Maintenance effect modeling of a railway system

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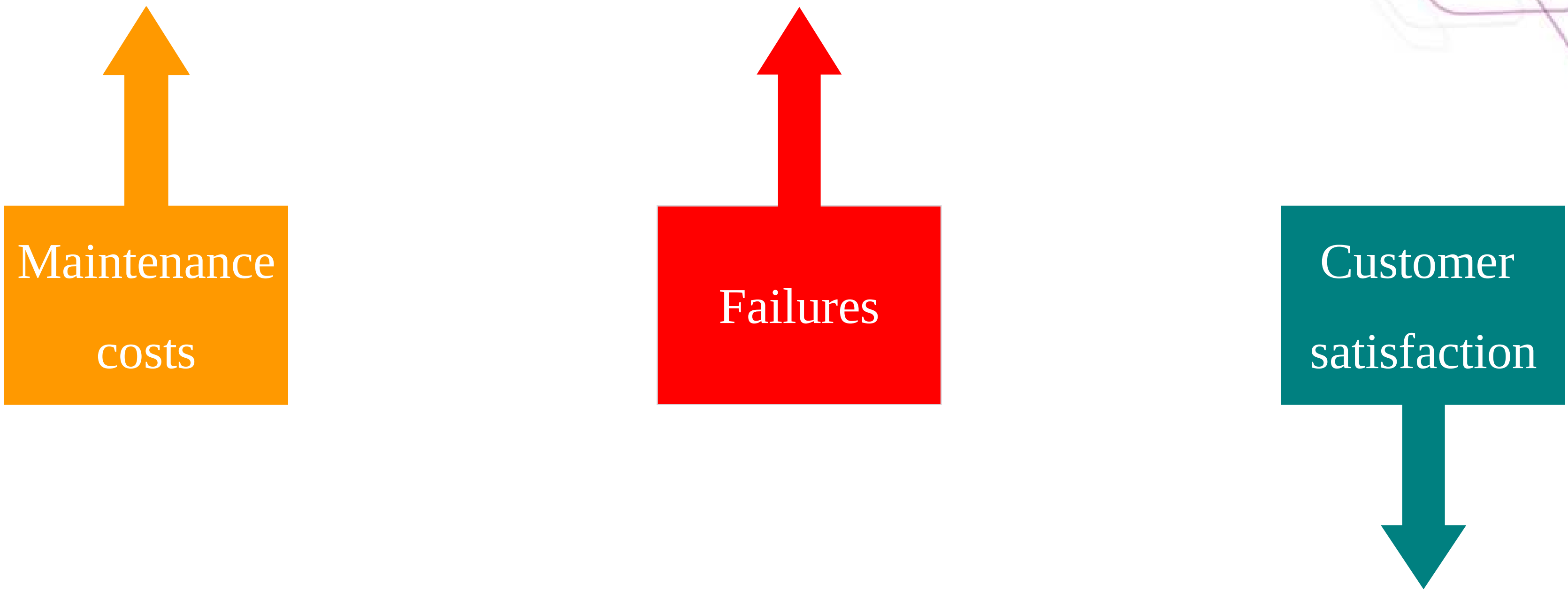
Summary

1. Context
2. A railway system
3. Lifetime distribution and preventive maintenance effect
4. System modeling
5. Discussion and conclusions

Context

Industrial issues

Aging systems



Solution : Preventive maintenance

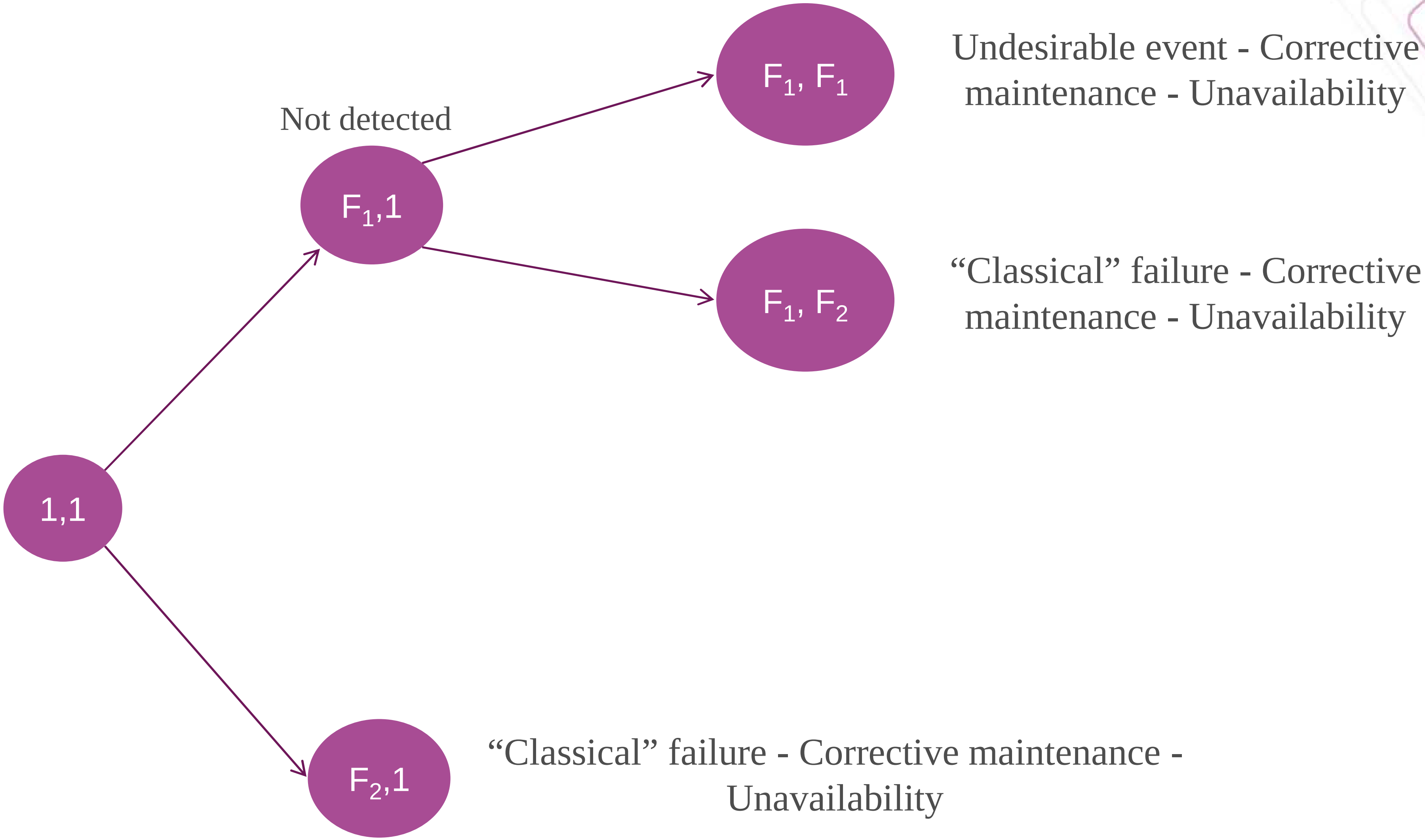
System modeling by probabilistic approach

A railway system

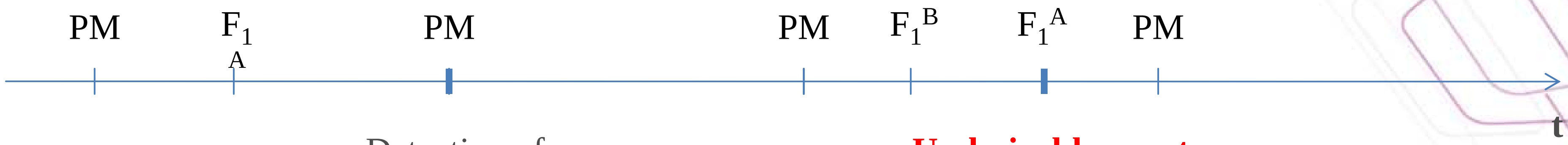
A maintained two-component system

- Two components (A and B): functionally dependent,
- For each component:
  - Two failure modes (F_1 and F_2):
    - the system remains up in case of one single failure in mode F_1,
    - two successive failures in mode F_1 lead to a system “severe” failure,
    - one single failure in mode F_2 leads to a system “classical” failure,
- Severe failure:
  - can lead to an undesirable event (safety issue) and unavailability (a few hours),
- Classical failure:
  - does not lead to safety issue but induces unavailability (a few hours),
- The present maintenance policy:
  - Corrective replacement of all down components at system failure,
  - Periodic (yearly) preventive maintenance:
    - Replacement of failed components (in mode F_1),
    - Adjustment of working components.

Event tree


Not detected
F1,1
F1, F1
Undesirable event - Corrective maintenance - Unavailability
F1, F2
“Classical” failure - Corrective maintenance - Unavailability
1,1
F2,1
“Classical” failure - Corrective maintenance - Unavailability

Examples of operating railway systems behavior



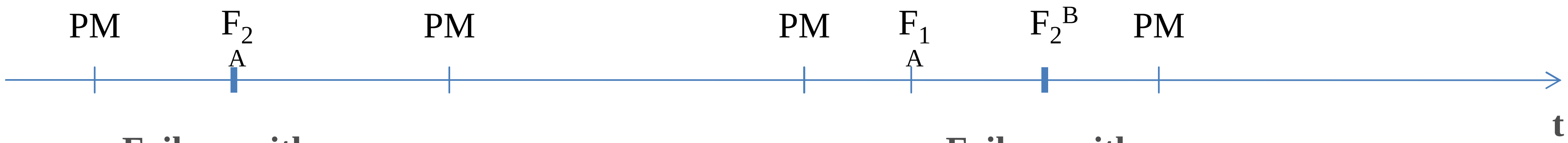
Detection of component A failure

Replacement of component A

Undesirable event

Both components A and B have failed with mode 1

Replacement of both components during a corrective maintenance action



Failure with no impact on safety

Replacement of component A during a corrective maintenance action

Failure with no impact on safety

Replacement of both components during a corrective maintenance action

Objectives

- ❑ Estimate the parameters of the components lifetimes p.d.f.,
- ❑ Estimate the effect of the preventive maintenance actions (adjustments),
- ❑ **Propose a new preventive maintenance strategy which reduces the maintenance cost with the same safety and availability constraints (is it reasonable to perform the yearly PM actions only every two years?)**
- ❑ This new maintenance strategy has to be GAME (in French) - globally at least equivalent - from a safety point of view.

Lifetime distributions and PM effects

Feedback data

We have at our disposal :

- ❑ Characteristics of operating components (technology, operating time,…),
- ❑ Number of achieved PM actions (PM times are unknown),
- ❑ The failure times,
- ❑ The failure modes.

Maintenance effect modelling

- ❑ ARA_1 model (Order 1 Arithmetic Redution of Age model) [Doyen & Gaudoin],

- ❑ Principle : arithmetic reduction of the component age since the last PM action,

$$A(t) = t - \rho T_{N_{t^-}} \qquad \lambda_t = \lambda(t - \rho T_{N_{t^-}})$$

- ❑ Objective : estimation of both intrinsic failure rate and maintenance effect coefficient

$$\rho = 1 : \text{ AGAN}$$

$$\rho = 0 : \text{ ABAO}$$

$$\rho \in \left]0,1\right[: \text{imperfect maintenance}$$

Intrinsic failure rate hypothesis

- Weibull :

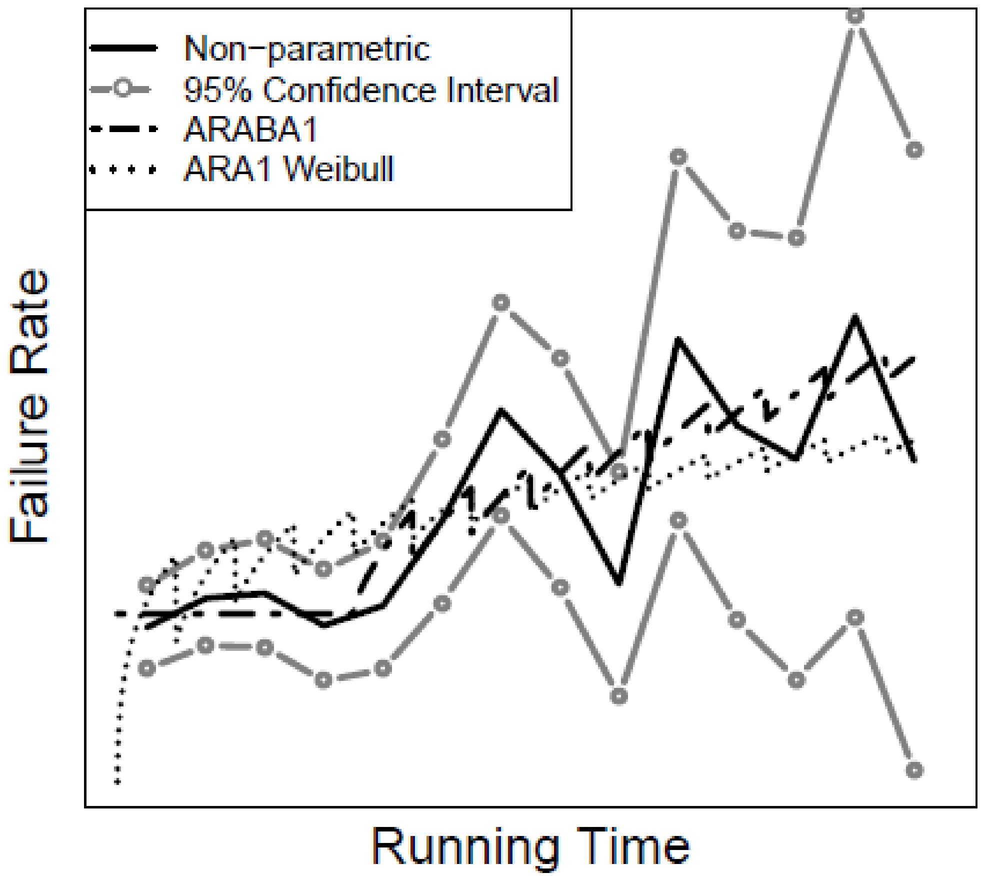
$$\lambda_t = \frac{\beta}{\eta}\left(\frac{t - \rho T_{N_{t^-}}}{\eta}\right)^{\beta-1}$$

- Bertholon : hypothesis ➔ a maintenance action has no effect before the beginning of the « ageing »

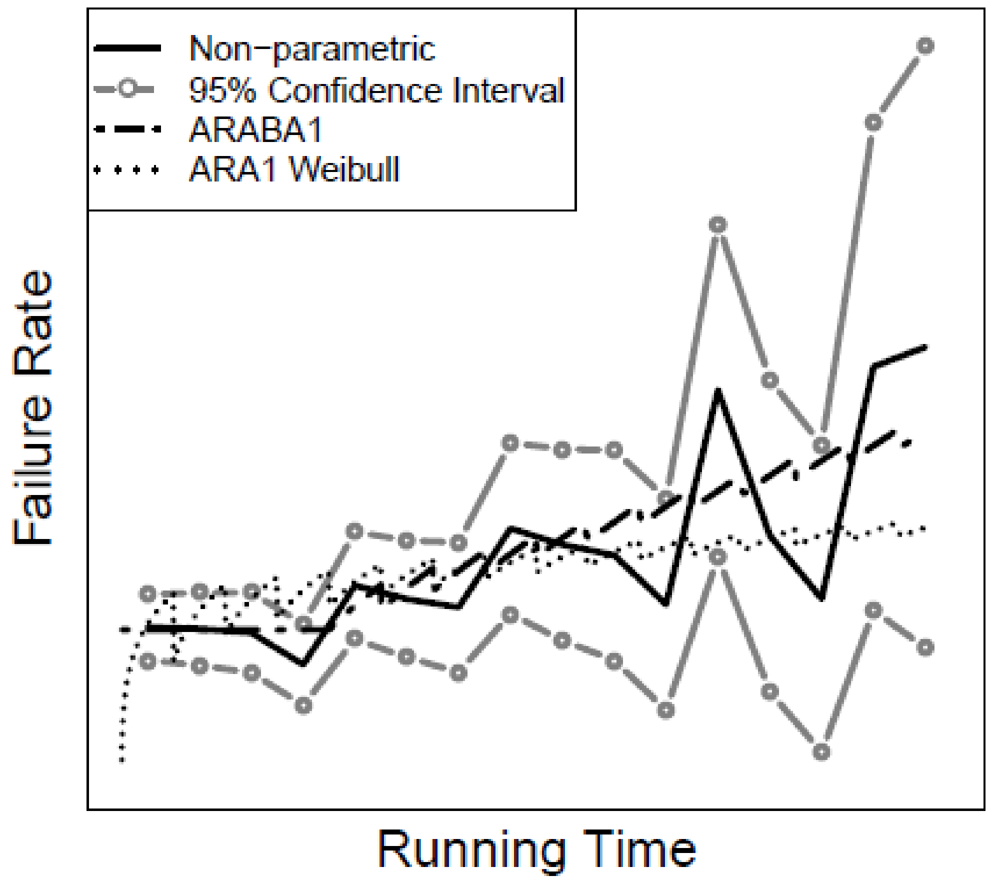
$$\lambda_t = \frac{1}{\eta_0} + \frac{\beta}{\eta_1}\left(\frac{(t - t_0)^+ - \rho\left(T_{N_{t^-}} - t_0\right)^+}{\eta_1}\right)^{\beta-1}$$

- Estimation with maximum likelihood method (gradient for Weibull and simulated annealing for Bertholon)

Results



Component A failure rate



Component B failure rate

Estimation of the failure mode

- When a failure occurs, we suppose that it is in mode 1 with probability p_A (or p_B) and in mode 2 with probability $1 – p_A$ (or $1 - p_B$), independently of anything else.

- For each component, p_A (or p_B) is estimated by the ratio between the number of failures in mode 1 and the total number of failures.

How to reach our objective?

Component A

Lifetime distribution and PM effect

Functional dependency

Component B

Lifetime distribution and PM effect

System modeling???

Mean number of undesirable events

Mean cost

Mean number of failures

System modeling

Non Homogeneous Piecewise Deterministic Markov Process

NHPDMP = (I_t , X_t)

- Used in dynamic reliability to model systems in interaction with their environment

- I_t: system state at time t (discrete)
  - State of the system components : up or down
  - {(1,1),(1,0),(0,1)}

- X_t: environmental condition at time t (continuous)
  - is deterministic between the jumps of process I_t
  - here: models the components **dates of entry into service**

- Rates between states: failure rates of the components (depend on time *t*)

- Two possible methods of quantification:
  - Monte-Carlo simulations (makes it difficult to use stochastic optimization algorithm)
  - Finite Volume scheme

Finite volume scheme

- Principle: quantify an approximation of the PDMP marginal distribution at time *t* through the discretization of the Chapman Kolmogorov equation (both in time and space),

- Deterministic results ➔ stochastic algorithm of optimization (simulated annealing),

- Quantification of rare events,

- For our system, calculations are fast.

Maintenance optimization

- Extension of the yearly PM policy:
  - by a PM action, preventive replacements of components older than some limit age (and adjustment of younger ones).

- Objective :
  - find both limit ages and PM periodicity (one or two years?) which minimize the maintenance cost, under safety constraints,
  - compare the results with the present PM policy.

- Costs:
  - failure costs + PM (adjustment) costs + PR costs + CR costs.

- Optimization:
  - Simulated annealing algorithm.

Assumption

The PM effect does not depend on the periodicity

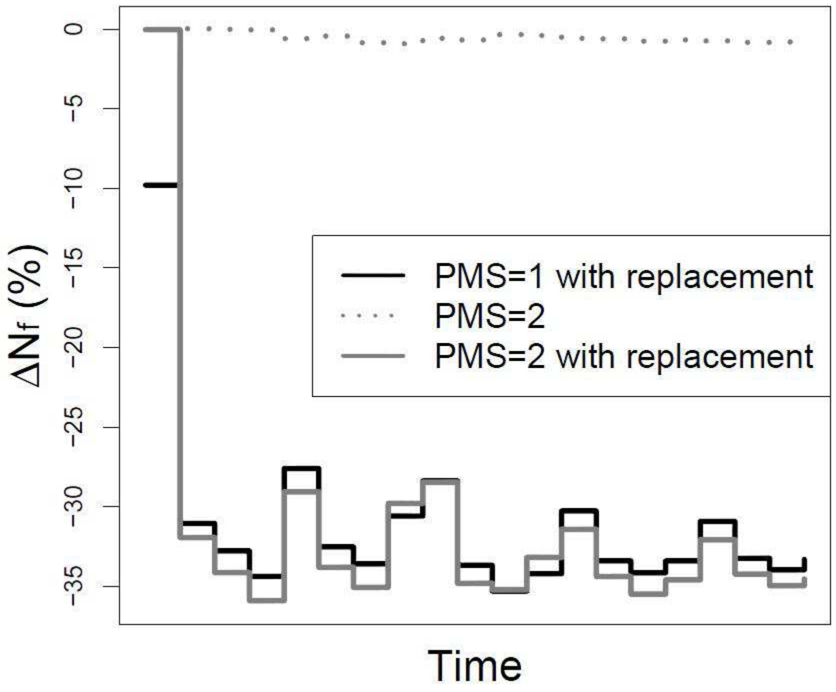
Justified by the choice of an ARA1 model

Maintenance optimization

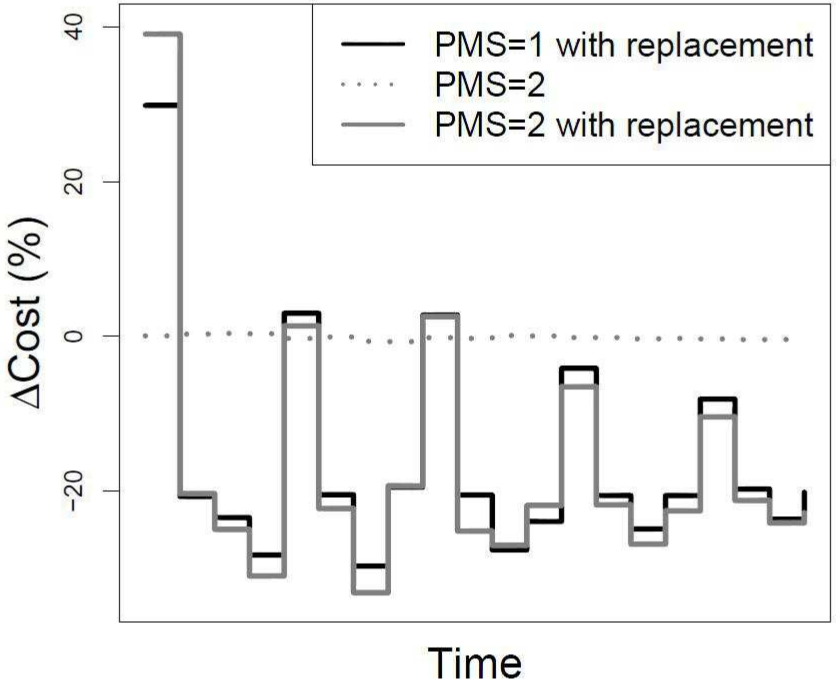
Preventive Maintenance Step (PMS)	1	1	2	2
Components renewal	No	Yes	No	Yes
Cost	Current strategy	-16%	-0.2%	-17%
Undesirable events		-42%	+200%	+66%
“Classical” failures		-31%	-0.5%	-31%

Results of different maintenance strategies

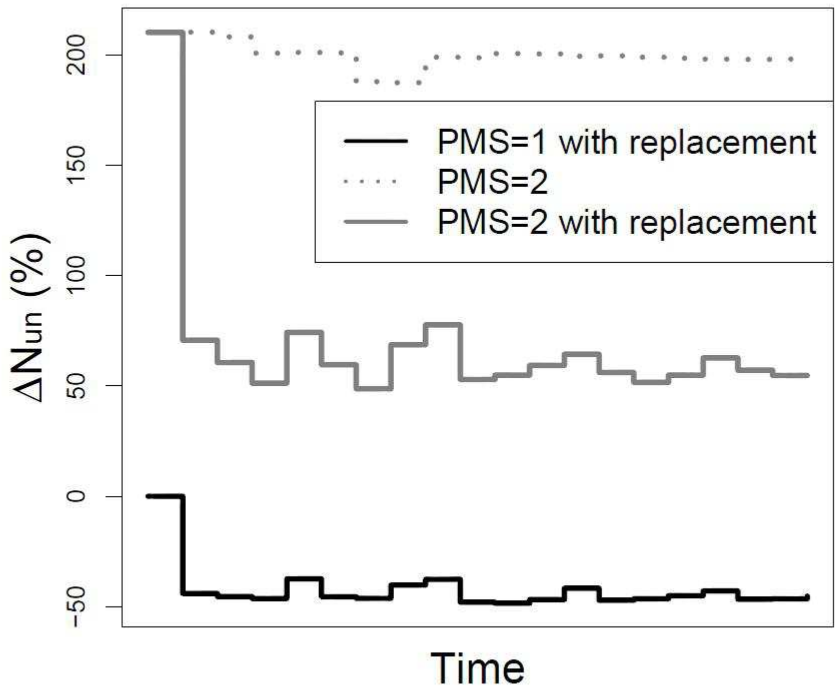
Maintenance optimization



Number of failures



Maintenance cost



Number of undesirable events

Discussion and conclusions

Discussion

- ❑ ARA_1 can be used to quantify the maintenance effect but a lot of data is required.

- ❑ How can we choose between ARA_1 or ARA_m, with $m>1$?

- ❑ Is it possible to evaluate a confidence interval for the ARA model?

- ❑ How can we take into account a periodicity change?

Conclusions

- ARA$_1$: estimation of 5 coefficients with Bertholon hypothesis ➔ requires a lot of data,

- PDMP: an interesting modeling solution for taking account ageing components and **maintenance effects**,

- Finite volumes scheme: quantification method adapted to maintenance optimization,

- Method has been used to optimize maintenance of SNCF systems with significant operating population.