Optimal Scheduling of Railroad Track Inspection Activities and Production Teams

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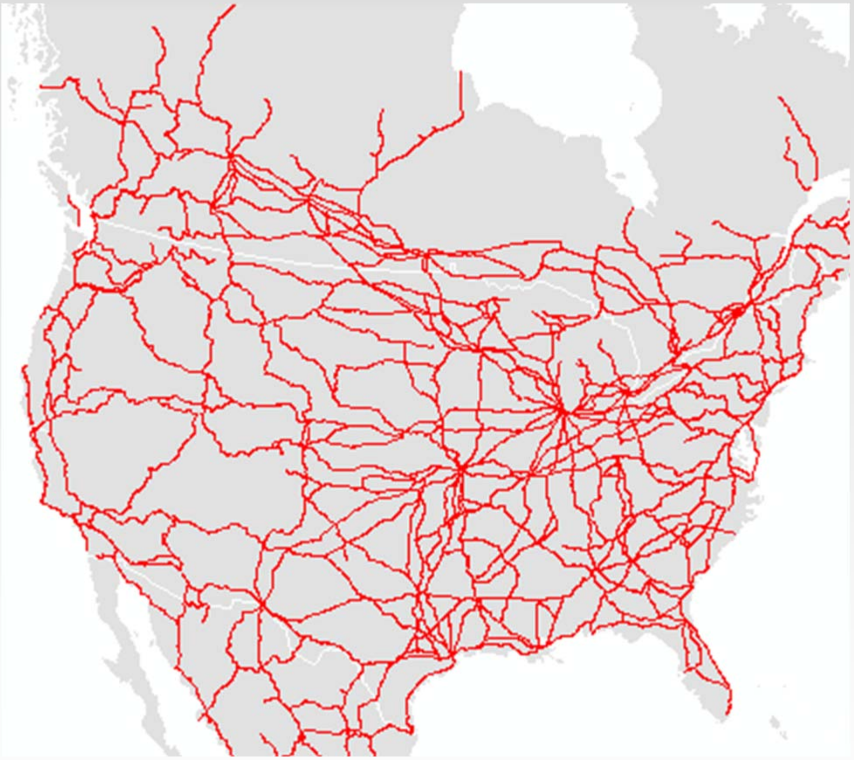
How tomorrow moves CSX

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

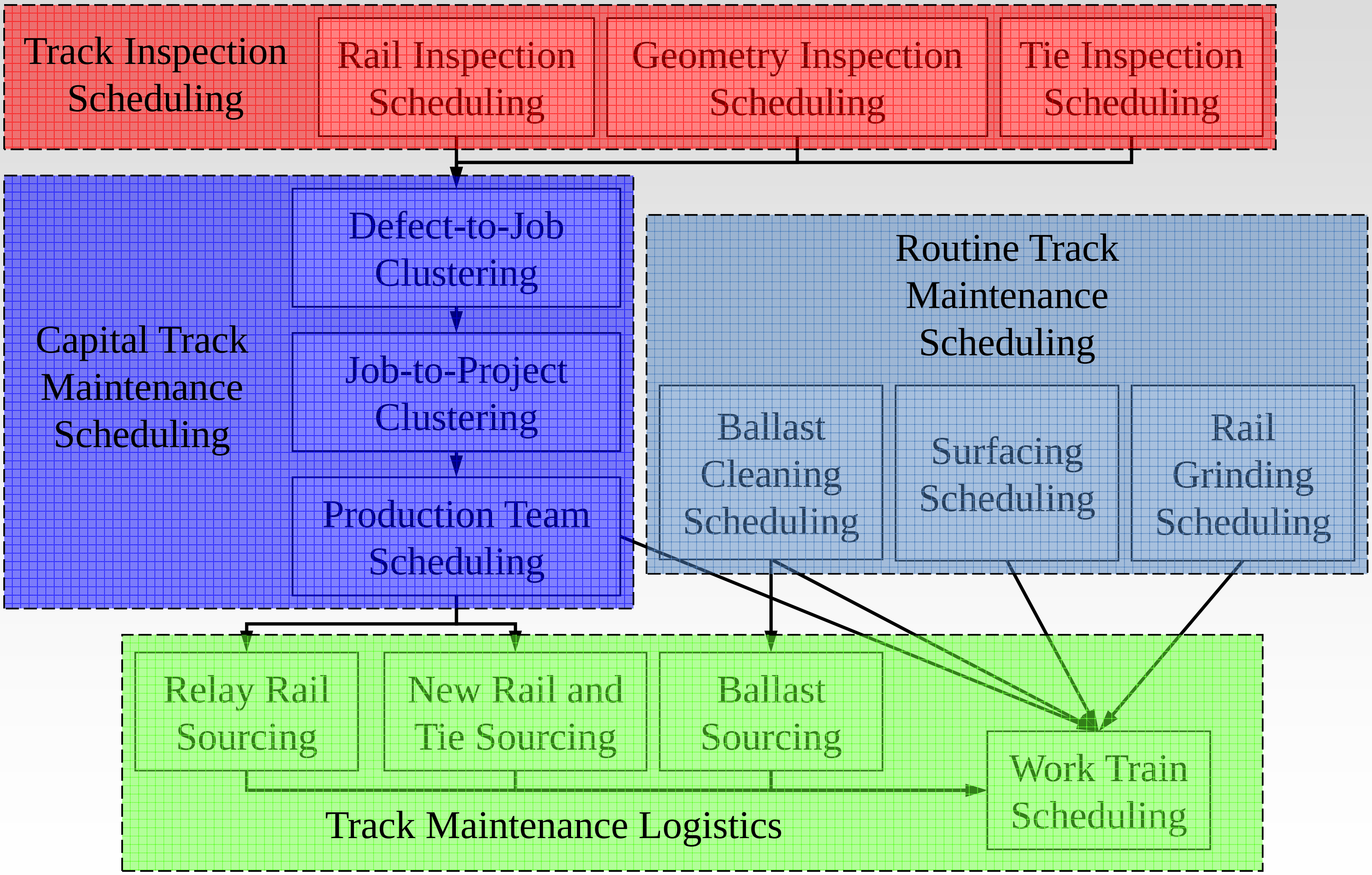
- Track maintenance costs
  - $7.52 billion by Class I railroads in 2008
- Train accident costs
  - Track defects have become the leading cause of train accidents in U.S. since 2009
  - 658 of 1,890 (34.8%) train accidents were caused by track defects in 2009, which incurred a $108.7 million loss
- Train 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



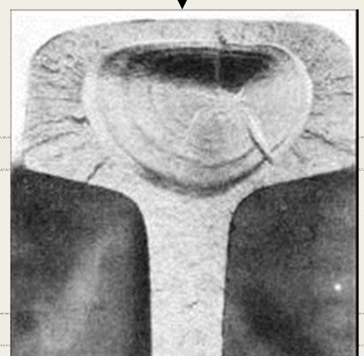
Track Inspection Scheduling

Track Inspection Scheduling

Rail Inspection Scheduling

Geometry Inspection Scheduling

Tie Inspection Scheduling



Capital Track Maintenance Scheduling

Production Team

Scheduling

Scheduling

Scheduling

Work Train Scheduling

Track Maintenance Logistics

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

Logistics

Track Maintenance Scheduling

Maintenance Activity	Maintenance Team	Scale	Schedule	Examples
Corrective	Local team	Small	On demand	Defect repair
Capital	Production team	Large	Pre-planned	Rail project, timber and surfacing (T&S) project
Routine	Routine maintenance team	Middle	At a frequency	Ballast cleaning, surfacing, rail grinding

Track Maintenance Logistics

Track Inspection Scheduling

Rail Inspection Scheduling

Geometry Inspection Scheduling

Tie Inspection Scheduling

Capital Mainter Scheduling

Relay Rail Sourcing

New Rail and Tie Sourcing

Ballast Sourcing

Work Train Scheduling

Track Maintenance Logistics

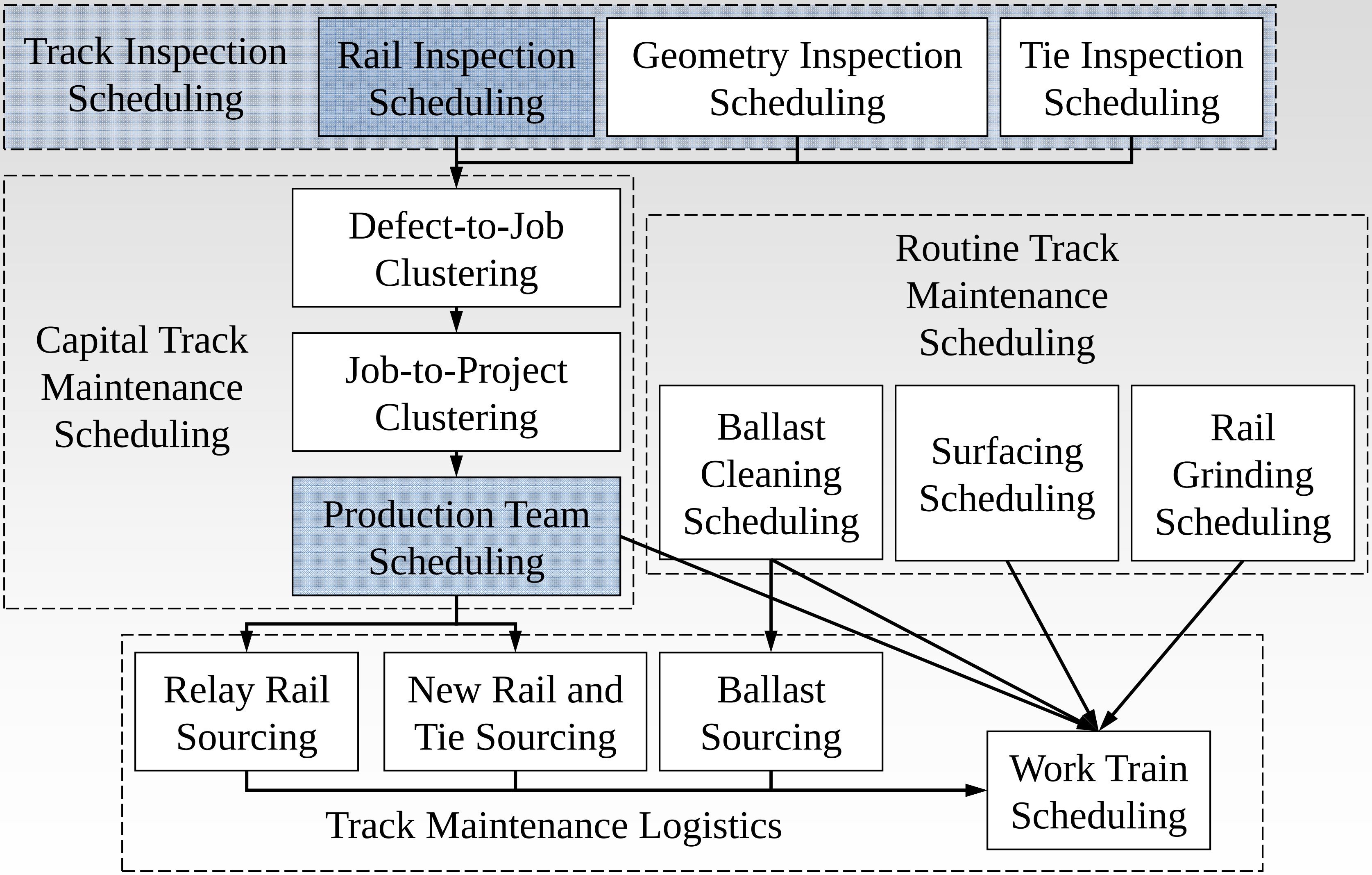
Current Practice in Railroad Industry

- 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

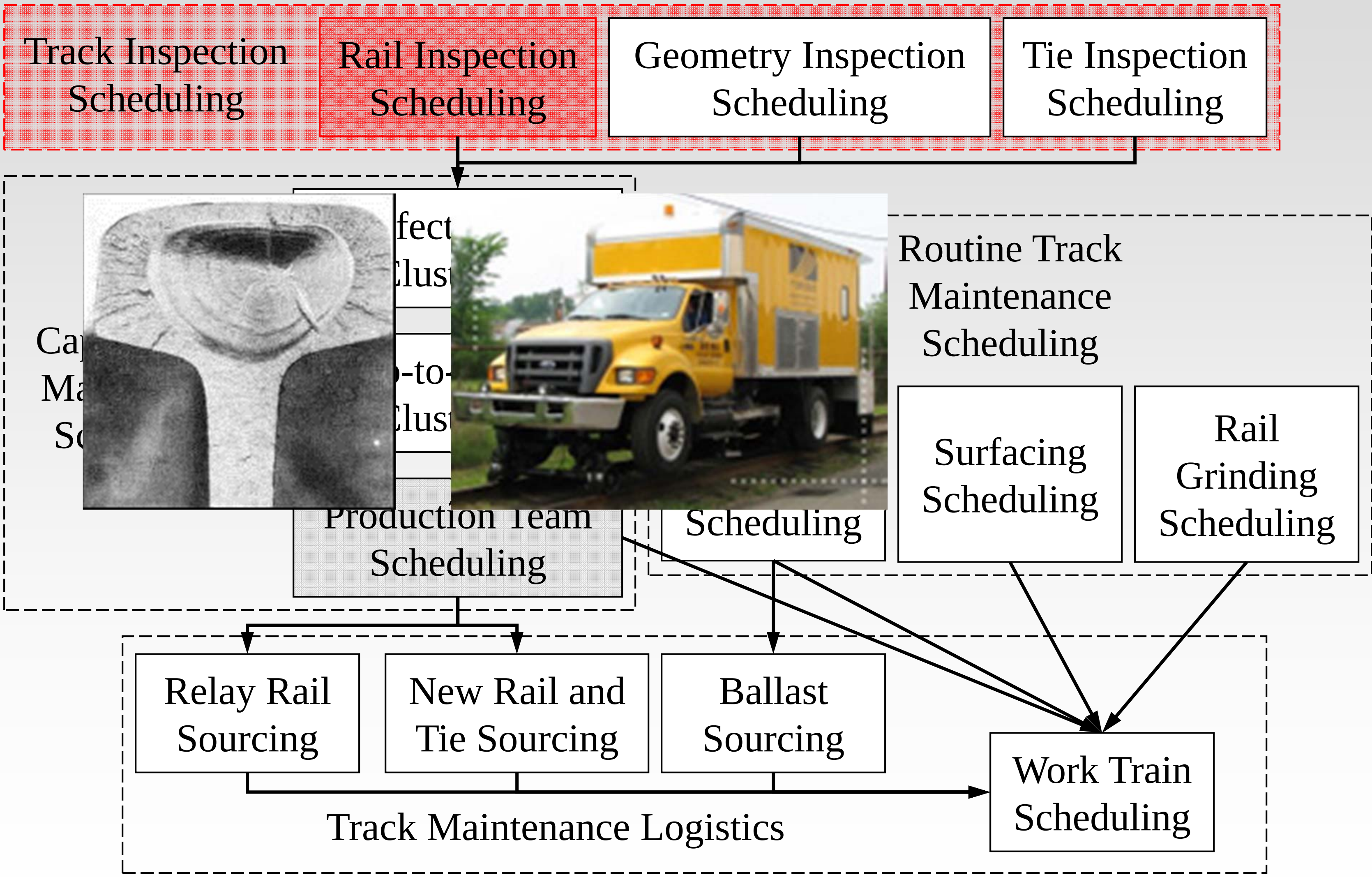
Objective

- 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



Track Inspection Scheduling

Track segments are inspected periodically

Inspection activities are called “tasks”

<table>
<tr><th></th><th>Team 1</th><th>Team 2</th><th>Team 3</th></tr>
<tr><td rowspan="5">Week 1</td><td rowspan="2">Task 1</td><td>Task 4</td><td rowspan="4">Task 8</td></tr>
<tr><td>Travel</td></tr>
<tr><td>Travel</td><td rowspan="4">Task 5</td></tr>
<tr><td rowspan="4">Task 2</td></tr>
<tr><td rowspan="4">Travel</td></tr>
<tr><td rowspan="6">Week 2</td></tr>
<tr><td rowspan="3">Task 6</td></tr>
<tr><td rowspan="2">Travel</td></tr>
<tr><td rowspan="3">Task 9</td></tr>
<tr><td rowspan="2">Task 3</td><td>Travel</td></tr>
<tr><td>Task 7</td></tr>
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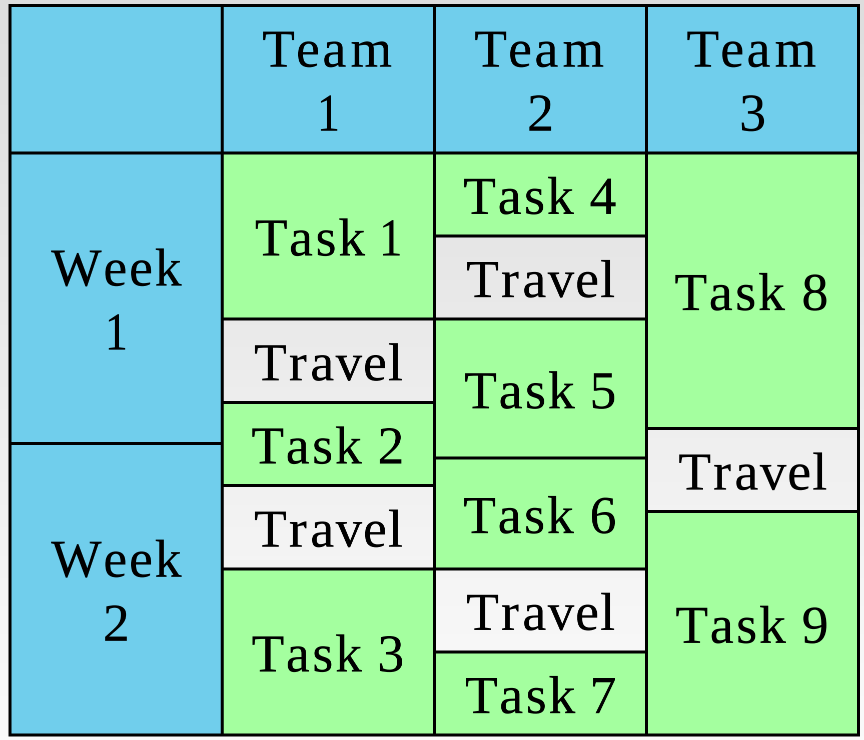
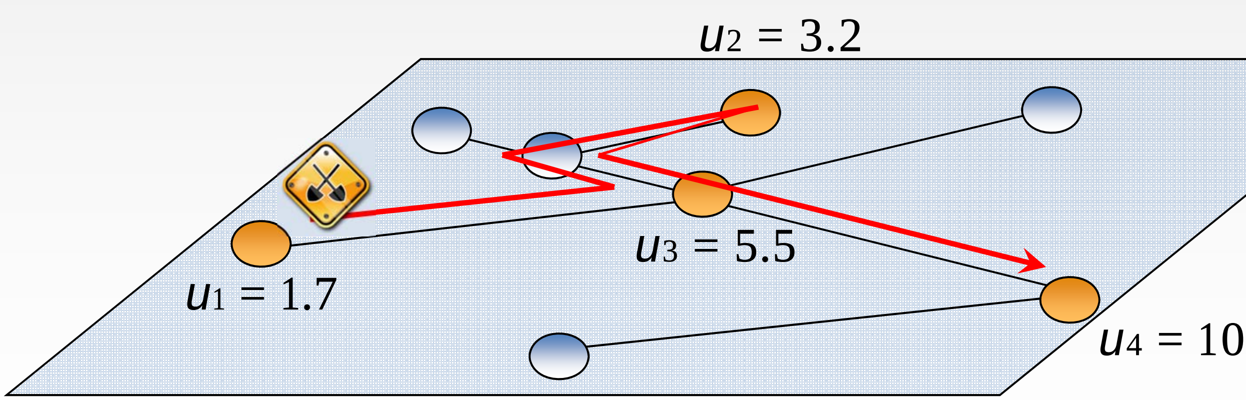
Model and Algorithm Selection

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



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

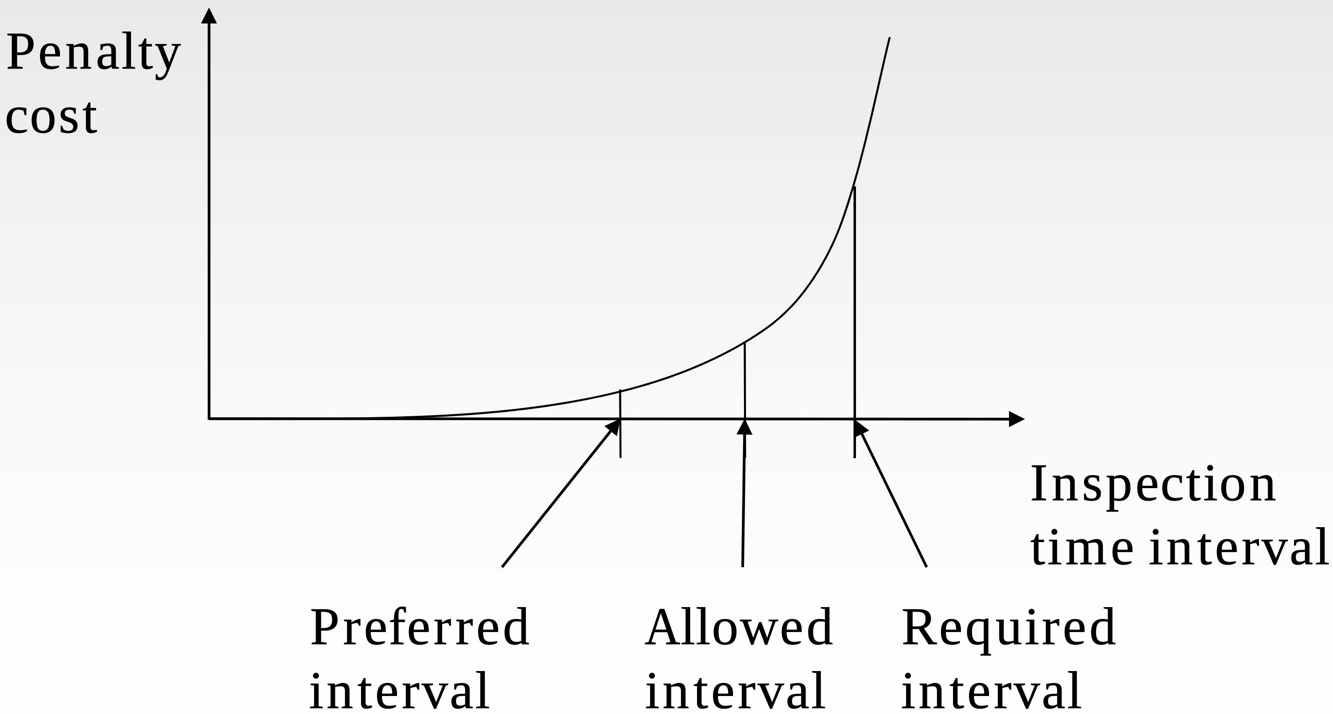


Side Constraints

- 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

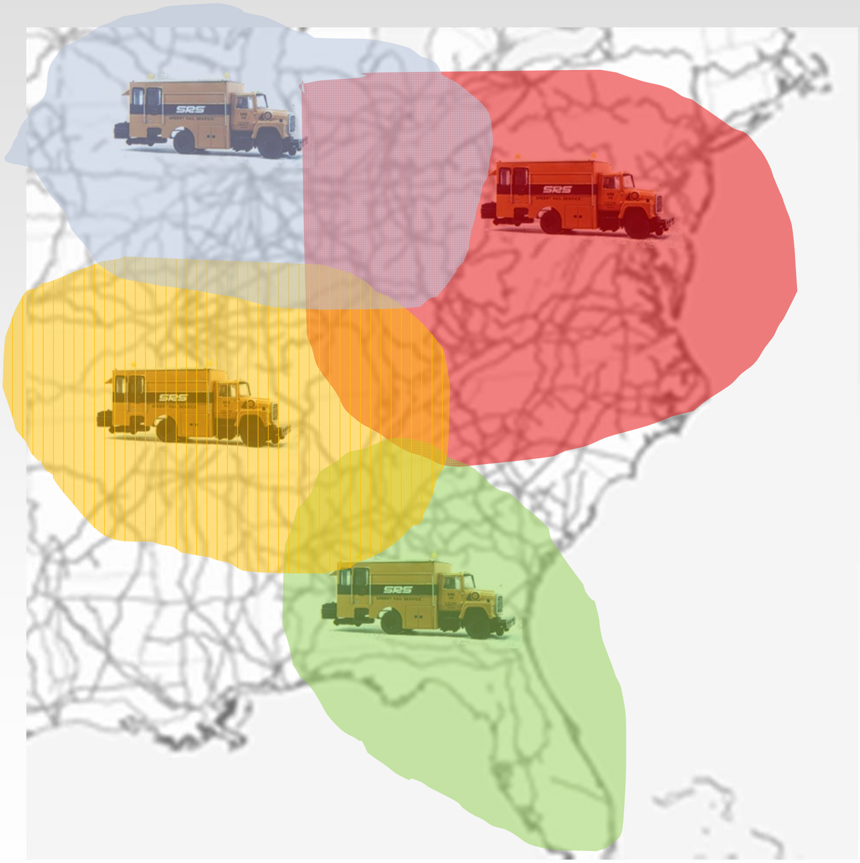
	Team 1	Team 2	Team 3
Week 1	**Task 1** Travel	**Task 4** Travel Task 5	Task 8
Week 2	Task 2 Travel Task 3	Task 6 Travel Task 7	Travel Task 9

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

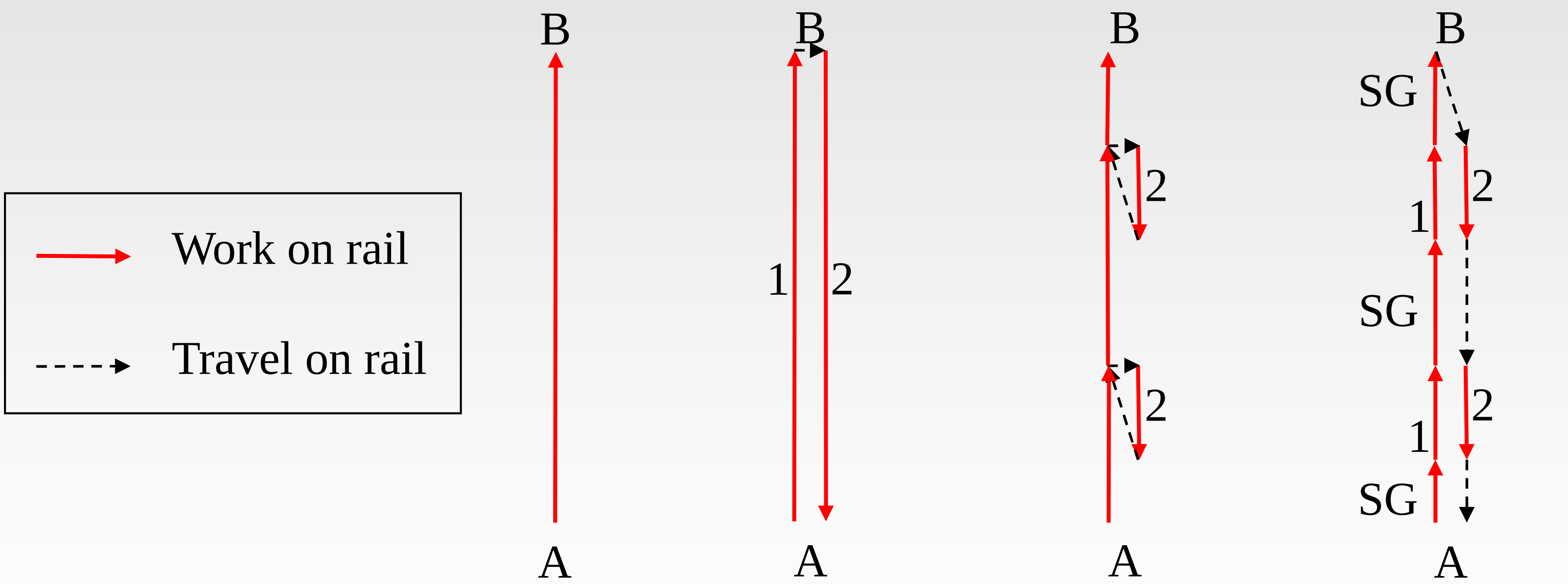
Preference Constraints

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



Network Topology Constraint

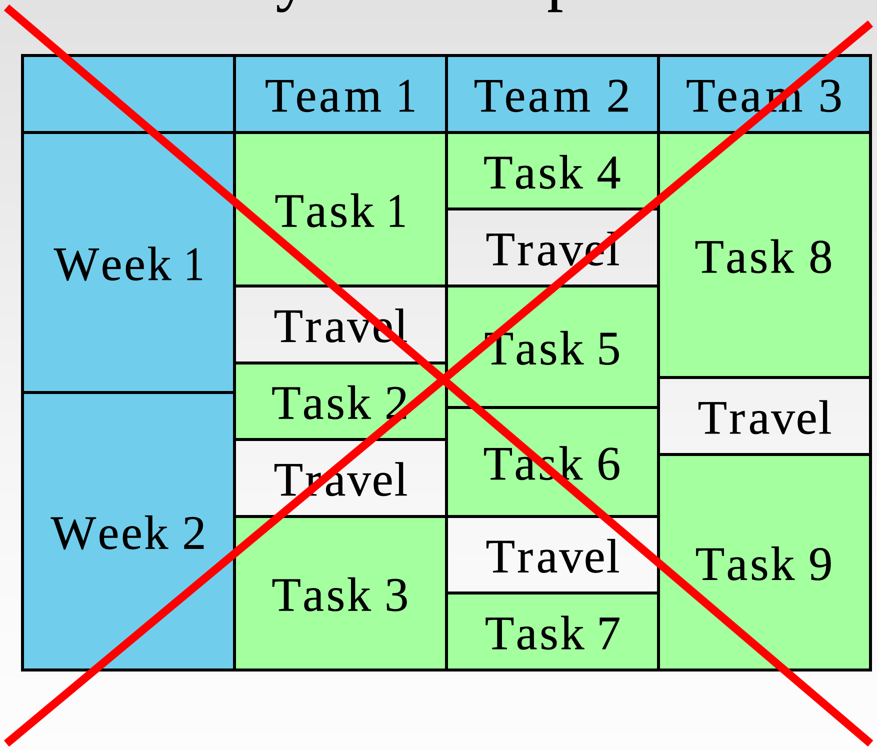
- A task is represented by an arc but not a single point
- Some tasks can be performed together without travelling between each other

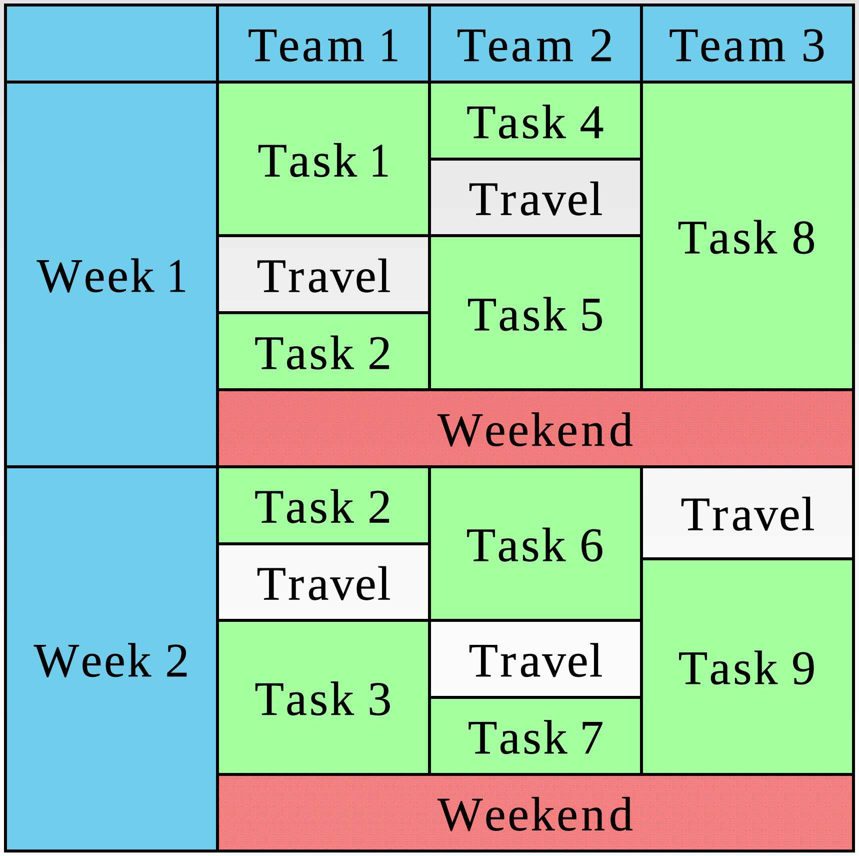


(a) Single track (b) One task on double track (c) One task on partial double track (d) Three tasks on partial double track

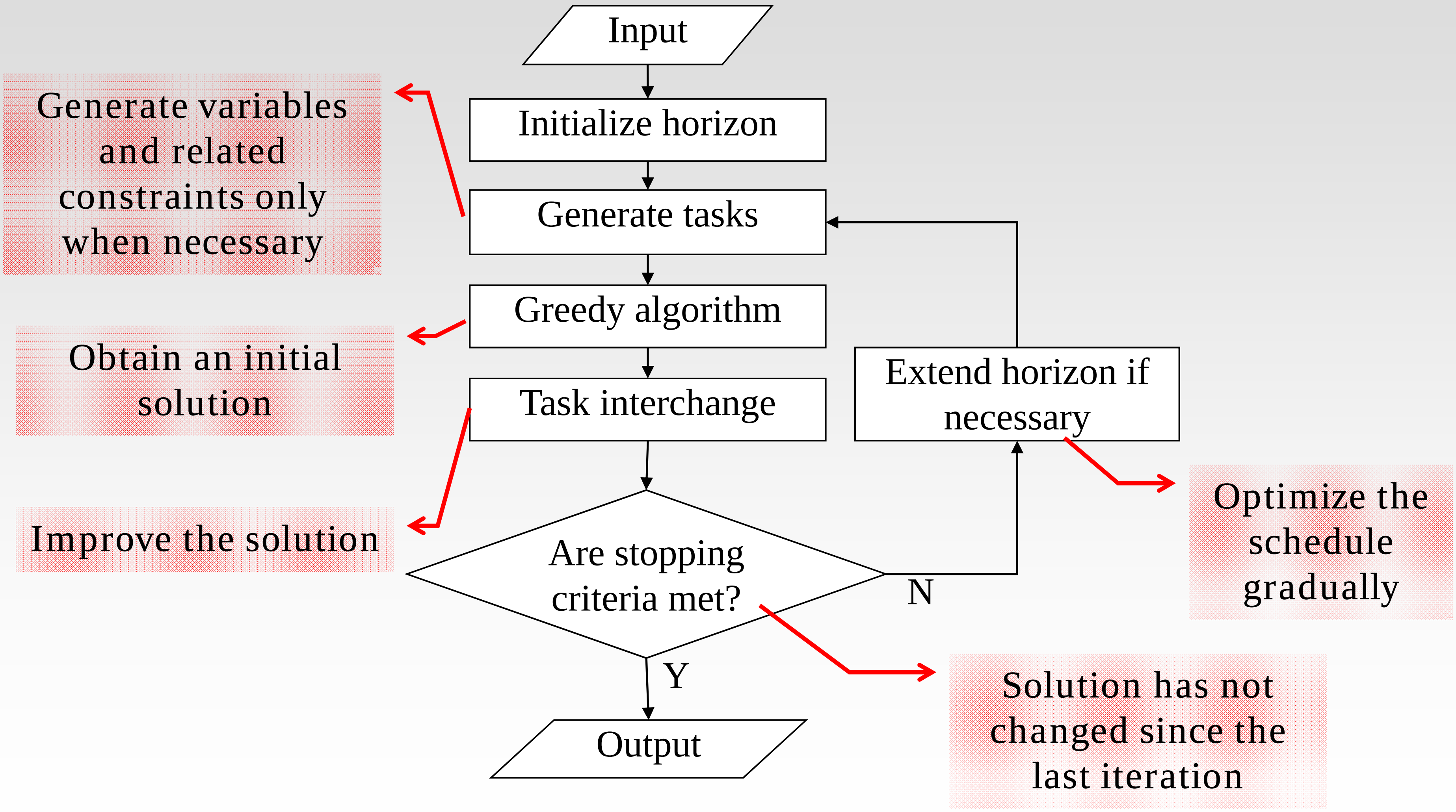
Discrete Working Time Constraint

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





Algorithm Framework



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

Statistics	*Manual solution*	*Model solution*	*Reduction (%)*
Total **overdue percentage** outside the required interval (%)	15.8	4.2	**73.7**
Total **travel distance** between tasks (miles per team per week)	63.2	47.4	**25.0**
Total non-simultaneity constraint **overlapping duration** (days per week)	0.66	0.42	**37.5**

All hard constraints are satisfied.

*Cost entries are scaled to protect data confidentiality

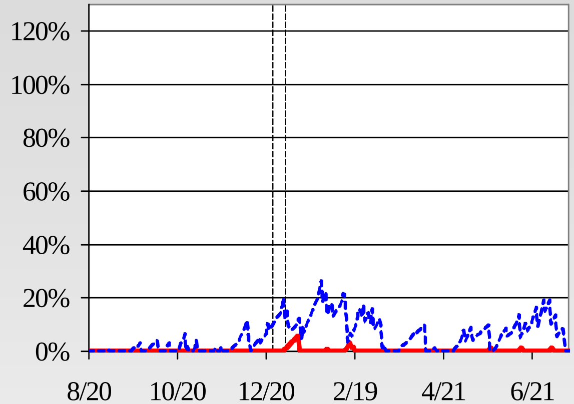
Case Study: Long-Term Planning

- 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

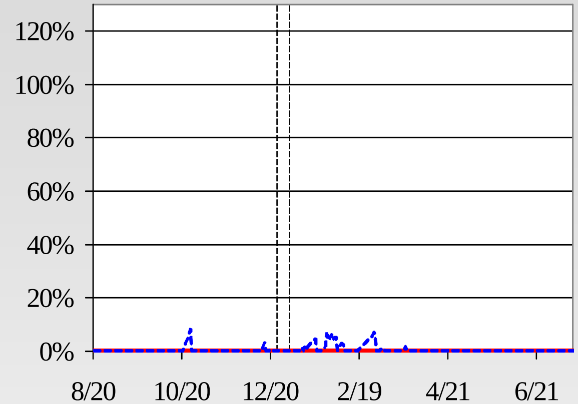
Long-Term What-If Analysis

Total overdue percentage outside the required interval

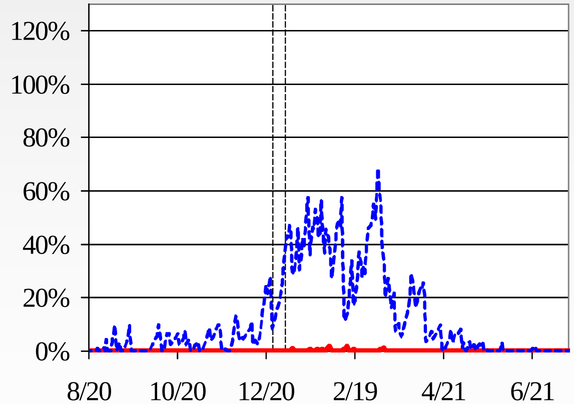
Total overdue percentage outside the allowed interval



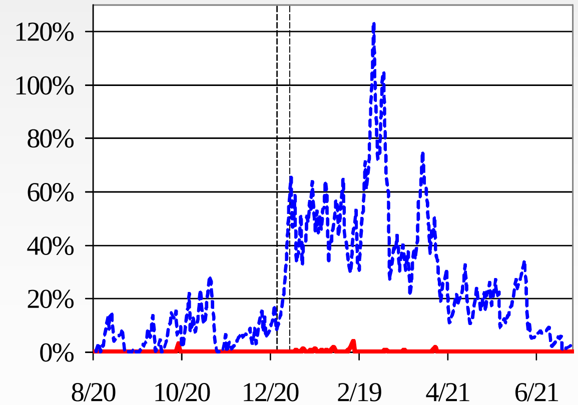
(a) 19 teams with geographic restrictions



(b) 19 teams without geographic restrictions

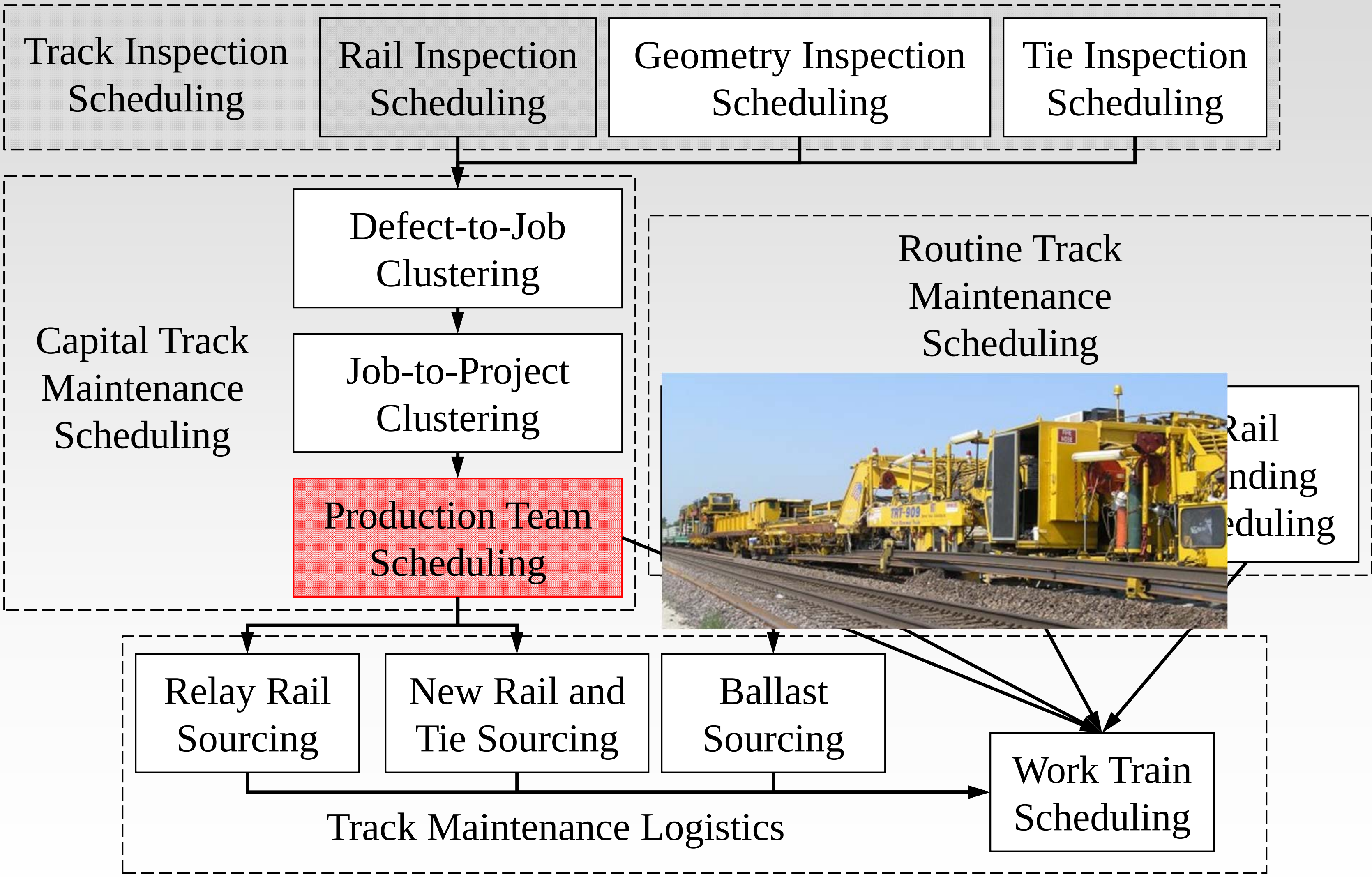


(c) 18 teams without geographic restrictions

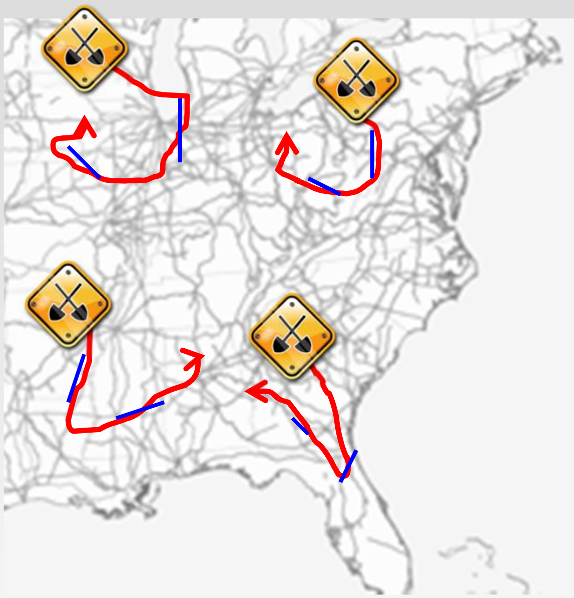


(d) 17 teams without geographic restrictions

Production Team Scheduling



Production Team Scheduling



Projects are identified every year

	Team 1	Team 2	Team 3
Week 1	Project 1	Project 2	Project 3
Week 2	Project 1	Project 6	Project 3
Week 3	Project 4	Project 6	Project 3
Week 4	Project 5	Project 10	Project 3
Week 5	Project 5	Project 8	Project 9
Week 6	Project 5	Project 7	Project 9

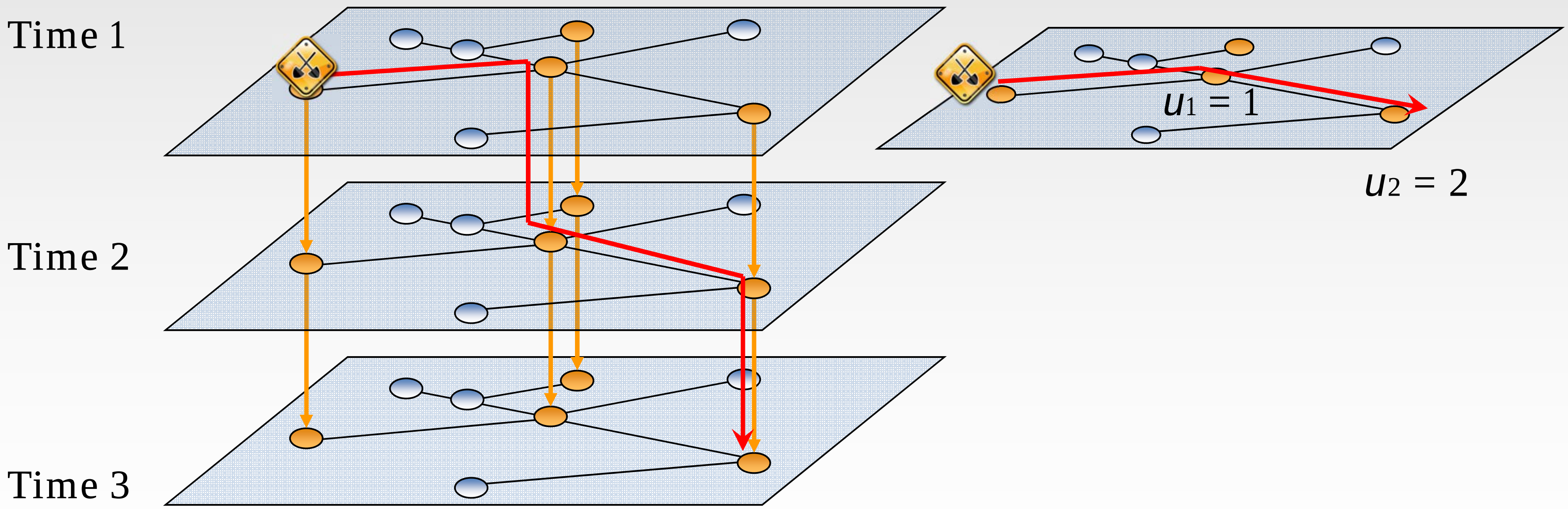
Model and Algorithm Selection

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

	Team 1	Team 2	Team 3
Week 1	Project 1	Project 2	Project 3
Week 2	Project 1	Project 6	Project 3
Week 3	Project 4	Project 6	Project 3
Week 4	Project 5	Project 10	Project 3
Week 5	Project 5	Project 8	Project 9
Week 6	Project 5	Project 7	Project 9

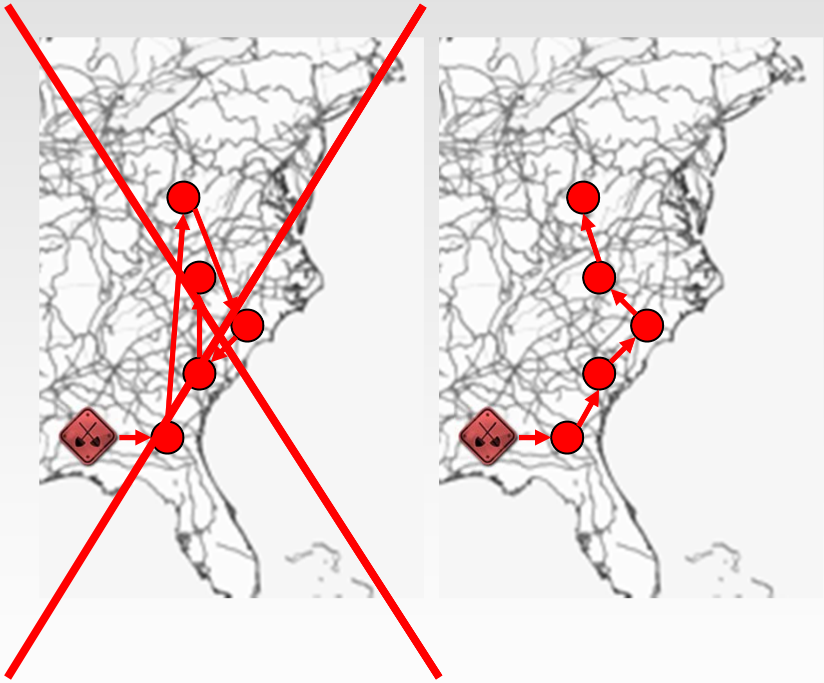
Time-Space Network Model

- 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

Junction Mutual Exclusion Constraint

- 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

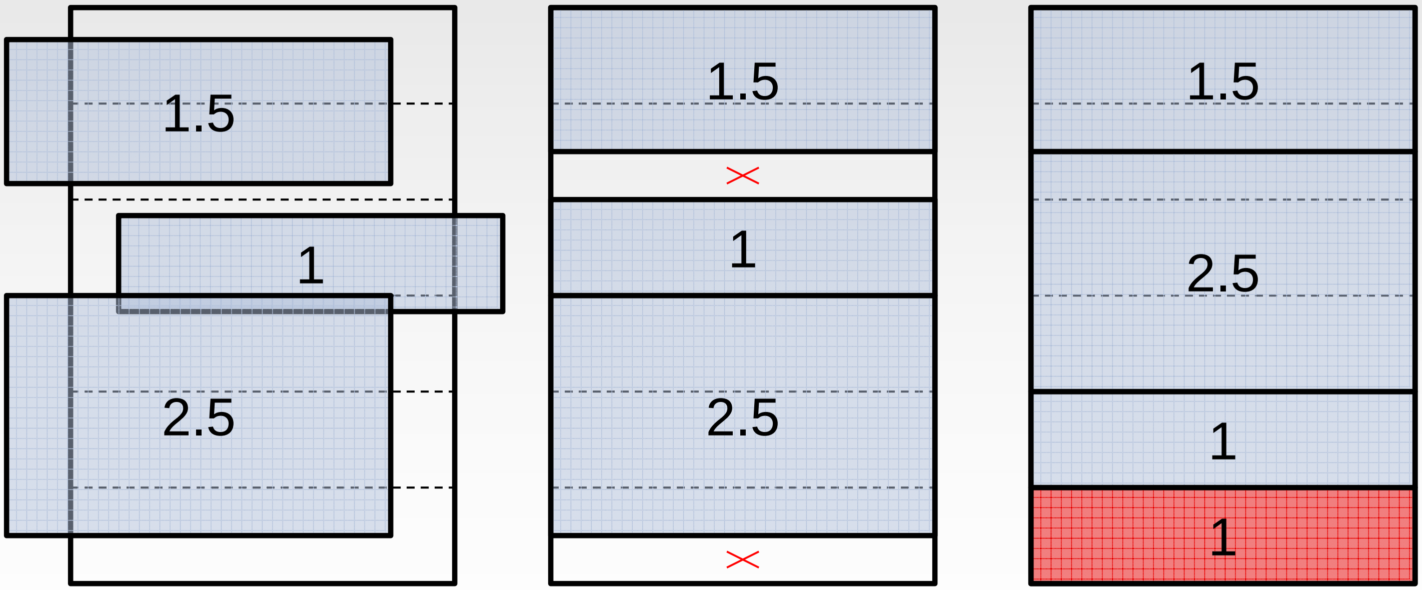
- Certain project should be performed before another project
  - Rail projects before tie projects so that the new ties are not damaged by pulling and inserting spikes

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



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

	Team 1	Team 2	Team 3
Week 1	Project 1	Project 2	Project 3-1
Week 2	Project 1	Project 6	Project 3-1
Week 3	Project 4	Project 6	Project 3-2
Week 4	Project 5	Project 7	Project 3-2
Week 5	Project 5	Project 8-1	Project 8-2
Week 6	Project 5	Project 8-1	Project 8-2

Limitation Constraint

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

	Team 1	Team 2	Team 3
Week 1	Project 1	Project 2	Project 3
Week 2	Project 1	Project 6	Project 3
Week 3	Project 4	Project 6	Project 3
Week 4	Project 5	Project 7	Project 3
Week 5	Project 5	Project 8	Project 9
Week 6	Project 5	Project 8	Project 9

	Team 1	Team 2	Team 3
Week 1	Project 6	Project 2	Project 3
Week 2	Project 6	Project 1	Project 3
Week 3	Project 4	Project 1	Project 3
Week 4	Project 5	Project 7	Project 3
Week 5	Project 5	Project 9	Project 8
Week 6	Project 5	Project 9	Project 8

Relay Rail Constraint

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

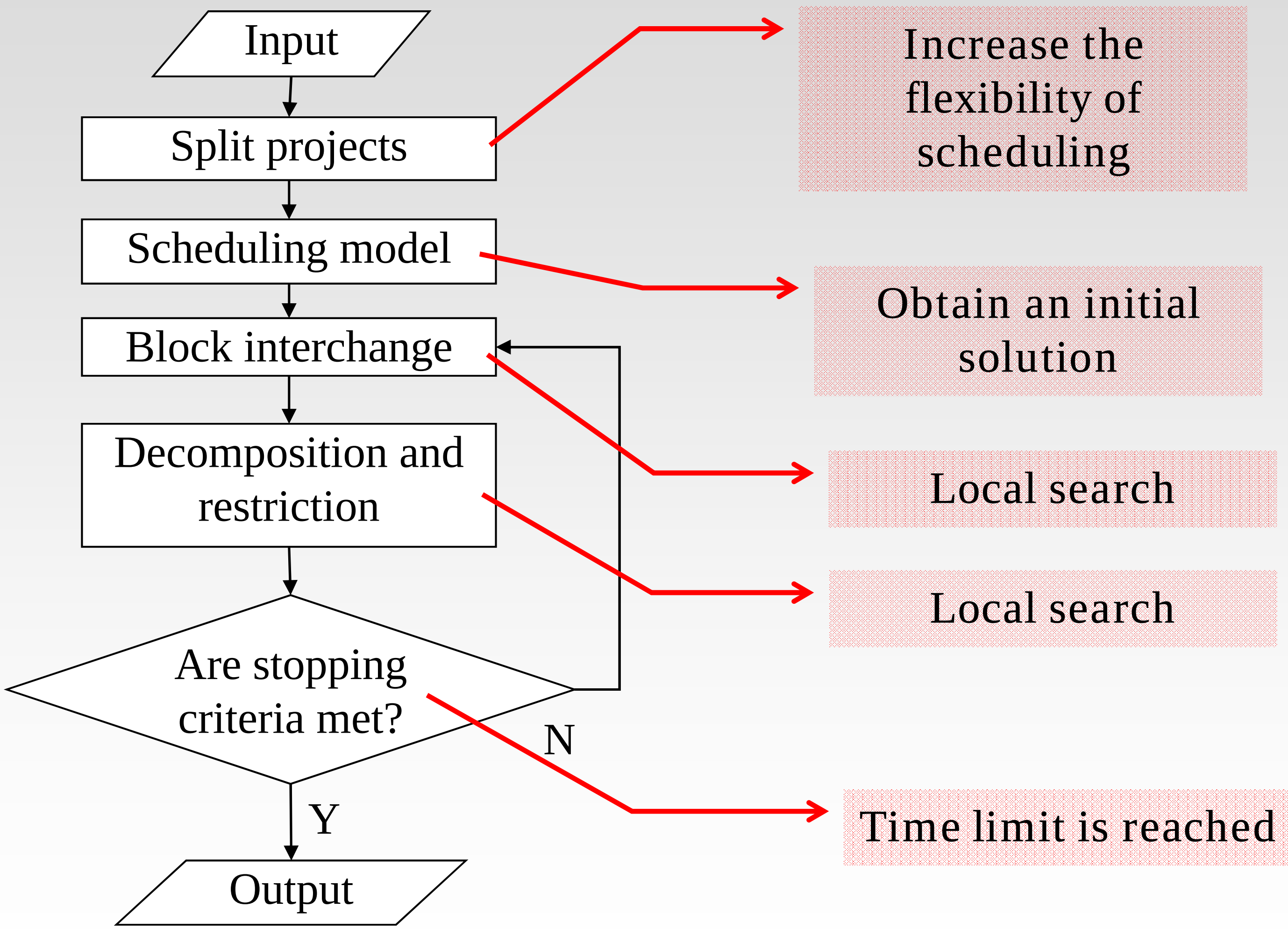
	Team 1	Team 2	Team 3
Week 1	Project 1	Project 2	Project 3
Week 2	Project 1	Project 6	Project 3
Week 3	Project 4	Project 6	Project 3
Week 4	Project 5	Project 10	Project 3
Week 5	Project 5	Project 8	Project 9
Week 6	Project 5	Project 7	Project 9

Jamboree Constraint

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

	Jamboree Teams		Team 3
Week 1	Project 1	Project 2	Project 3
Week 2	Project 1	Project 4	Project 3
Jamboree Weeks	Jamboree Projects		Project 3
			Project 3
Week 5	Project 5	Project 4	Project 7
Week 6	Project 5	Project 6	Project 7

Algorithm Framework



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

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

-66.7% **-18.8%**

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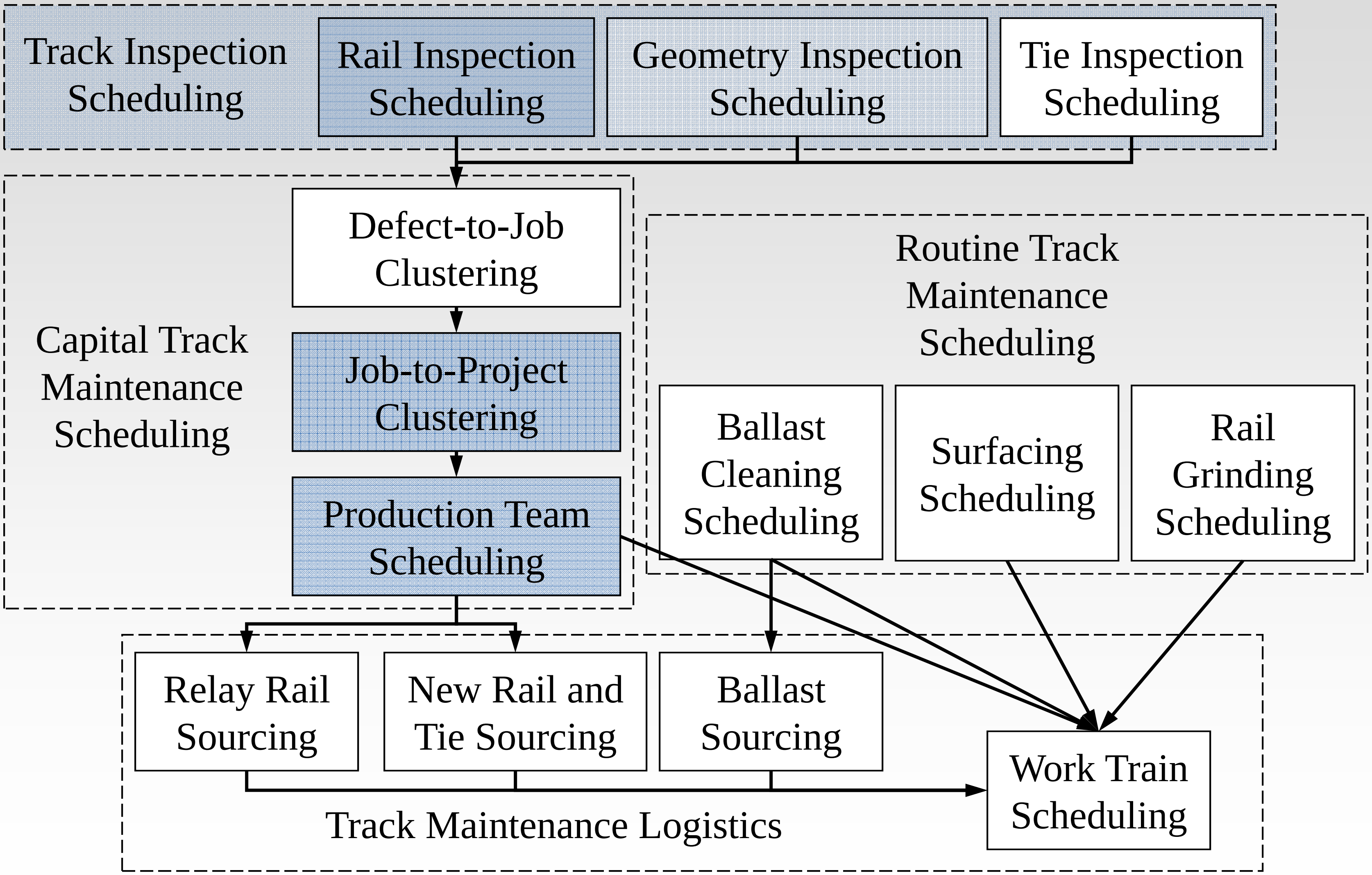
Future Research



Thank you!