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# 6ème Journée Régionale des Doctorants en Automatique

*Jeudi 04 Juillet 2019 – Université Catholique de Lille*

**Yncrea Hauts de France, Université Catholique de Lille, Ecole Doctorale SPI Université Lille Nord de France ED 072, GRAISyHM, CRIStAL UMR CNRS 9189, Région Hauts de France.**

# Elaboration of an economic model for decision aid optimizing the maintenance strategy of transport systems

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## Introduction

### Project context :

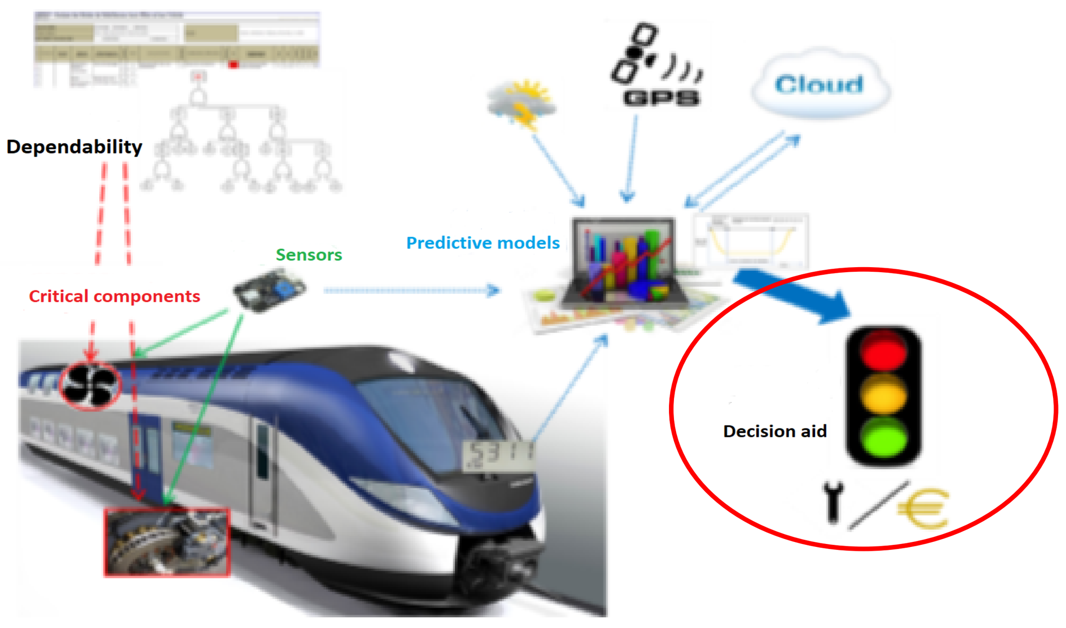
– ***MAPSYD (« Predictive Maintenance of transport SYstems in presence of incomplete/uncertain Data »)*** **is** ***a referenced*** **ANR project (project reference : *ANR17-CE22-0013*).**

**- Project partnerships :**

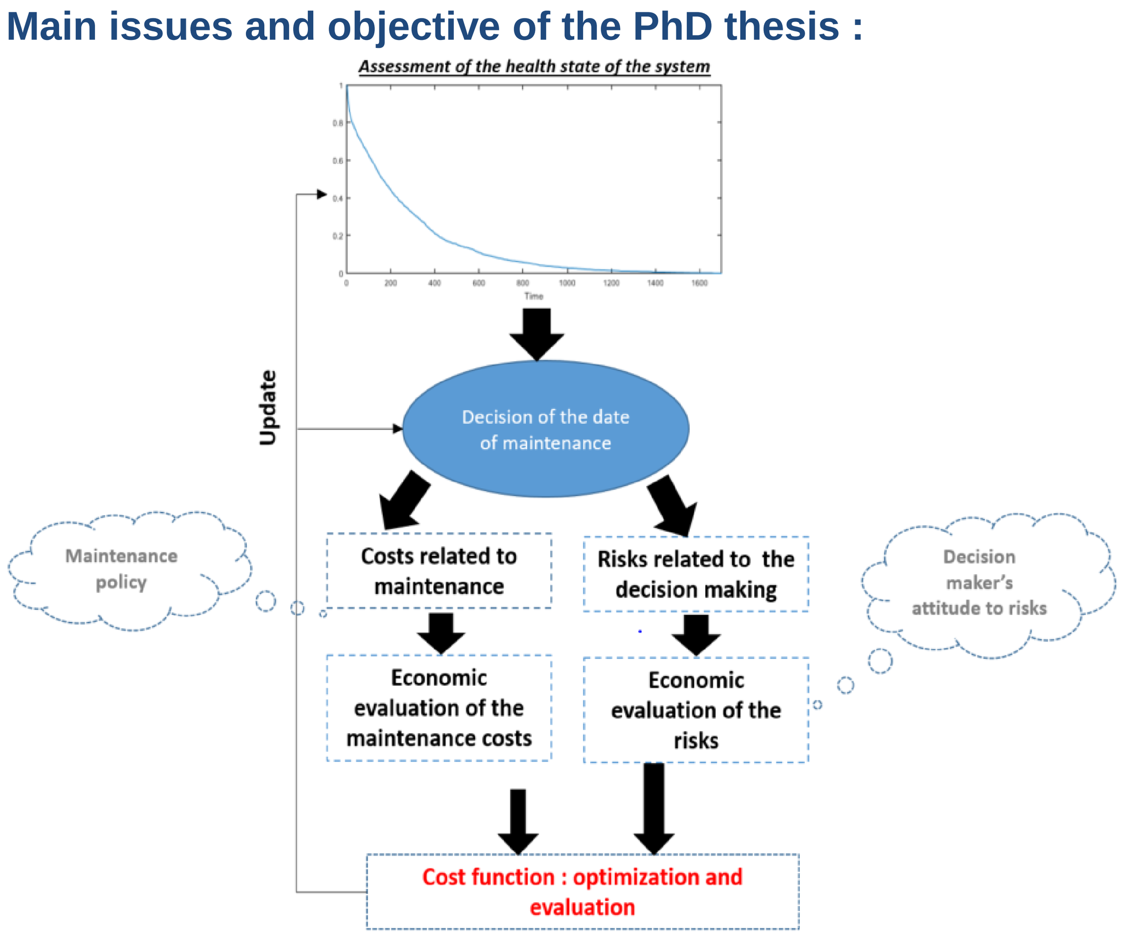
***Industrial partnerships***

***Academic partnerships***

**- Main industrial issues tackled by MAPSYD project :**




### Main issues and objective of the PhD thesis :



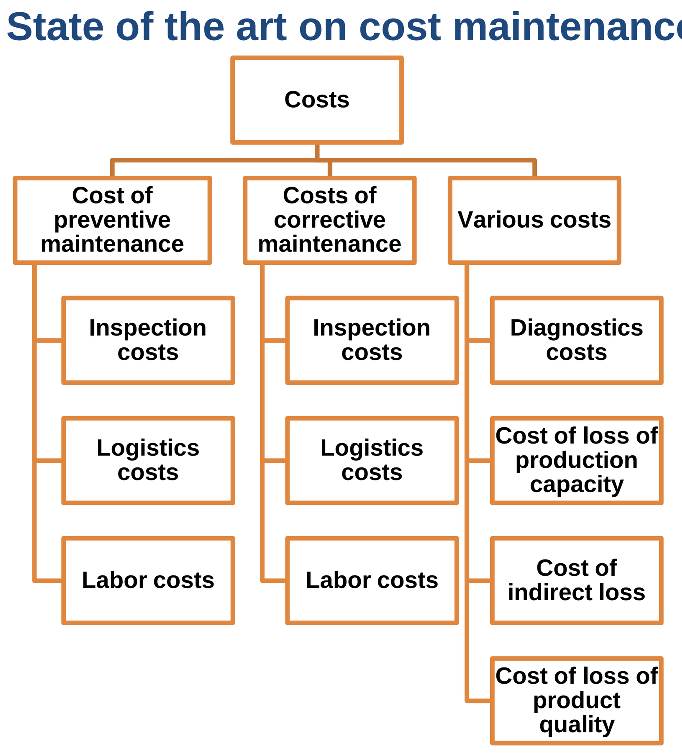

***Objective*** **: Deployment of an approach for decision making to optimize maintenance costs by taking into account the economic risks and the decision-maker's risk behavior.**

## State of the art

### Technical definitions :

| | |
|---|---|
| Maintenance | combination of all technical, administrative and managerial actions during the life cycle of a system intended to retain it in, or restore it to, a state in which it can perform the required function (1). |
| Predictive maintenance | maintenance carried out following a forecast derived from repeated analysis or known characteristics and evaluation of the significant parameters of the degradation of the system (1). |
| Corrective maintenance | maintenance carried out after fault recognition and intended to restore a system into a state in which it can perform a required function (1). |
| Inspection | examination for conformity by measuring, observing, or testing the relevant characteristics of a system (1). |
| Remaining Useful Life (RUL) | the *RUL* of a system is defined as the expected lifetime between the current time and the end of life of the system (2). |
| Risk | risk is defined as the product of the probability of occurrence of a hazardous event and the severity of that event (3) : Risk= probability of occurrence X severity of a hazardous event. |

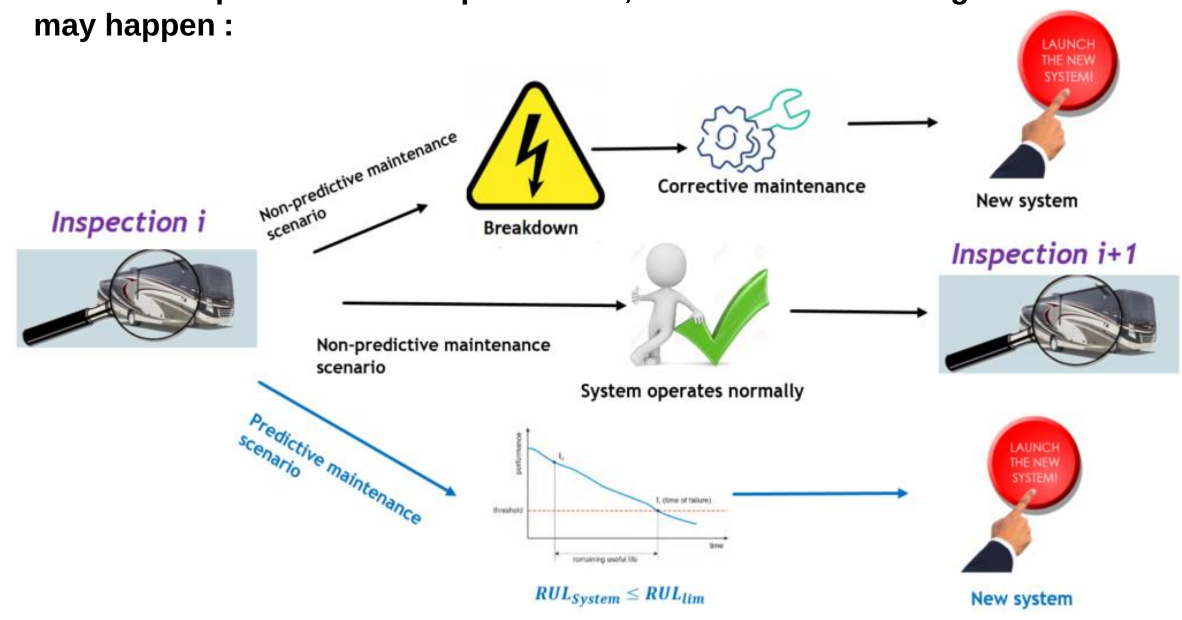
### State of the art on cost maintenance :




## Methodology for maintenance cost optimization

### Assumptions :

- The system under study is a single component.
- The system under study is a part of a complex system with a known duration of exploitation, called *D*.
- The inspection is performed regularly on the system under study and it gives information on the health state of the system, i.e. the inspection gives a real estimation of the *RUL* of the system.
- The inspection does not alter the system's performance.
- An inspection is required at the beginning of the life of the system but the system's state of health does not imply a system replacement because the system is supposed to be new.
- Between inspection *i* and inspection *i+1*, one of these following scenarii may happen :




- The cost of a predictive/corrective replacement and the cost of a single inspection are supposed to be constant and known.
- The duration of predictive/corrective replacement is supposed to be constant and known.
- The system's failure follows the Weibull distribution.

### Mathematical formulation of cost optimization :

***Objective :*** minimize the total cost $Cost_{total}$ including the cost of corrective maintenance $C_c$, the cost of predictive maintenance $C_p$, the cost of inspections $C_i$, the cost of operating loss $C_{ol}$ and the cost of indirect loss $C_{il}$ during the cycle *D*.

$$minimize(Cost_{total}) = minimize(C_c + C_p + C_{ol} + C_{il})$$

under the following constraints :

- The costs are positive : $C_c, C_p, C_{ol}, C_i, C_{il} \geq 0$
- The decision $N_i$ to perform predictive maintenance between inspection i and i +1 is binary : $N_i\ binary$
- There is at most one predictive maintenance action to perform on the system under study : $\sum_{i=1}^{N_{in}-1} N_i \leq 1$.
- The total number of inspections $N_{in}$ is integer and superior to 1 : $N_{in}\ integer, N_{in} \geq 1$.
- The durations of both predictive and corrective replacements ($D_p$ and $D_c$) should be too small comparing to the inspection step to ensure the availability of the system.

$$D_c \leq \varepsilon . \frac{D}{N_{in}}$$
$$D_p \leq \varepsilon . \frac{D}{N_{in}}$$

### Mathematical equations of costs :

| | |
|---|---|
| Cost of predictive maintenance | $C_p = \sum_{i=1}^{N_{in}-1} c_p . N_i$ |
| Cost of corrective maintenance | $C_c = \sum_{i=1}^{N_{in}-1} c_c . (1 - N_i) \frac{\int_{t_i, T \geq t_i}^{t_{i+1}} f_i(t).dt}{R_i(t_i)}$ |
| Cost of inspection | $C_i = N_{in} . c_i$ |
| Cost of operating loss | $C_{ol} = \sum_{i=1}^{N_{in}-1} c_{dt} . D_p . N_i + \sum_{i=1}^{N_{in}-1} c_{dt} . D_c . (1 - N_i) \frac{\int_{t_i, T \geq t_i}^{t_{i+1}} f_i(t).dt}{R_i(t_i)}$ |
| Cost of indirect loss | $C_{il} = human\ risk + fianncial\ risk + environmental\ risk$ |

Considering the following notation :

- $c_p$ : cost of a predictive replacement
- $c_c$ : cost of corrective replacement
- $c_i$ : cost of an inspection
- $c_{dt}$ : cost of system down time per unit of time
- $f_i$ : failure probability density function at inspection *i*
- $R_i$ : reliabilty of the system at inspection *i*
- $t_i$ : time of inspection *i*

## Risk assessment

### Human risks :

- ***Value of Statistical Life (VSL) :*** terminology refering to the trade-off between fatality risks and money. It reflects the worker's willingness to pay to accept risks and to pay for more safety.
- ***Expression of human risks :*** If *n* persons may probably be affected by the occurrence of a failure scenario with a probability of death equal to $p_j^d$ for the *j*th person, then the human risks can be evaluated as follows :

$$Human\ risks = \sum_{j=1}^{n} VSL . p_d^j . \sum_{i=1}^{N_{in}-1} . (1 - N_i) \frac{\int_{t_i, T \geq t_i}^{t_{i+1}} f_i(t).dt}{R_i(t_i)}$$

### Financial risks :

- ***Churn rate :*** the proportion of customers that a business loses during a given period of time.
- ***Assumptions :*** the business loses *x%* in case of predictive maintenance and *y%* in case of corrective maintenance.
- ***Expression of financial risks :***

$$Financial\ risks = M.C. \left( x\% . \sum_{i=1}^{N_{in}-1} N_i + y\% . \sum_{i=1}^{N_{in}-1} (1 - N_i) \frac{\int_{t_i, T \geq t_i}^{t_{i+1}} f_i(t).dt}{R_i(t_i)} \right)$$

Where :

- ***M :*** number of potential customers at the beginning of period ***D***.
- ***C :*** cost of loss of one customer.

### Environmental risks :

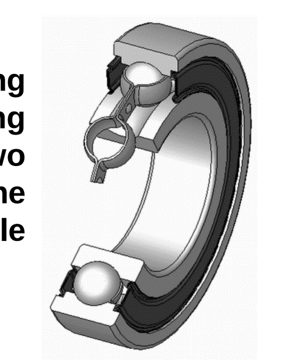
- ***Assumptions :*** a failure of the system may cause damages to environment by emission of harmful pollutants. We assume that :
  - the total number of chemicals that may be emitted is equal to *m*.
  - $P_j$ is the probability of emission of chemical *j*.
  - $V_j$ is the volume of emission of chemical *j*.
  - $\rho_j$ is the density value of chemical *j*.
  - $D_{aj}$ is the cost of damage per tonne emission of chemical *j*
- ***Expression of environmental risks :***

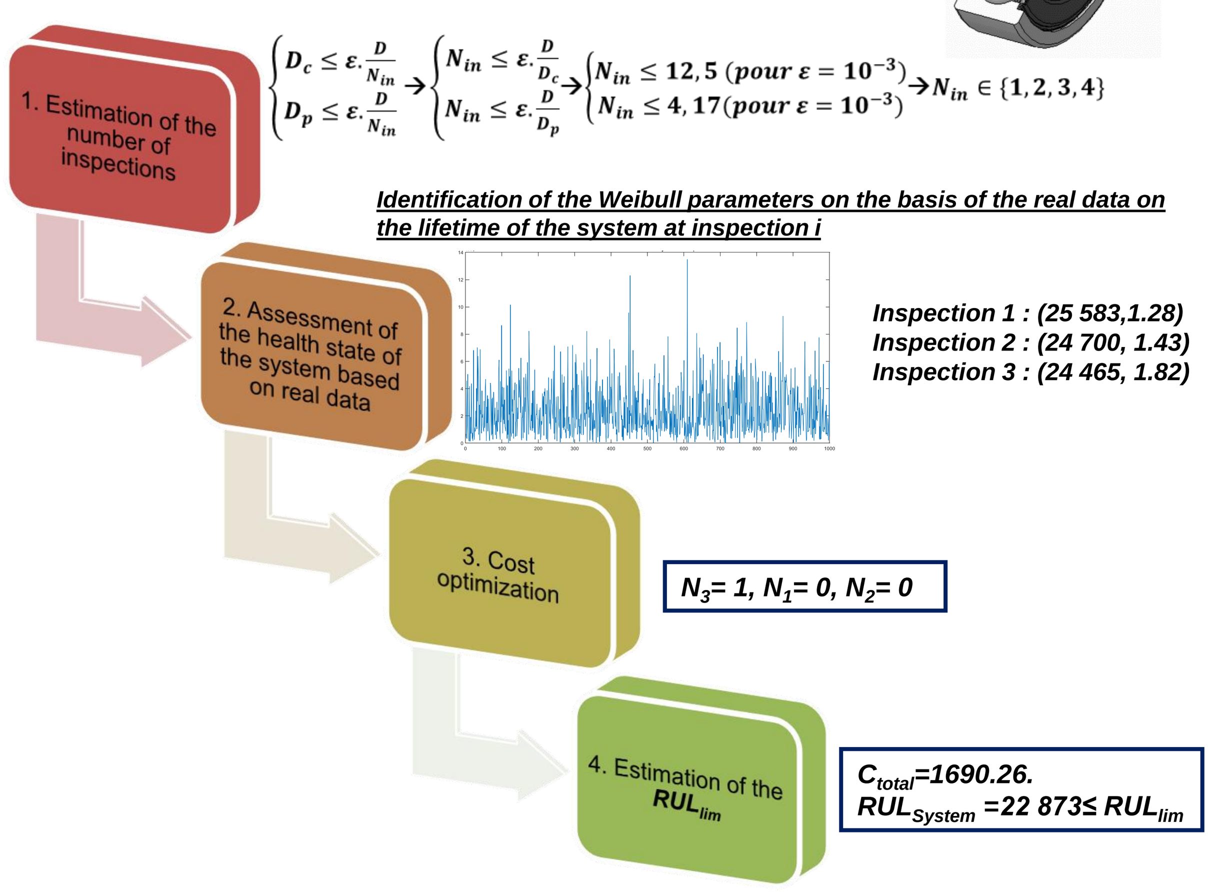
$$Environmental\ risks = \left( \sum_{j=1}^{m} P_j . V_j . \rho_j . D_{aj} \right) . \left( \sum_{i=1}^{N_{in}-1} (1 - N_i) \frac{\int_{t_i, T \geq t_i}^{t_{i+1}} f_i(t).dt}{R_i(t_i)} \right)$$

## Example

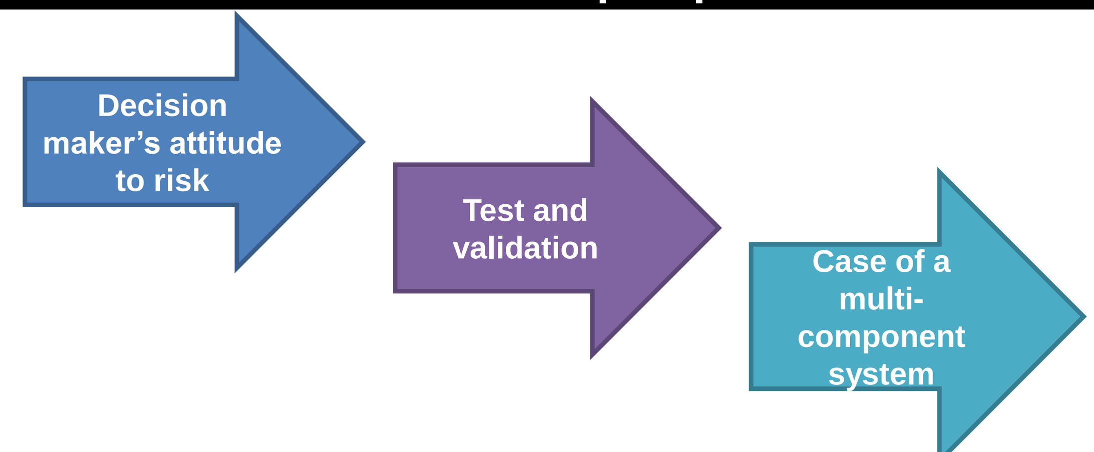
### System under study :

- A **rolling-element bearing**, also known as a rolling bearing, is a bearing which carries a load by placing rolling elements (such as balls or rollers) between two bearing rings called races. The relative motion of the races causes the rolling elements to roll with very little rolling resistance and with little sliding.






## Future research perspectives

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