From Single-Asset Health Monitoring to dynamic Fleet Maintenance

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Presentation outline

- Introduction: Asset monitoring and Fleet Challenges in Railways
- Problem Formulation: dynamic Resource allocation
- Problem Resolution 1: a linear Programming Model
- Problem Resolution 2: a multi-agent System
- Some preliminary Results
- Future Developments
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Managing the Health of one individual Asset

The search for the best maintenance policy for ONE asset can be seen as:
How to maintain just enough to avoid failures, rather than over-maintaining.

Minimize Cost subject to Availability constraint

Predictive Maintenance: "not too early, not too late"
New Challenges when moving from individual Asset to Fleet

- An individual asset can be studied in a lab environment (test bench)
- A fleet of assets (all passenger doors on 600 trains, 1000 point machines in a country…)
  - Is comprised of numerous assets, each with its own profile, environment and context
  - Subject to operational constraints

Can be studied only in the actual field environment
The Vision: by 20XX (xx=?), in our industry

- **Real-time**
  - Every railway asset in the world will be remotely monitored in real-time

- **Dynamic**
  - Maintenance schedules will be created dynamically based on the predicted condition of each single component

- **Automatic**
  - Workload balancing in depots will be done automatically
What’s needed to fulfil that vision

Missions (Operations constraints)

I1: rolling stock and infrastructure
I2: maintenance resources
I3: human resources
I4: health indicators or RULs with uncertainties

Dynamic Maintenance decisions

01: train routing
02: predictive maintenance planning
03: personnel planning
04: performance indicators (cost, quality of service, confidence, ...)

Predictive maintenance for a fleet of assets with material and human resource constraints
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Dynamic Resource Allocation

Systematic Maintenance ➔ Maintenance Plan ➔ Depot / Field Constraints

Corrective Maintenance ➔ Corrective Notification ➔ DEMAND OPTIMIZER

Predictive Maintenance ➔ Predictive Notification ➔ MMIS Backlog

Diagramming

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Resolution based on Linear Programming – Assumptions

Network and infrastructure
- track sections, turnouts, ...

Operation
- P tramways per day
  - P missions per day
    - (1 mission = 1 set of rides assigned to 1 tramway)
    - each mission is associated to a degradation rate $\delta$

Depot
- m tramways
  - m tramways of same type (interchangeable)
    - granularity:
      - system – tramway
      - sub-system – air conditioning system
      - component – filter
    - 1 RUL value for each tramway (RUL of the limiting component)
    - no degradation when not in use
    - the degradation of a sub-system has no impact on the degradation of other sub-systems

Maintenance center
- human resources
- tools
- spare parts

Maintenance planning
- maintenance capacity expressed as a number of tramways that can be maintained each day
  - c maintenance operations per day
  - duration of each maintenance operation: 1 day

- maintenance dates
- maintenance operations (type, grouping, ...)
- choice of tramways to send to revenue service each day

Network and infrastructure
- track sections, turnouts, ...

resolution based on Linear Programming
Resolution based on Linear Programming – use case

○ Assumptions: 4 tramways, 1 sub-system per tramway for predictive maintenance

○ Simulations: degradation for each RS unit follows a Weibull distribution

\[ k_1 = 3, \lambda_1 = 21, \theta_1 = -1 \] \[ k_2 = 8, \lambda_2 = 18, \theta_2 = -14 \] \[ k_3 = 6, \lambda_3 = 9, \theta_3 = 0 \] \[ k_4 = 6, \lambda_4 = 10, \theta_4 = -13 \]
Resolution based on Linear Programming

- **Linear Programming**
  - Assumptions:
    - \( m \) rolling stock units \( M_j \) (\( j=1,\ldots,m \)) – \( \text{RUL}_j \)
    - \( P \) missions \( T_p \) per day (\( p=1,\ldots,P \)) – \( \delta_p = \delta \)
    - 1 maintenance op. for each rolling stock unit – duration: \( \Delta T \)
    - maintenance capacity: \( c \) operations per \( \Delta T \)
    - horizon \( H = K\Delta T \) (\( k=1,\ldots,K \))
  - Decision variables:
    \[ x_{j,k} = 1 \text{ if the RS unit } M_j \text{ performs a mission during Day } k \]
    \[ y_{j,k} = 1 \text{ if the RS unit } M_j \text{ is maintained on Day } k \]
Resolution based on Linear Programming: constraints

- **Linear Programming**
  - assignment of rolling stock to the P missions
  - Compliance with RUL values (modeled as deterministic)
  - no assignment during maintenance
  - maintenance capacity constraint
  - only one maintenance op. per rolling stock unit

\[
\sum_{j=1}^{m} x_{j,k} = P \quad \forall 1 \leq k \leq K
\]

\[
\sum_{k=1}^{K} \delta \cdot x_{j,k} (1 - y_{j,k}) \leq RUL_j \quad \forall 1 \leq j \leq m
\]

\[
y_{j,k} - y_{j,k-1} \leq 1 - x_{j,k} \quad \forall 1 \leq j \leq m, \forall 1 \leq k \leq K
\]

\[
\sum_{i=1}^{m} (y_{j,k} - y_{j,k-1}) \leq c \quad \forall 1 \leq k \leq K
\]

\[
\sum_{k=1}^{K} (y_{j,k} - y_{j,k-1}) \leq 1 \quad \forall 1 \leq k \leq K
\]
Resolution based on Linear Programming – use case

Assumptions:

- \( m = 4 \) tramways, \( n = 1 \) sub-system per tramway for predictive maintenance
- \( P = 3 \) missions per day \( k \)
- \( H = 20 \) days (\( K = 20 \))
- \( c = 1 \) maintenance operation per day

Output Schedule

\( M_1, M_2, M_3, M_4 \)

\( M_1: \) RUL\(_1(0) = 27\)
\( M_2: \) RUL\(_2(0) = 6\)
\( RUL_2(M) = 2\)
\( M_3: \) RUL\(_3(0) = 11\)
\( RUL_3(M) = 3\)
\( M_4: \) RUL\(_4(0) = 0\)
\( RUL_4(M) = 0\)
Linear Programming (LP): various objective functions

- Objective 1: maximize degradation level before maintenance
- Objective 2: minimize the number of maintenance operations over the scheduling horizon.
- Objective 3: maximize service provided, i.e. number of missions.

→ Each leads to different decisions.

LP: a sound approach but quickly breaks downs when number of systems or time horizon increases…. The “curse of dimensionality”.
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Multi-Agent System Approach

- Multi-Agent Systems (MAS): approximate solutions to very complex problems by distributing them to agents, which can be seen as autonomous problem solvers (but need to coordinate)

- Well suited to the functionally and geographically distributed characteristics of a rail transport system.

- Who are the agents?
  - A Maintenance Agent: elaborates maintenance plans
  - An Operations Agent: assigns assets to missions
  - Resource Agents: provide resources (rolling stock, maintenance facilities)
  - System Agents: manage the state of health of each asset

- Agents’ “conflicting” goals:
  - Operations: fulfil missions
  - Maintenance: keep assets healthy
  - They need to ‘negotiate’.
Interactions between Agents

**Systems**
- m systems

**Operations**
- choice of systems to send in revenue service each day
- set of rides
- associated expected degradation rates

**Resources**
- human resources
- tools
- Tracks

**Maintenance**
- choice of systems to send in maintenance each day
- maintenance dates
- maintenance operations (type, grouping, …)

Schedule

System Availability
Agents’ Data

Systems
- Number of systems
- Sub-systems that require Predictive maintenance
- RULs of sub-systems after maintenance
- Sub-systems that require Systematic maintenance
- Periodicity of each systematic maintenance
- Cost of lost Km for each sub-system

Operations
- Number of missions per day
- Length of missions
- Degradation rate of missions
- Cost of lost mission
- Planning horizon
- choice of systems to send in revenue service each day
- set of rides
- associated expected degradation rates

Maintenance
- Number of resources
- Availability of resources
- choice of systems to send in maintenance each day
- maintenance dates
- maintenance operations (type, grouping, …)

- human resources
- tools
- Tracks
- Needed time for maint tasks
- Needed resources (Number + Time) for maint tasks
- Cost of each maint task
Some Preliminary Results

- **Linear Programming Model**

Figure 7: Maximum number of maintenance operations per day for the three objective functions and maintenance capacities $c = 1, 2, 3, 4$ and $5 - m = 18$ systems, $P = 15$ missions.
Evaluation Metrics (KPIs)

KPI1: Number of lost (non-performed) missions.
   → key for Operations

KPI2: Number of maintenance operations per day.
   → Maintenance capacity requirements

KPI3: Number of maintenance operations/component over planning horizon → LCC.

KPI4: ‘Lost km per maintenance action’: kms that still could have been performed given the state of health.

KPI5: Resource Load Ratio: % of time during which a resource is effectively utilized.

Various policies impact those metrics differently
Heuristic Policies

S1: assign most degraded train to easiest mission → keep best systems available

S2: assign easiest mission to most degraded system that can perform it → postpone next maintenance of each system

S3: -- in a first step, S1
   -- in a second step, Operations and Maintenance agents communicate to minimize number of lost missions

S4: Distribution maintenance operations over time

S5: choose systems to be maintained so as to maximize maintenance resource use

S6: use S4 for mission assignment and S5 for maintenance assignment
Resolution approach based on Multi-Agent Model

Heuristic Decision Making

6 Strategies (S1, S2,….. S6)
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Some Future Developments

- More-general types of networks (Main Lines–several depots)
- Model RULs as random variables
- Model more explicitly the “negotiation process” between Operations and Maintenance agents
- Encapsulate some linear-programming algorithms inside the agents
- Formalize operating costs to evaluate cost of lost missions
- Rigorous derivation of system (train)-level health attributes from subsystem ones
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Bibliography


