scheduling
- Rail Inspection
- Tie Inspection
- Geometry Inspection
- Rail Grinding
- Ballast Cleaning

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- Production Team Scheduling
- Cleaning Scheduling
- Grinding Scheduling

- Track Maintenance Logistics
- Work Train Scheduling
- Rail Inspection
- Tie Inspection
- Geometry Inspection
- Rail Grinding
- Ballast Cleaning
Track Inspection Scheduling

- **Input**
  - Tasks
  - Teams
  - Scheduling horizon

- **Output**
  - Assign every task a team and a start time

- **Goal**
  - Minimize costs
  - Satisfy business constraints
Track Maintenance Scheduling

Track Inspection Scheduling
Rail Inspection Scheduling
Geometry Inspection Scheduling
Tie Inspection Scheduling

Capital Track Maintenance Scheduling
Defect-to-Job Clustering
Job-to-Project Clustering
Production Team Scheduling

Routine Track Maintenance Scheduling
Ballast Cleaning Scheduling
Surfacing Scheduling
Rail Grinding Scheduling

Production Team Scheduling
Logistics

University of Illinois at Urbana-Champaign
### Track Maintenance Scheduling

<table>
<thead>
<tr>
<th>Maintenance Activity</th>
<th>Maintenance Team</th>
<th>Scale</th>
<th>Schedule</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrective</td>
<td>Local team</td>
<td>Small</td>
<td>On demand</td>
<td>Defect repair</td>
</tr>
<tr>
<td>Capital</td>
<td>Production team</td>
<td>Large</td>
<td>Pre-planned</td>
<td>Rail project, timber and surfacing (T&amp;S) project</td>
</tr>
<tr>
<td>Routine</td>
<td>Routine maintenance team</td>
<td>Middle</td>
<td>At a frequency</td>
<td>Ballast cleaning, surfacing, rail grinding</td>
</tr>
</tbody>
</table>
Track Maintenance Logistics

- Track Inspection Scheduling
- Rail Inspection Scheduling
- Geometry Inspection Scheduling
- Tie Inspection Scheduling
- Capital Maintenance Scheduling
- Production Scheduling
- Relay Rail Sourcing
- New Rail and Tie Sourcing
- Ballast Sourcing
- Work Train Scheduling
Current Practice in Railroad Industry

• Large-scale and complex problem instances
  – Thousands of activities
  – Tens of teams
  – Thousands of business constraints
• Manual solution process based on expert knowledge and experience
Objective

• Develop mathematical models and corresponding algorithms for the identified problems
  – Models are complex and realistic enough to accurately reflect the business goals and constraints
  – Algorithms are effective and efficient and can be applied to large-scale practical problem instances
• The developed models and algorithms have been adopted by CSX in the past two years
  – Improve operational performance and safety
  – Improve solution efficiency
Scope of Presentation

Track Inspection Scheduling
Rail Inspection Scheduling
Geometry Inspection Scheduling
Tie Inspection Scheduling

Defect-to-Job Clustering
Job-to-Project Clustering
Production Team Scheduling

Capital Track Maintenance Scheduling

Ballast Cleaning Scheduling
Surfacing Scheduling
Rail Grinding Scheduling

Routine Track Maintenance Scheduling

Relay Rail Sourcing
New Rail and Tie Sourcing
Ballast Sourcing

Production Team Scheduling

Track Maintenance Logistics

Work Train Scheduling
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- Work Train Scheduling

Track Maintenance Logistics
Track segments are inspected periodically

Inspection activities are called “tasks”
Model and Algorithm Selection

- **Vehicle routing problem model**
  - Real number task durations
  - Real number travel times
- **Heuristic algorithm**
  - Fast solution speed

<table>
<thead>
<tr>
<th>Week 1</th>
<th>Team 1</th>
<th>Team 2</th>
<th>Team 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task 1</td>
<td>Task 4</td>
<td>Task 8</td>
<td></td>
</tr>
<tr>
<td>Travel</td>
<td>Travel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task 2</td>
<td>Task 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Travel</td>
<td></td>
<td>Travel</td>
<td></td>
</tr>
<tr>
<td>Task 3</td>
<td>Task 6</td>
<td>Task 9</td>
<td></td>
</tr>
<tr>
<td>Travel</td>
<td>Task 7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Week 2</th>
<th>Team 1</th>
<th>Team 2</th>
<th>Team 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task 1</td>
<td>Task 4</td>
<td>Task 8</td>
<td></td>
</tr>
<tr>
<td>Task 2</td>
<td>Task 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task 3</td>
<td>Task 6</td>
<td>Task 9</td>
<td></td>
</tr>
<tr>
<td>Task 7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Vehicle Routing Problem Model

- Spatial network composed of vertices and edges
- Binary variables for team routes
- A real number variable $u$ for each activity, representing the start time of that activity
- Difficult to solve with integer programming algorithm if there are difficult side constraints

\[ u_1 = 1.7 \]
\[ u_2 = 3.2 \]
\[ u_3 = 5.5 \]
\[ u_4 = 10 \]
Side Constraints

• Constraint types
  – Periodicity
  – Non-simultaneity
  – Time window
  – Preference
  – Network topology
  – Discrete working time

• Hard vs. soft constraints
Periodicity Constraint

- A segment should be inspected periodically at a certain frequency, i.e., the interval between two consecutive tasks on a segment should be within a certain value
  - Penalty cost is due to the risk of defects
Non-Simultaneity Constraint

- **Subdivision non-simultaneity constraint**
  - Two tasks in the same subdivision should not be performed simultaneously

- **Roadmaster non-simultaneity constraint**
  - Two tasks involving the same roadmaster (or some other railroad employee) should not be performed simultaneously
Time Window Constraint

- A task should not be performed during certain times
  - Rail inspection teams should avoid conflicts with
    - Railroad geometry inspection teams
    - Government geometry inspection teams
    - Track maintenance teams
Preference Constraints

- A task should be performed by certain teams
  - Closeness to home
  - Familiarity
Network Topology Constraint

- A task is represented by an arc but not a single point
- Some tasks can be performed together without travelling between each other

(a) Single track
(b) One task on double track
(c) One task on partial double track
(d) Three tasks on partial double track

Work on rail
Travel on rail
Discrete Working Time Constraint

- Inspection teams do not work during weekends and holidays unless paid for overtime.
Algorithm Framework

1. Input
2. Initialize horizon
3. Generate tasks
4. Greedy algorithm
5. Task interchange
6. Are stopping criteria met?
   - Y: Output
   - N: Extend horizon if necessary
7. Generate variables and related constraints only when necessary
8. Obtain an initial solution
9. Improve the solution
10. Optimize the schedule gradually
11. Solution has not changed since the last iteration
Case Study: **Short-Term** Scheduling

- Weekly scheduling for operations
- Data from CSX
  - 700+ segments
  - 19 teams
  - 8-week horizon
- Thousands of tasks and side constraints
- Solution time: less than 1 minute
## Short-Term Scheduling: Results

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Manual solution</th>
<th>Model solution</th>
<th>Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total <strong>overdue percentage</strong> outside the required interval (%)</td>
<td>15.8</td>
<td>4.2</td>
<td><strong>73.7</strong></td>
</tr>
<tr>
<td>Total <strong>travel distance</strong> between tasks (miles per team per week)</td>
<td>63.2</td>
<td>47.4</td>
<td><strong>25.0</strong></td>
</tr>
<tr>
<td>Total non-simultaneity constraint <strong>overlapping duration</strong> (days per week)</td>
<td>0.66</td>
<td>0.42</td>
<td><strong>37.5</strong></td>
</tr>
</tbody>
</table>

All hard constraints are satisfied.

*Cost entries are scaled to protect data confidentiality*
Case Study: Long-Term Planning

- Resource planning
  - Decision of the number of teams to hire
  - Balance of workload across teams
  - Prediction of workload peaks

- Data from CSX
  - 1-year horizon

- Tens of thousands of tasks and side constraints
- Cannot be performed manually
- Solution time: less than 1 hour
Long-Term What-If Analysis

Total overdue percentage outside the required interval

Total overdue percentage outside the allowed interval

(a) 19 teams with geographic restrictions
(b) 19 teams without geographic restrictions
(c) 18 teams without geographic restrictions
(d) 17 teams without geographic restrictions
Production Team Scheduling

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Production Team Scheduling

Projects are identified every year

<table>
<thead>
<tr>
<th>Week</th>
<th>Team 1</th>
<th>Team 2</th>
<th>Team 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Week 1</td>
<td>Project 1</td>
<td>Project 2</td>
<td>Project 3</td>
</tr>
<tr>
<td>Week 2</td>
<td>Project 1</td>
<td>Project 6</td>
<td>Project 3</td>
</tr>
<tr>
<td>Week 3</td>
<td>Project 4</td>
<td>Project 6</td>
<td>Project 3</td>
</tr>
<tr>
<td>Week 4</td>
<td>Project 5</td>
<td>Project 10</td>
<td>Project 3</td>
</tr>
<tr>
<td>Week 5</td>
<td>Project 5</td>
<td>Project 8</td>
<td>Project 9</td>
</tr>
<tr>
<td>Week 6</td>
<td>Project 5</td>
<td>Project 7</td>
<td>Project 9</td>
</tr>
</tbody>
</table>
Model and Algorithm Selection

- Time-space network model
  - Integer number project durations
  - No travel time
- Integer programming and heuristic algorithms
  - Longer solution time (a few hours) allowed

<table>
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<tr>
<th>Week</th>
<th>Team 1</th>
<th>Team 2</th>
<th>Team 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Project 1</td>
<td>Project 2</td>
<td>Project 3</td>
</tr>
<tr>
<td>2</td>
<td>Project 1</td>
<td>Project 6</td>
<td>Project 3</td>
</tr>
<tr>
<td>3</td>
<td>Project 4</td>
<td>Project 6</td>
<td>Project 3</td>
</tr>
<tr>
<td>4</td>
<td>Project 5</td>
<td>Project 10</td>
<td>Project 3</td>
</tr>
<tr>
<td>5</td>
<td>Project 5</td>
<td>Project 8</td>
<td>Project 9</td>
</tr>
<tr>
<td>6</td>
<td>Project 5</td>
<td>Project 7</td>
<td>Project 9</td>
</tr>
</tbody>
</table>
Time-Space Network Model

- Continuous time horizon is discretized into time points
- Network is duplicated at every time point
- Easier to solve with integer programming algorithms
Travel Costs

• Minimize the travel costs between projects
Side Constraints

- Constraint types
  - Time window, preference, mutual exclusion, precedence, simultaneity, non-simultaneity, consecution, split project, limitation, relay rail, Jamboree
- Hard vs. soft constraints
Time Window Constraint

• A project should not be performed in certain weeks
  – Weather
  – Seasonal high railroad traffic volume
Preference Constraint

• A project should be performed by certain teams
  – Closeness to home
  – Familiarity
• Some adjoining subdivisions should not have simultaneous ongoing projects
Corridor Mutual Exclusion Constraint

- Some subdivisions in a corridor should not have simultaneous ongoing projects
Yard Mutual Exclusion Constraint

- A yard and its adjoining mainline should not have simultaneous ongoing projects
Precedence Constraint

• Certain project should be performed before another project
  – Rail projects before tie projects so that the new ties are not damaged by pulling and inserting spikes
Simultaneity and Non-Simultaneity Constraints

• Simultaneity: two projects should be performed simultaneously
  – Technical difficulty
  – Busy train traffic

• Non-simultaneity: two projects should not be performed simultaneously
  – Limited space
Consecution Constraint

• Some projects should be performed consecutively by the same team
  – to improve efficiency

Diagram showing consecutive constraints with times and markers.
Split Project Constraint

- Some projects are split in order to increase the flexibility of scheduling.
- Two parts of a split project should be performed either simultaneously by different teams or consecutively by the same team.
Limitation Constraint

- A team should not perform a certain class of projects for too many weeks
  - 5-day projects

<table>
<thead>
<tr>
<th>Week</th>
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<th>Team 3</th>
</tr>
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<tbody>
<tr>
<td>Week 1</td>
<td>Project 1</td>
<td>Project 2</td>
<td>Project 3</td>
</tr>
<tr>
<td>Week 2</td>
<td>Project 1</td>
<td>Project 6</td>
<td>Project 3</td>
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<tr>
<td>Week 3</td>
<td>Project 4</td>
<td>Project 6</td>
<td>Project 3</td>
</tr>
<tr>
<td>Week 4</td>
<td>Project 5</td>
<td>Project 7</td>
<td>Project 3</td>
</tr>
<tr>
<td>Week 5</td>
<td>Project 5</td>
<td>Project 8</td>
<td>Project 9</td>
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<tr>
<td>Week 6</td>
<td>Project 5</td>
<td>Project 8</td>
<td>Project 9</td>
</tr>
</tbody>
</table>
Relay Rail Constraint

- Projects supplying relay rail should be scheduled before projects demanding relay rail

<table>
<thead>
<tr>
<th>Week 1</th>
<th>Team 1</th>
<th>Team 2</th>
<th>Team 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Project 1</td>
<td>Project 2</td>
<td>Project 3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Week 2</th>
<th>Team 1</th>
<th>Team 2</th>
<th>Team 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Project 1</td>
<td>Project 6</td>
<td>Project 3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Week 3</th>
<th>Team 1</th>
<th>Team 2</th>
<th>Team 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Project 4</td>
<td>Project 6</td>
<td>Project 3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Week 4</th>
<th>Team 1</th>
<th>Team 2</th>
<th>Team 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Project 5</td>
<td>Project 10</td>
<td>Project 3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Week 5</th>
<th>Team 1</th>
<th>Team 2</th>
<th>Team 3</th>
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<tbody>
<tr>
<td></td>
<td>Project 5</td>
<td>Project 8</td>
<td>Project 9</td>
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</table>

<table>
<thead>
<tr>
<th>Week 6</th>
<th>Team 1</th>
<th>Team 2</th>
<th>Team 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Project 5</td>
<td>Project 7</td>
<td>Project 9</td>
</tr>
</tbody>
</table>
Jamboree Constraint

- All Jamboree teams should perform Jamboree projects during Jamboree weeks
  - Ongoing projects can be interrupted during Jamboree weeks and resumed after them

<table>
<thead>
<tr>
<th>Jamboree Weeks</th>
<th>Jamboree Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Week 1</td>
<td>Project 1, Project 2, Project 3</td>
</tr>
<tr>
<td>Week 2</td>
<td>Project 1, Project 4, Project 3</td>
</tr>
<tr>
<td>Week 5</td>
<td>Project 5, Project 4, Project 7</td>
</tr>
<tr>
<td>Week 6</td>
<td>Project 5, Project 6, Project 7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Jamboree Teams</th>
<th>Team 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Team 3</td>
</tr>
<tr>
<td>Week 1</td>
<td>Project 3</td>
</tr>
<tr>
<td>Week 2</td>
<td>Project 3</td>
</tr>
<tr>
<td></td>
<td>Project 3</td>
</tr>
<tr>
<td>Week 5</td>
<td>Project 7</td>
</tr>
<tr>
<td>Week 6</td>
<td>Project 7</td>
</tr>
</tbody>
</table>
Algorithm Framework

Input
Split projects
Scheduling model
Block interchange
Decomposition and restriction
Are stopping criteria met?
Y
Output

N
Increase the flexibility of scheduling
Obtain an initial solution
Local search
Local search
Time limit is reached
Case Study: 2011 Data

- Data from CSX
  - 300+ projects
  - 20 teams
  - 1-year horizon
  - Thousands of side constraints
- Solution time: 8 hours
- All hard and most soft constraints are satisfied
- Solution was implemented with some revisions
Case Study: 2009 Data

- Data from CSX
- Solution time: 6 hours
- Solution is compared with those obtained by
  - railroad’s manual process
  - our previous approach used in 2010 scheduling
## 2009 Data: Solution Comparison

<table>
<thead>
<tr>
<th>Costs and violations</th>
<th>Manual procedure</th>
<th>Previous approach in 2010</th>
<th>Proposed approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel costs</td>
<td>161,944</td>
<td>158,598</td>
<td>139,921</td>
</tr>
<tr>
<td>Soft side constraints (penalty costs / # of violations)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Junction MX</td>
<td>24,117 / 72</td>
<td>8,709 / 26</td>
<td>2,345 / 7</td>
</tr>
<tr>
<td>Corridor MX</td>
<td>12,661 / 54</td>
<td>5,158 / 22</td>
<td>3,751 / 16</td>
</tr>
<tr>
<td>Time window</td>
<td>257,965 / 95</td>
<td>14,664 / 41</td>
<td>6,062 / 36</td>
</tr>
<tr>
<td>Precedence</td>
<td>670 / 20</td>
<td>603 / 18</td>
<td>435 / 13</td>
</tr>
<tr>
<td>Total costs (travel + penalty)</td>
<td>457,357</td>
<td>187,733</td>
<td>152,647</td>
</tr>
<tr>
<td>Hard side constraints (# of violations)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time window</td>
<td>15</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Precedence</td>
<td>8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total hard constraint violations</td>
<td>23</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

-66.7%  -18.8%

*Cost entries are scaled to protect data confidentiality*
Future Research

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Thank you!