From Single-Asset Health Monitoring to dynamic Fleet Maintenance

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Designing fluidity

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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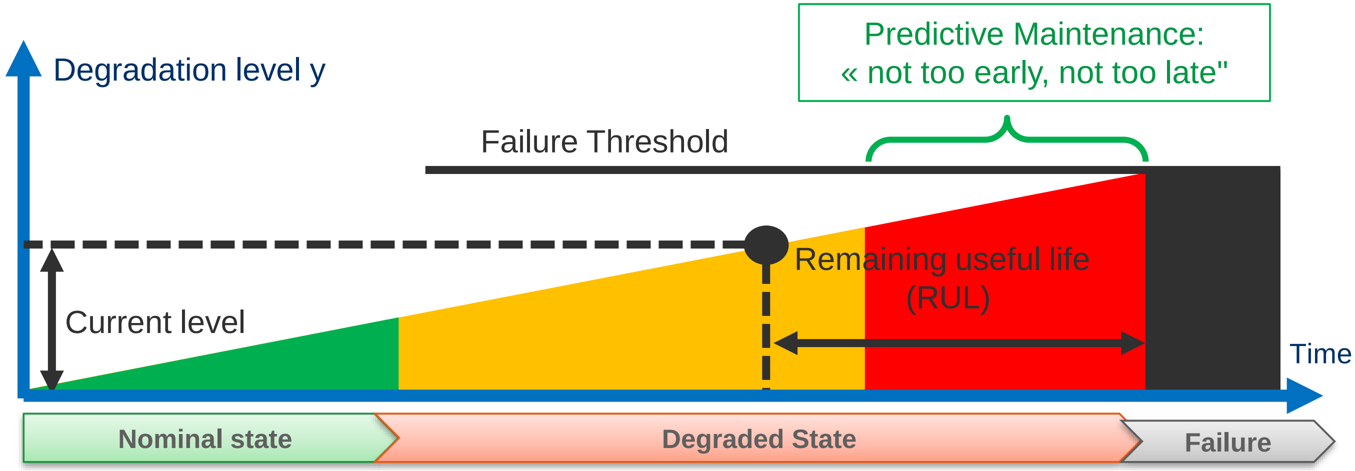
Managing the Health of one individual Asset

- 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

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

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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

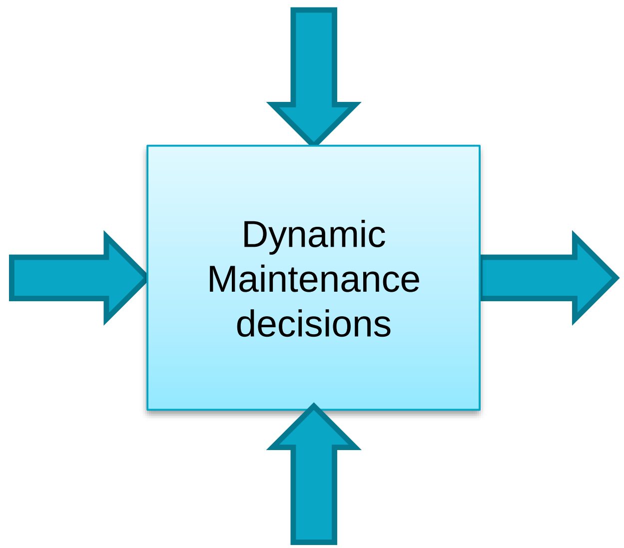
Missions
(Operations
constraints)

I1: rolling stock and infrastructure

I2: maintenance resources

I3: human resources

I4: health indicators or RULs
with uncertainties



O1: train routing

O2: predictive maintenance planning

O3: personnel planning

O4: performance indicators
(cost, quality of service,
confidence, …)

performance objectives
(schedule adherence,
availability, ..)

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

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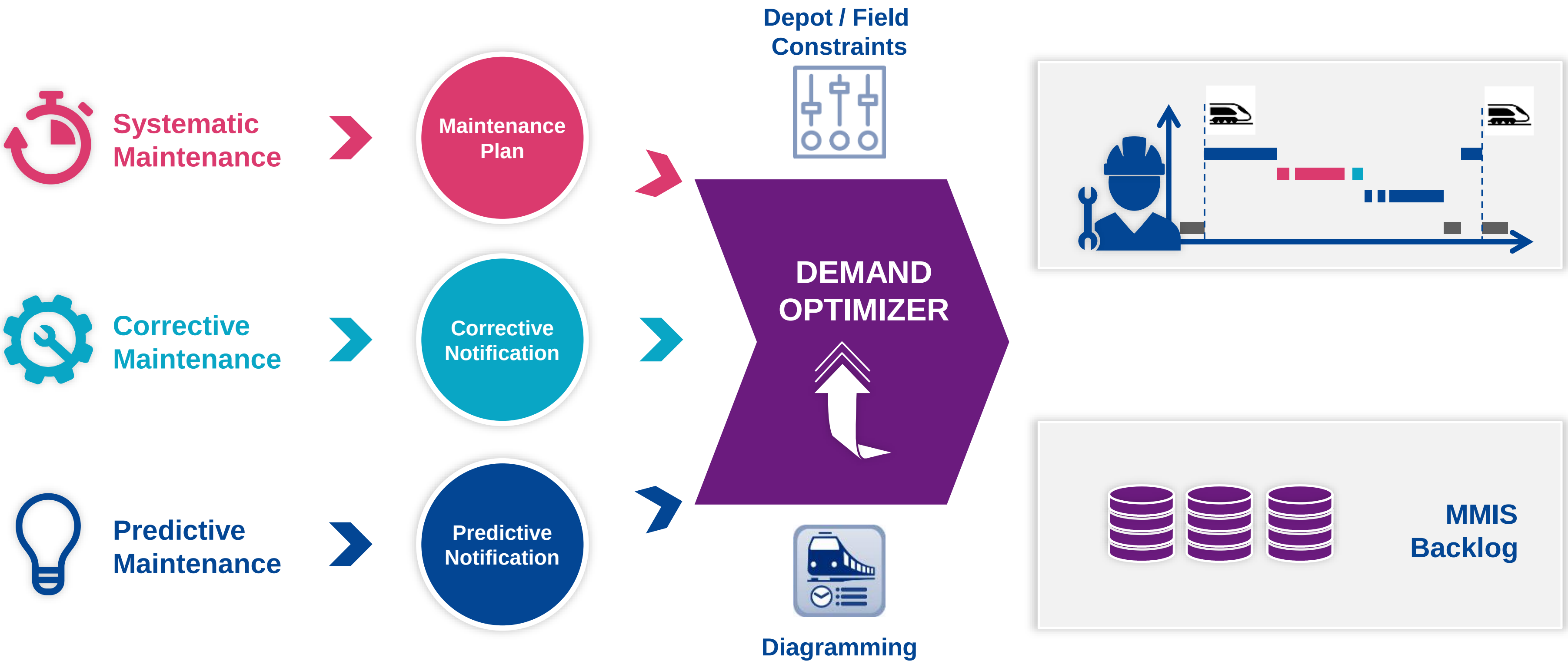
Dynamic Resource Allocation



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Resolution based on Linear Programming – Assumptions

Network and infrastructure

track sections, turnouts, ...

P missions per day
(1 mission = 1 set of rides assigned to 1 tramway)
- each mission is associated to a degradation rate δ

Operation

P tramways per day

...

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

resolution based on **Linear Programming**

Maintenance planning

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

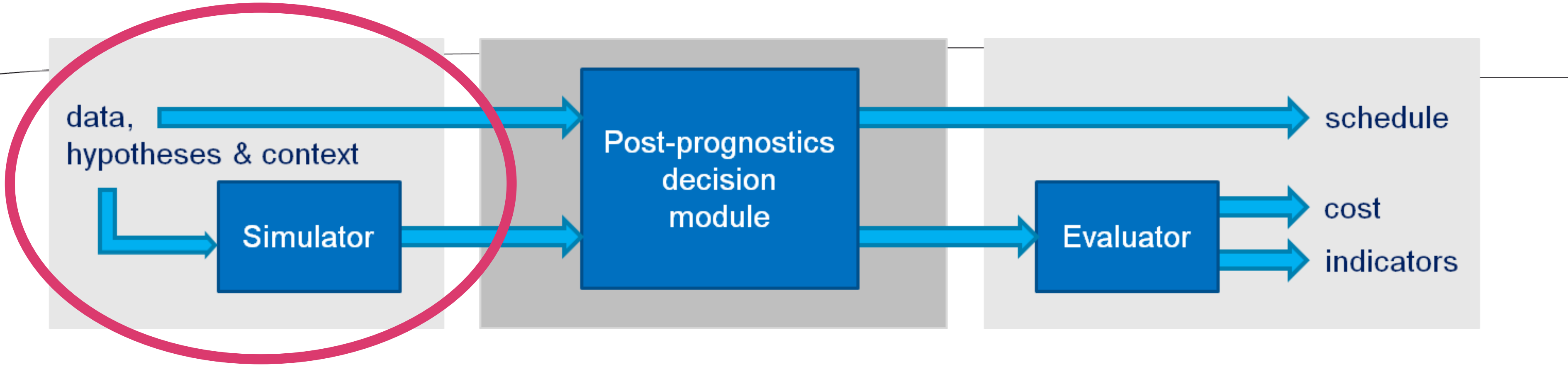
Maintenance center

- human resources
- tools
- spare parts

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

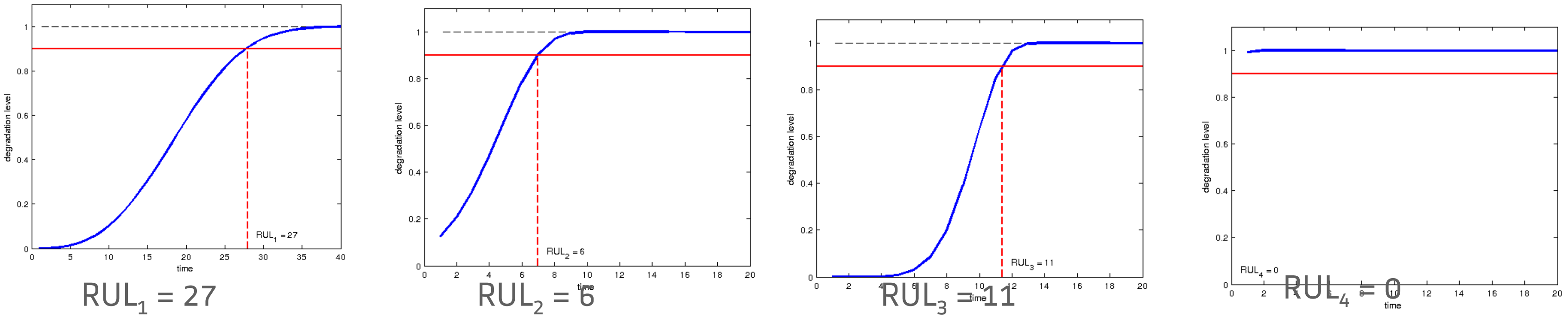
Resolution based on Linear Programming – use case



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

- **Simulations:** degradation for each RS unit follows a Weibull distribution

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



$RUL_1 = 27$ $RUL_2 = 6$ $RUL_3 = 11$ $RUL_4 = 0$

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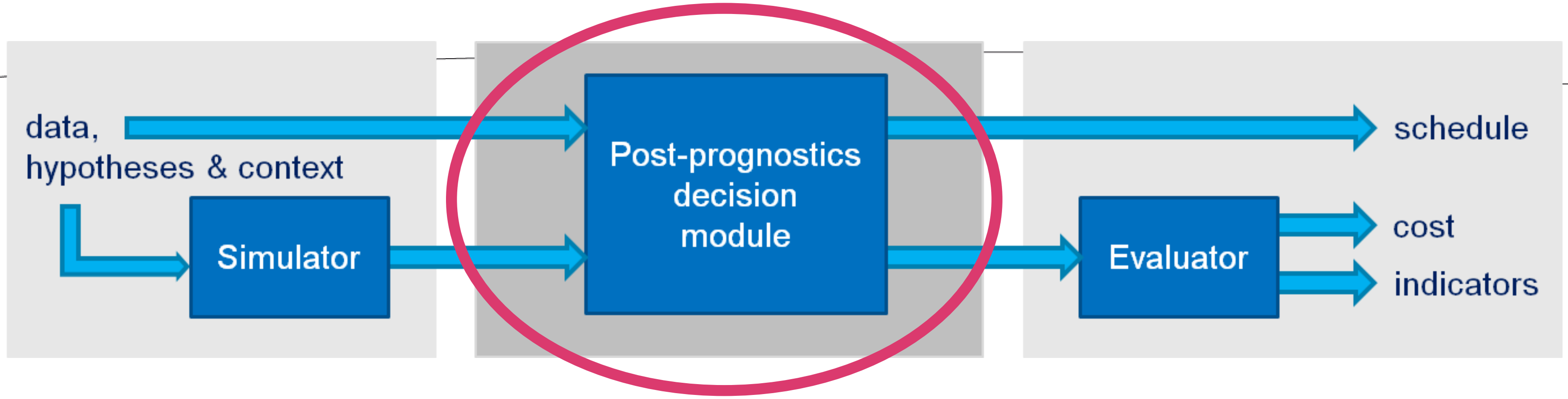
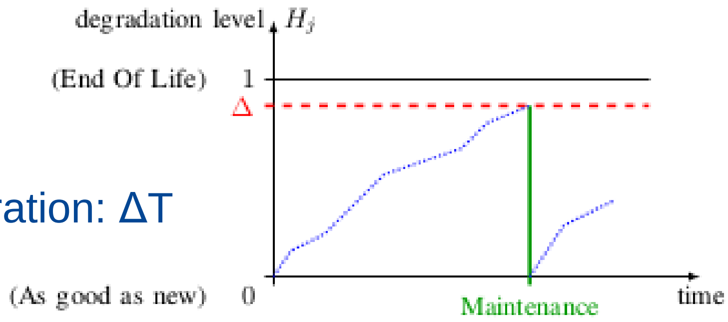
Resolution based on Linear Programming



Linear Programming

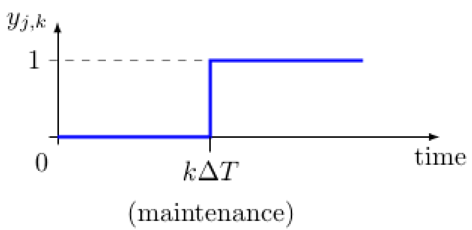
- Assumptions:
  - **m** rolling stock units M_j (j=1,…,m) – **RUL_j**
  - **P** missions T_p per day (p=1,…,P) – **δ_p** = **δ**
  - **1** maintenance op. for each rolling stock unit – duration: ΔT
  - maintenance capacity: **c** operations per ΔT
  - horizon **H** = KΔT (k=1,…,K)



- Decision variables:

$x_{j,k}$ = 1 if the RS unit M_j performs a mission during Day k

$y_{j,k}$ = 1 if the RS unit M_j is maintained on Day k



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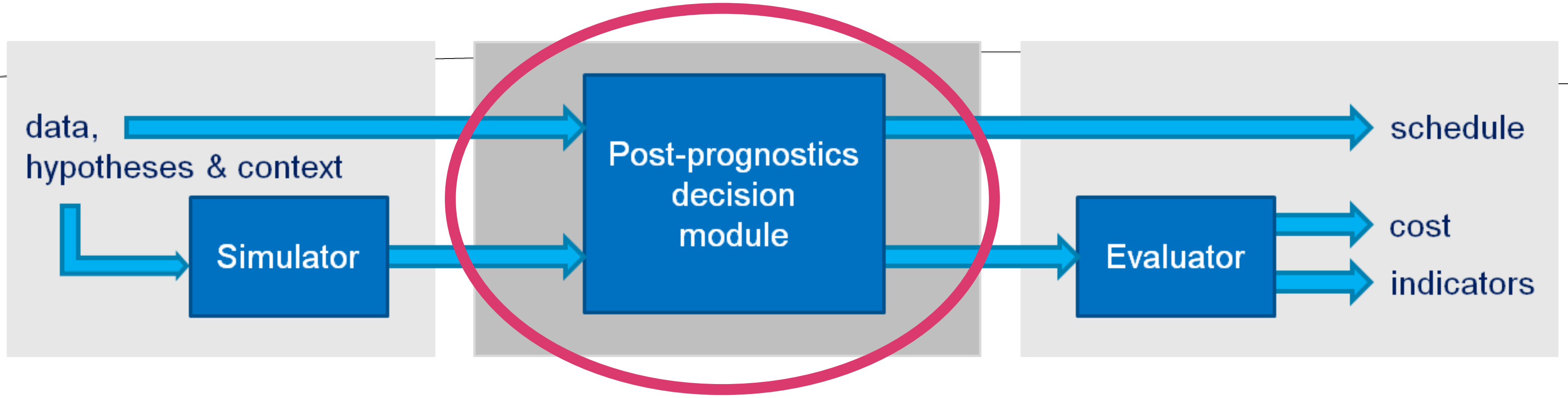
Resolution based on Linear Programming : constraints

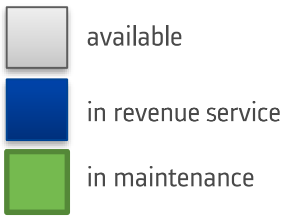


- Linear Programming
  - assignment of rolling stock to the P missions
    $$\sum_{j=1}^{m} x_{j,k} = P \qquad \forall 1 \leqslant k \leqslant K$$
  - Compliance with RUL values (modeled as deterministic)
    $$\sum_{k=1}^{K} \delta \cdot x_{j,k}(1 - y_{j,k}) \leqslant RUL_j \qquad \forall 1 \leqslant j \leqslant m$$
  - no assignment during maintenance
    $$y_{j,k} - y_{j,k-1} \leqslant 1 - x_{j,k} \qquad \forall 1 \leqslant j \leqslant m,\ \forall 1 \leqslant k \leqslant K$$
  - maintenance capacity constraint
    $$\sum_{j=1}^{m} (y_{j,k} - y_{j,k-1}) \leqslant c \qquad \forall 1 \leqslant k \leqslant K$$
  - only one maintenance op. per rolling stock unit
    $$\sum_{k=1}^{K} (y_{j,k} - y_{j,k-1}) \leqslant 1 \qquad \forall 1 \leqslant k \leqslant K$$

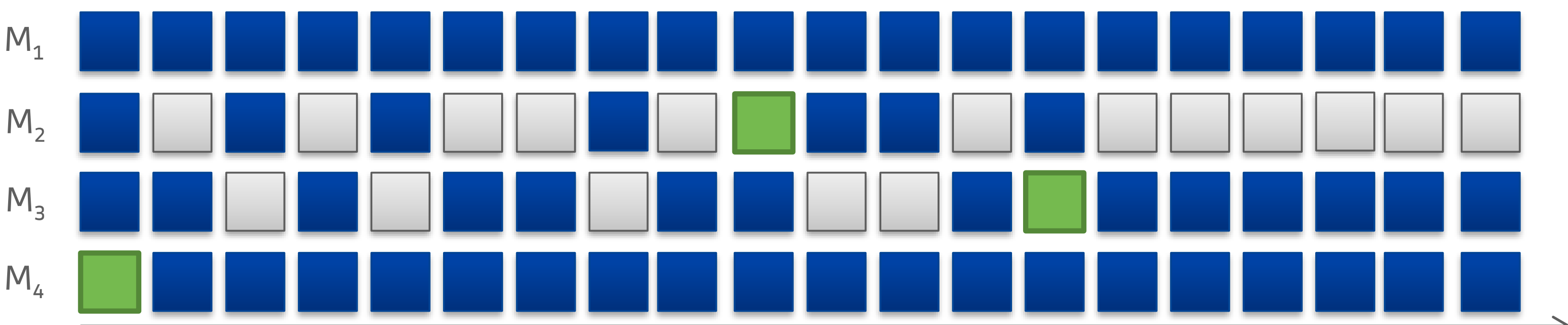
Resolution based on Linear Programming – use case

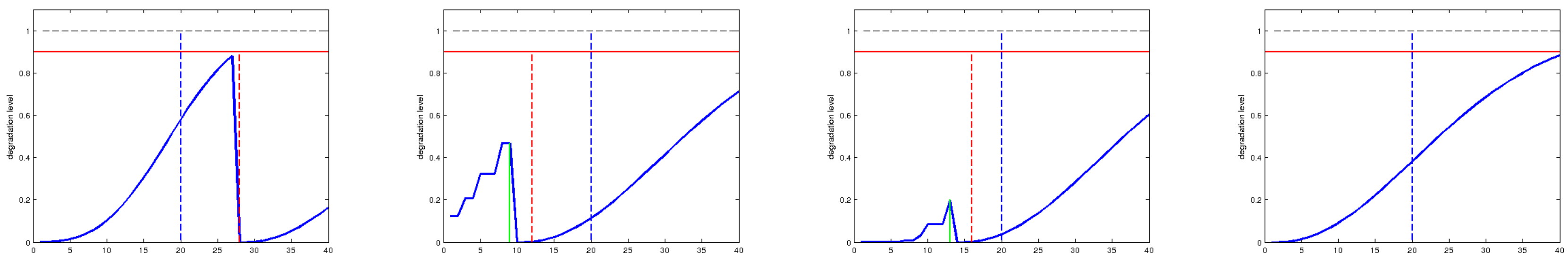
Assumptions:

- 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: $RUL_1(0) = 27$

M_2: $RUL_2(0) = 6$
$RUL_2(M) = 2$

M_3: $RUL_3(0) = 11$
$RUL_3(M) = 3$

M_4: $RUL_4(0) = 0$
$RUL_4(M) = 0$

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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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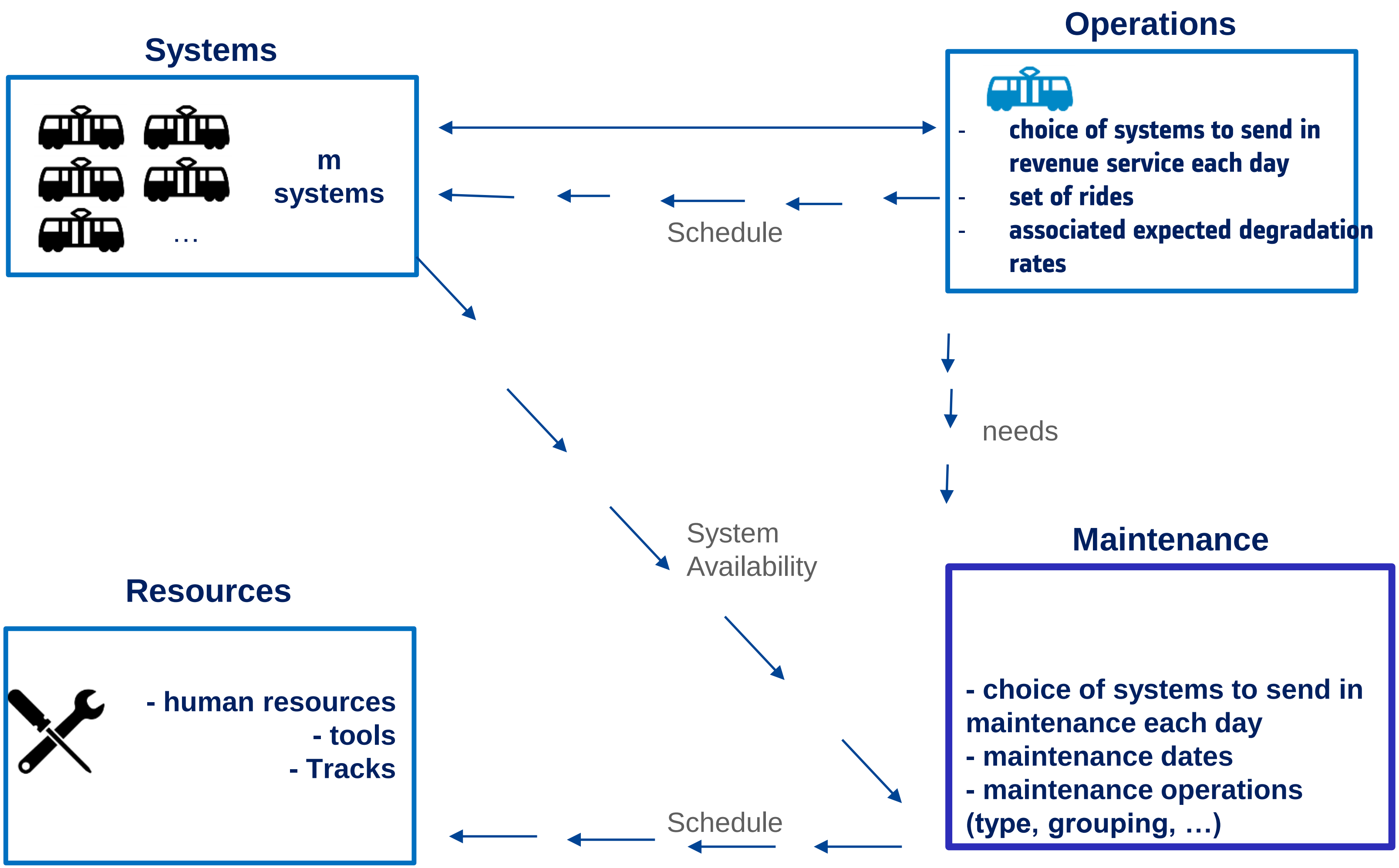
Multi-Agent System Approach

- 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



Agents' Data

Systems

m 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

- Number of missions per day
- Length of missions
- Degradation rate of missions
- Cost of lost mission
- Planning horizon

Operations

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

- Needed time for maint tasks
- Needed resources (Number + Time) for maint tasks
- Cost of each maint task

Maintenance

- human resources
- tools
- Tracks

- Number of resources
- Availability of resources

Maintenance

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

Some Preliminary Results

- Linear Programming Model

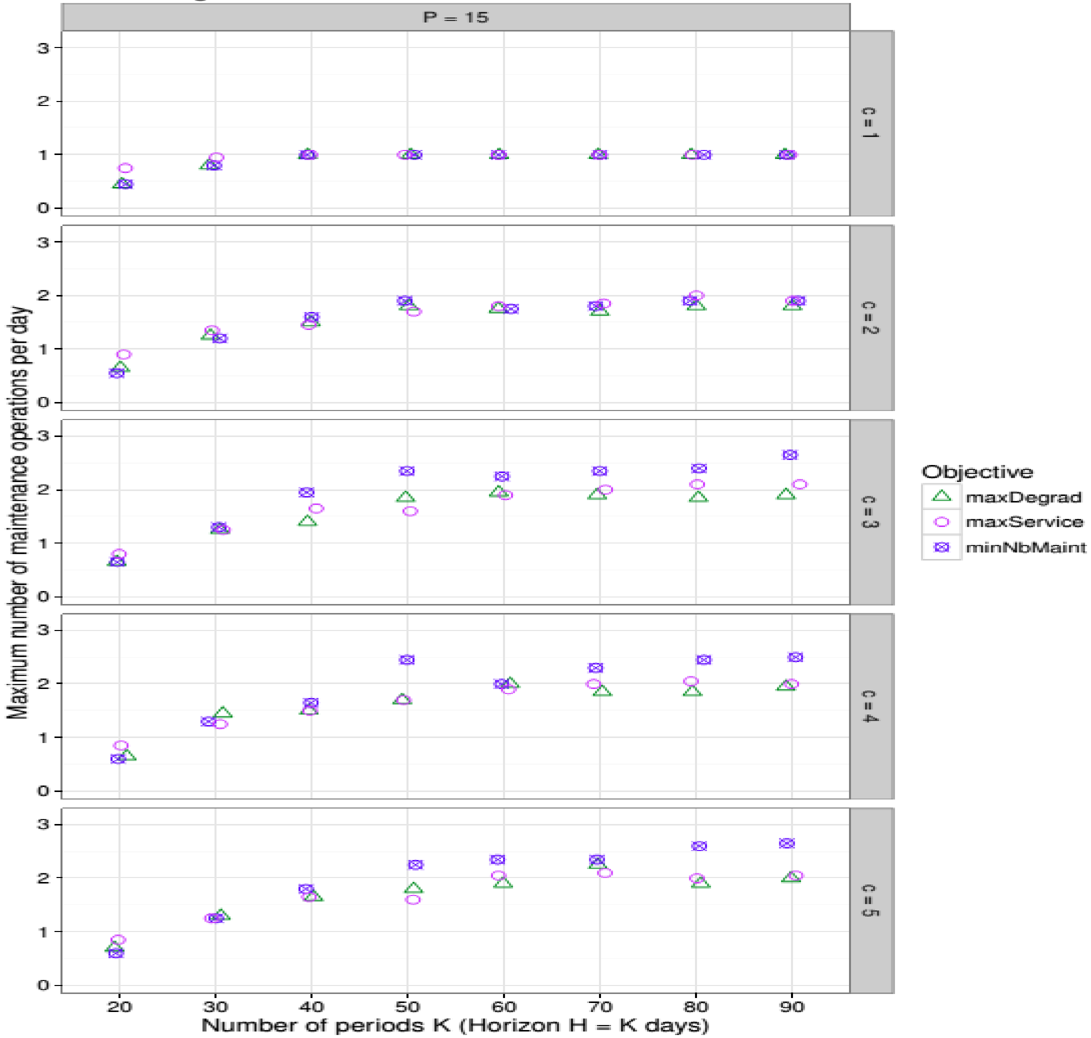


Figure 7: Maximum number of maintenance operations per day for the three objective fun[...] and maintenance capacities $c = 1, 2, 3, 4$ and 5 – $m = 18$ systems, $P = 15$ missions

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

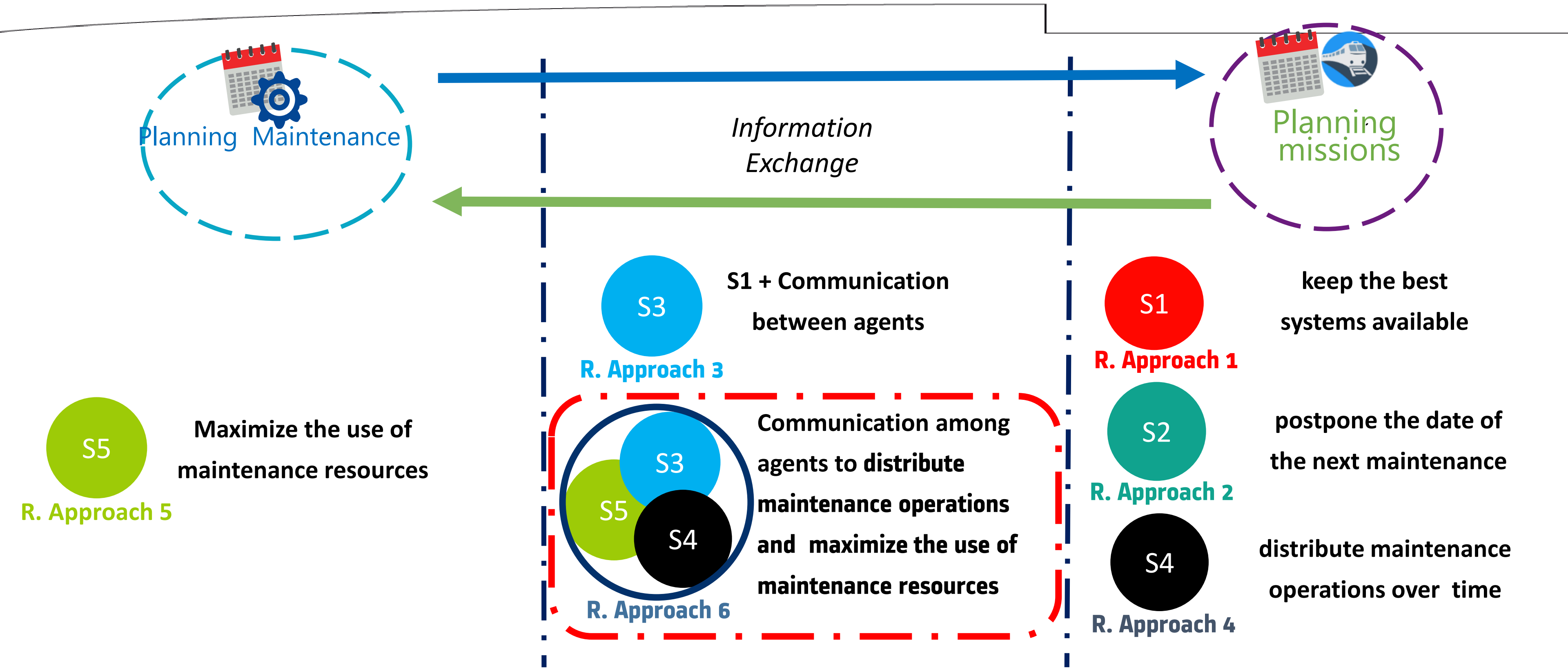
-- in a second step,Operations and Maintenance agents communicate to minimize number of lost missions

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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