Development of an economic decision support model optimizing the maintenance strategy for transport systems

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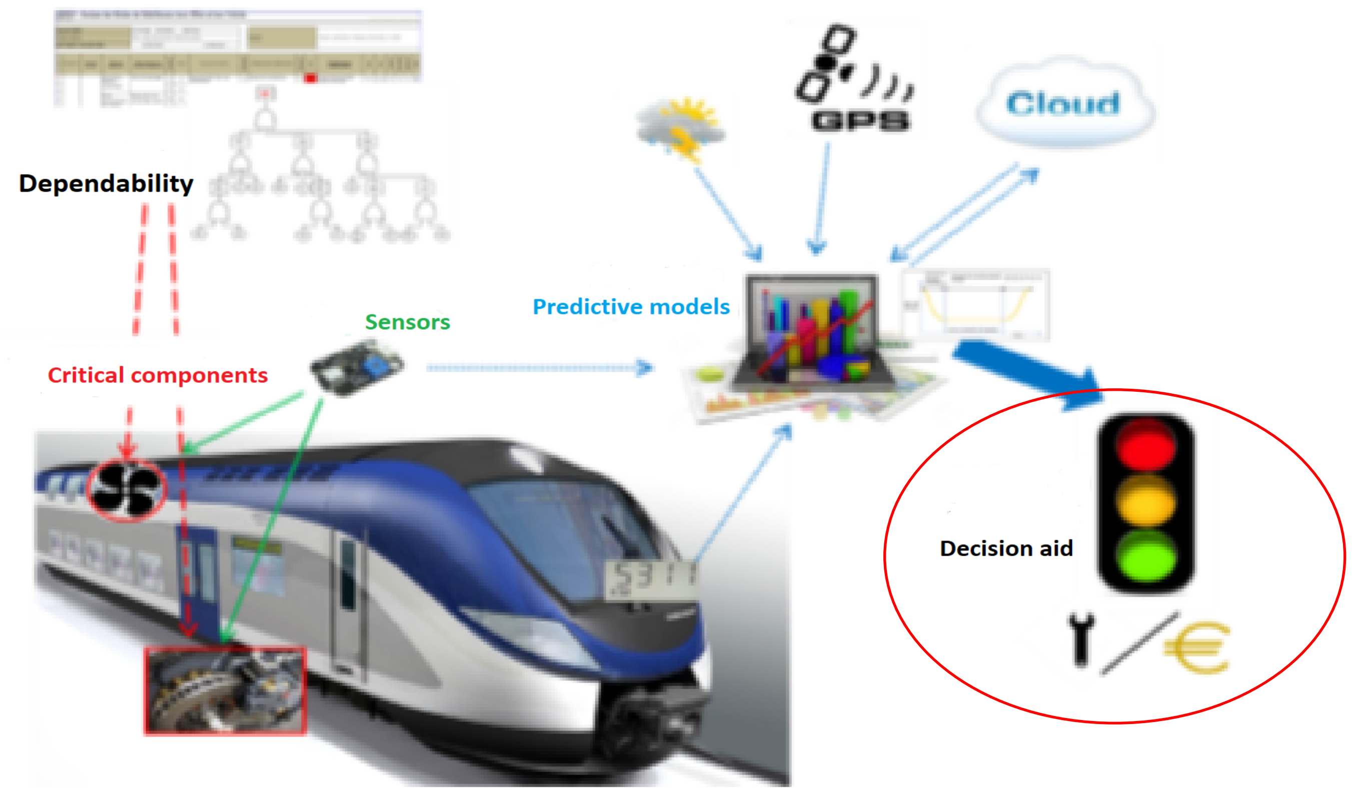
I. Project context and research issue

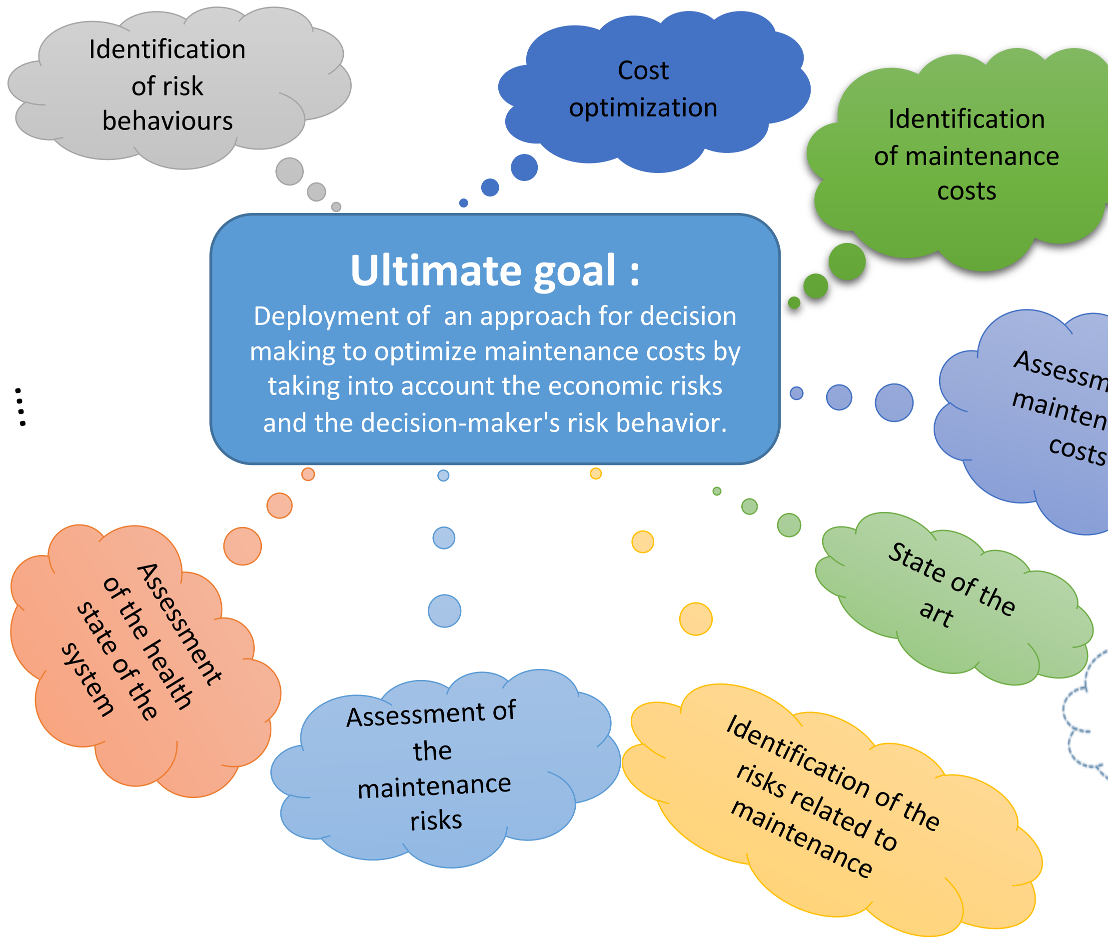
General context of MAPSYD poject (« Maintenance Prévisionnelle des Systèmes de transport en présence de données incomplètes ou incertaines »)

Thesis starting date : 02nd Mai 2018

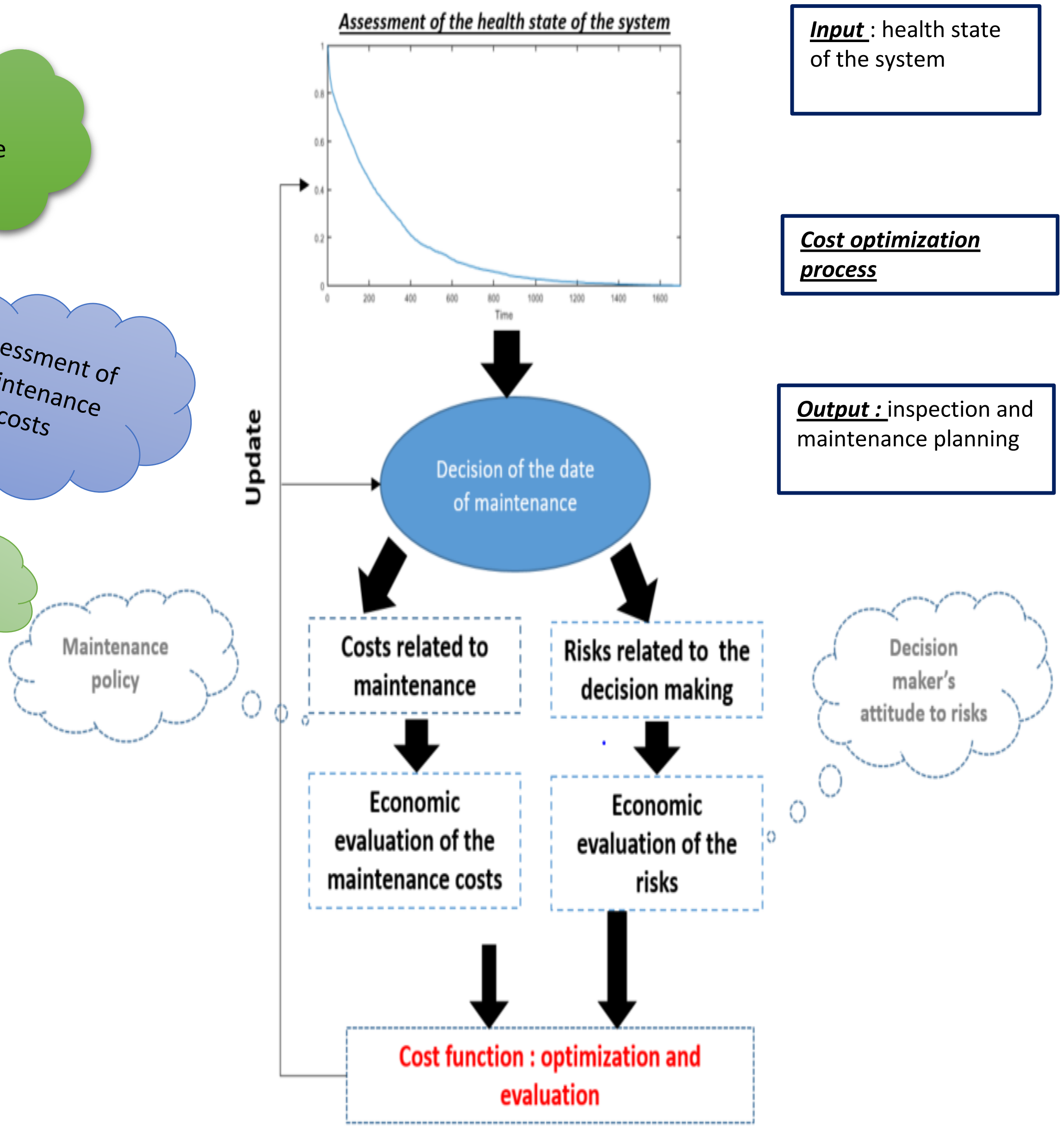
- **Industrial partnership**
  - Sector
  - Synox
- **Academic partnership**
  - ANR
  - Heudiasyc-UTC
  - Institut Louis Bachelier



I. Project context and research issue



__Final goal and thoughts on how to approach the goal__

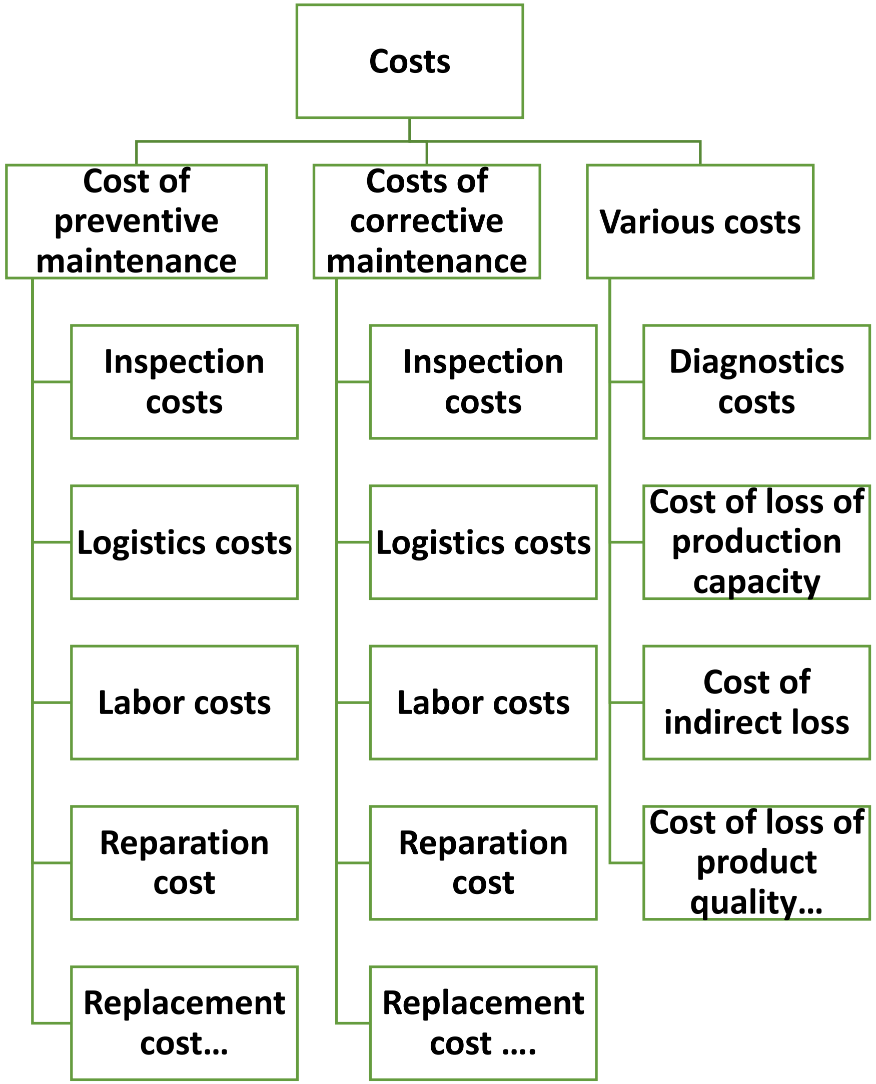


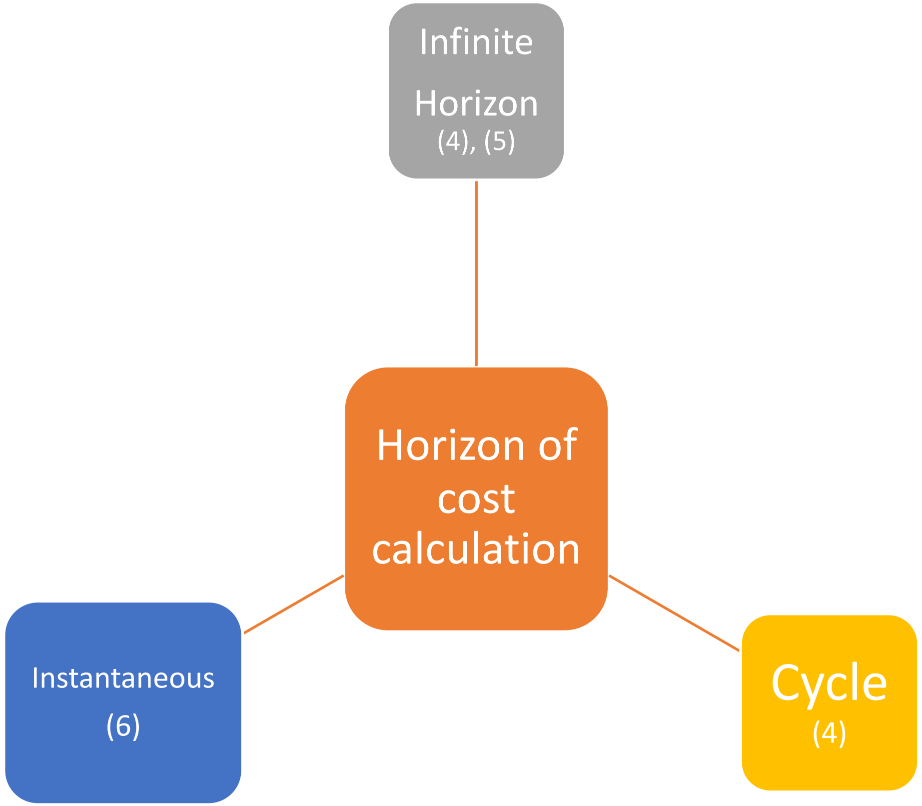
II. State of art

Technical concepts

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.**

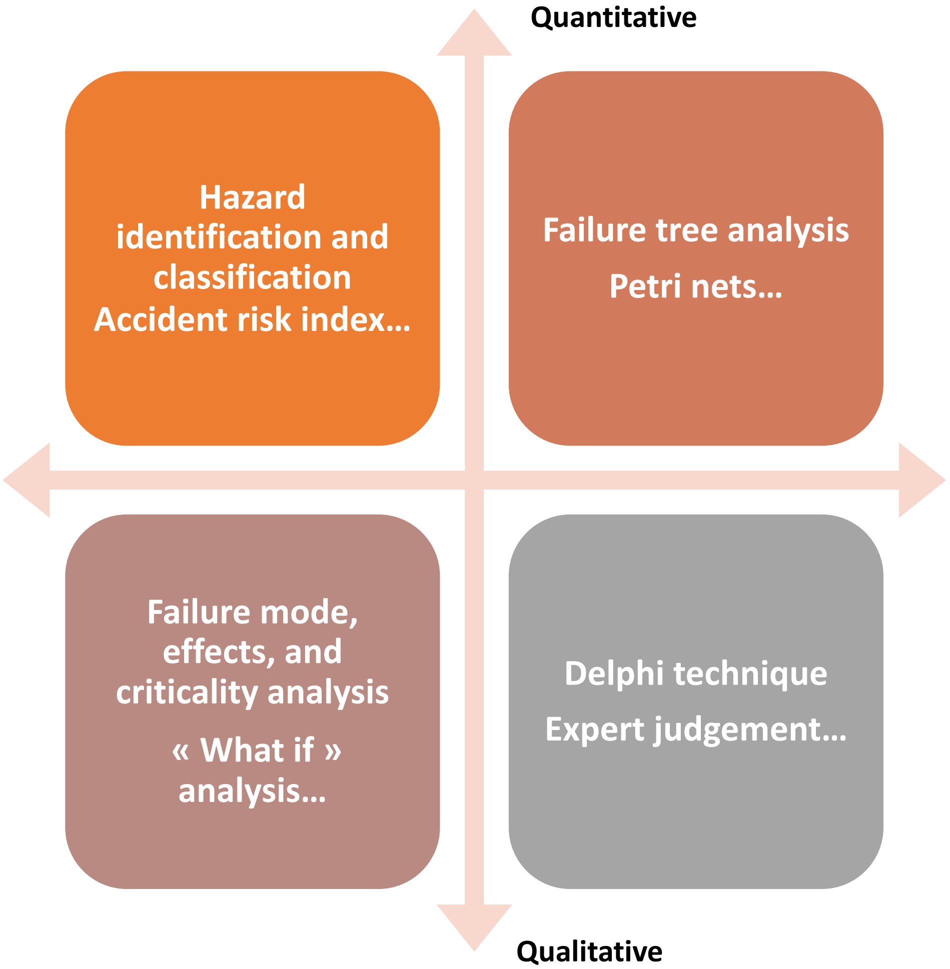
II. State of art

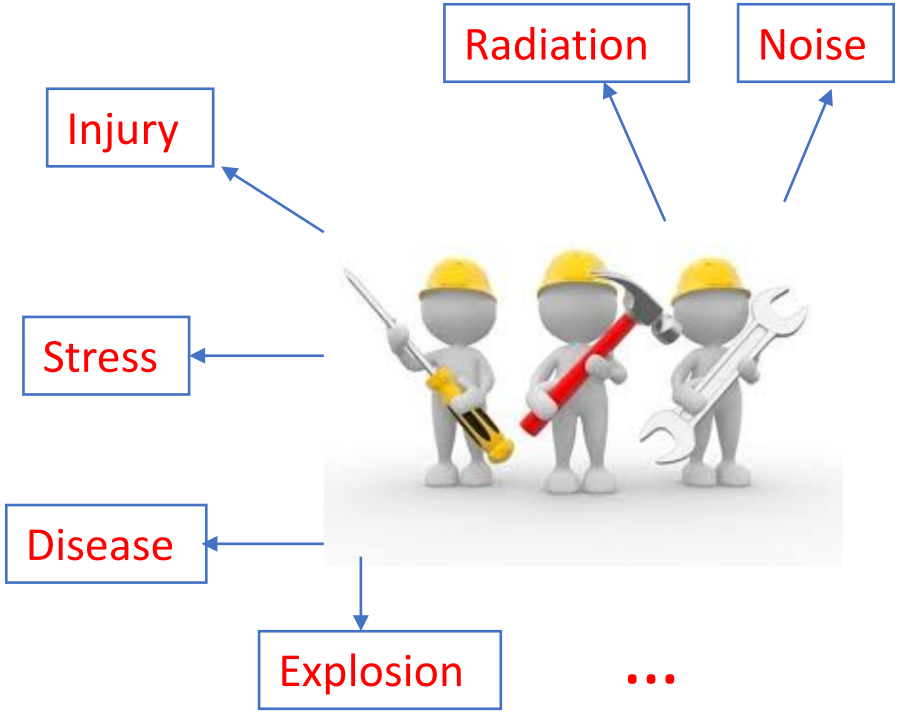




II. State of art

__Risk analysis:__ identification, characterization, quantification and evaluation of loss from a failure event (3).





II. State of art

What to remember…

Maintenance policy

impact

Maintenance costs

are part of

Human accidents

are part of

Financial risks

are part of

Environmental risks

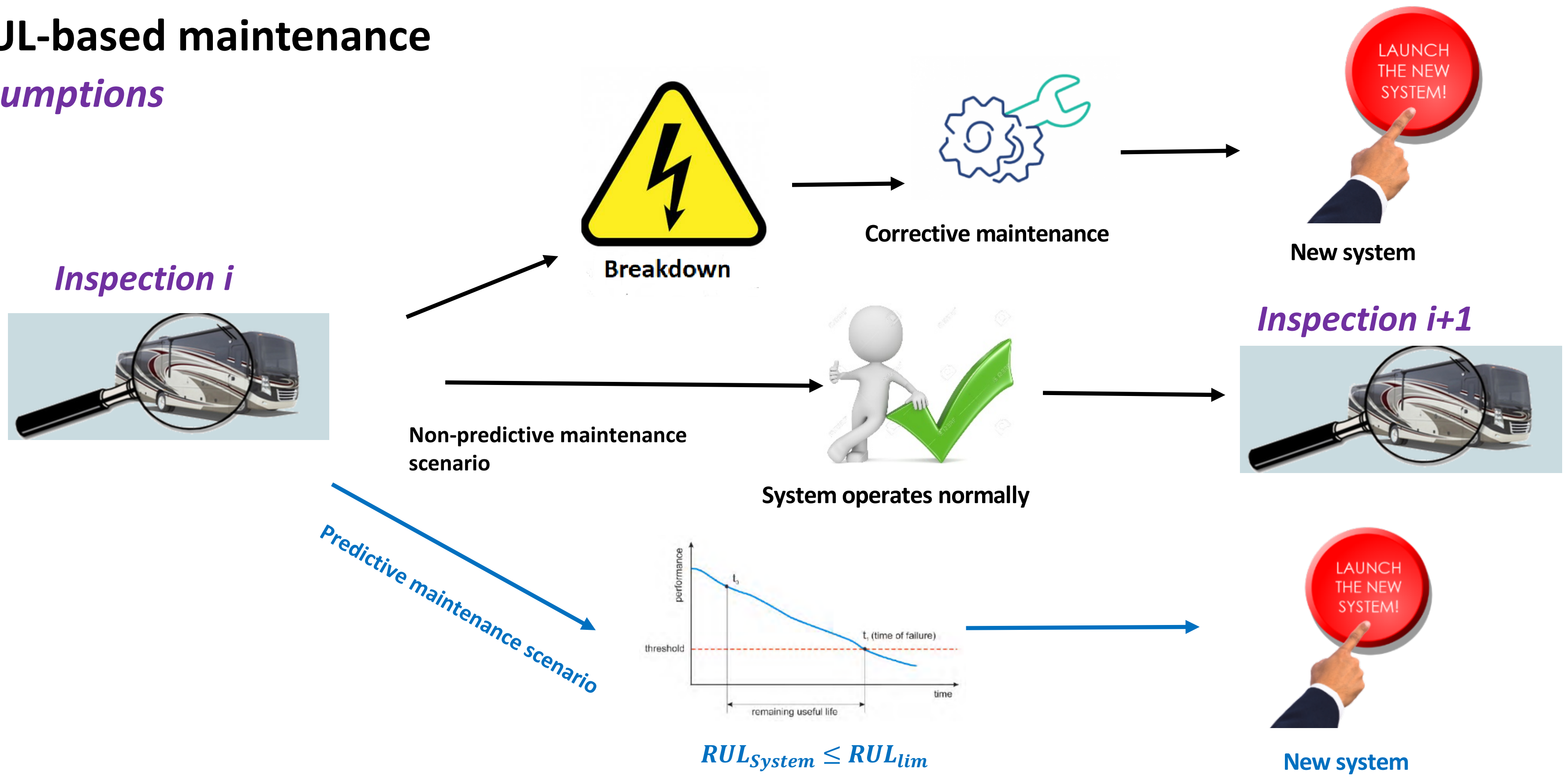
III. RUL-based maintenance

1. 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 :
  - ***Predictive maintenance scenario :*** the ***RUL*** attains a threshold RUL_{lim} under which the system is considered to be deteriorated. The system is then replaced by a new one before the next inspection ***i+1***.
  - ***Non-predictive maintenance scenario :*** the system is not predictively replaced in this scenario. In this case, the system may fall down or not :
    - The system falls down before the next inspection ***i+1***.
    - The system continues to operate normally until the next inspection ***i+1***.

III. RUL-based maintenance

1. Assumptions



- 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 with :
  - $\boldsymbol{\eta}$: scale parameter
  - $\boldsymbol{k}$: shape parameter

III. RUL-based maintenance

2. Mathematical formulation

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 :** $N_{in}\ integer, N_{in} \geq 1.$

III. RUL-based maintenance

2. Mathematical formulation

Cost of predictive maintenance	• $C_p = \sum_{i=1}^{N_{in}-1} c_p . N_i$	c_p : cost of a predictive replacement (constant).
Cost of corrective maintenance	• $C_c = \sum_{i=1}^{N_{in}-1} c_c . (1 - N_i) \frac{\int_{t_i, T \geq t_i}^{t_{i+1}} f_i(t).dt}{R_i(t_i)}$	c_c : cost of a corrective replacement (constant). f_i: failure probability density between inspection i and i+1. R_i : reliability of the system at inspection i. t_i: time of inspection i.
Cost of inspection	• $C_i = N_{in} . c_i$	c_i : cost of a single inspection (constant).
Cost of operating loss	• $C_{ol} = \sum_{i=1}^{N_{in}-1} c_{dt} . D_p . N_i + \sum_{i=1}^{N_{in}-1} c_{dt} . D_c . (1 - N_i) \frac{\int_{t_i, T \geq t_i}^{t_{i+1}} f_i(t).dt}{R_i(t_i)}$	c_{dt} : cost of the system down time per unit of time (constant).
Cost of indirect loss	• $C_{il} = human\, risk + financial\, risk + environmental\, risk$	

III. RUL-based maintenance

2. Mathematical formulation

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.
- If $\boldsymbol{n}$ persons may probably be affected by the occurrence of a failure scenario with a probability of death equal to $\boldsymbol{p_j^d}$ for the $\boldsymbol{j^{th}}$ person, then the human risks can be evaluated as follows :

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

→ By way of similarities, we may carry out the same study by considering different levels of injury.

III. RUL-based maintenance

2. Mathematical formulation

Financial risks

- ***Definition of the 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.
- The business loses ***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.

III. RUL-based maintenance

2. Mathematical formulation

Environmental risks

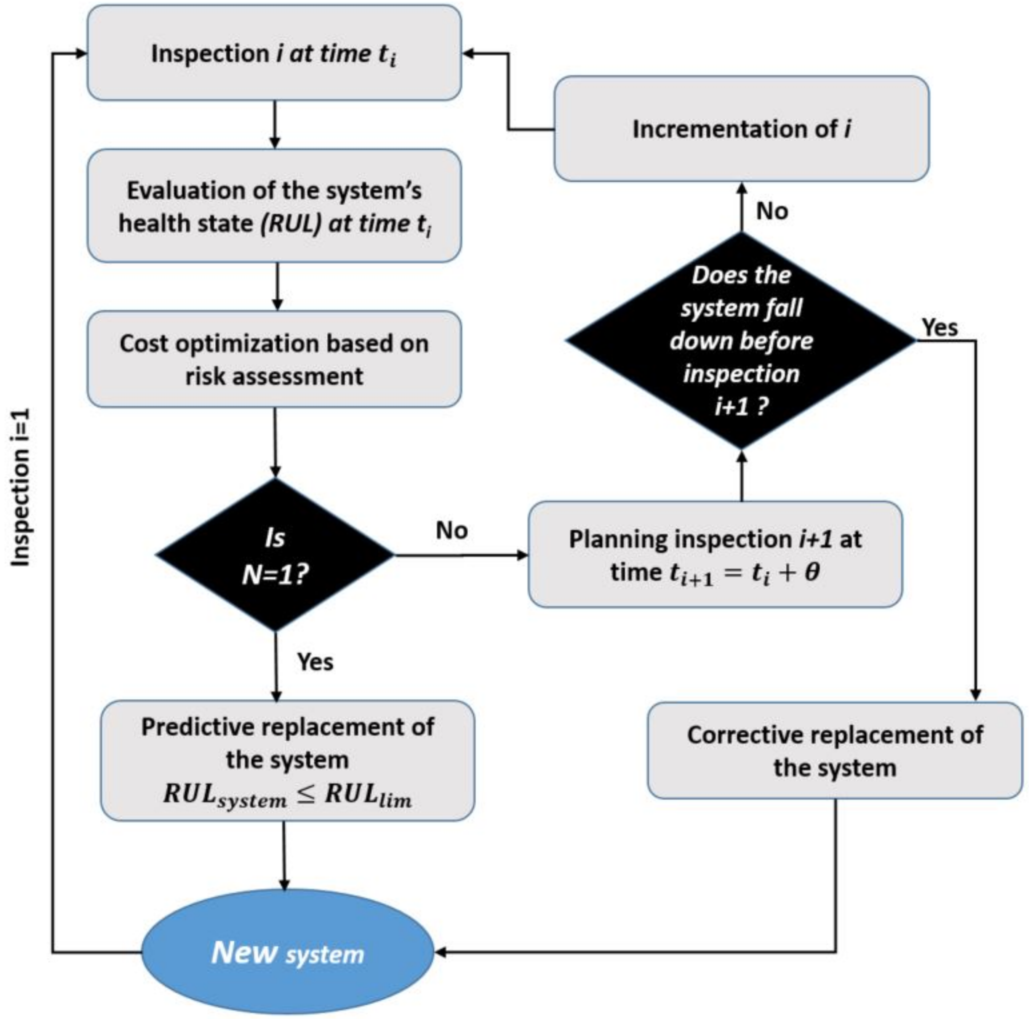
- ***Assumptions :***
- A failure of the system may cause damages to environment by emission of harmful pollutants. We assume that :
  - the total number of chemicals that may be emitted is equal to ***m***.
  - P_j is the probability of emission of chemical ***j***.
  - V_j is the volume of emission of chemical ***j***.
  - ρ_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 :***

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

III. RUL-based maintenance

3. Flowchart of the global approach



IV. Reliability-centered maintenance

1. Assumptions

- The system undergoes relatively constant conditions of stress, environment and a single maintenance activity in life cycle [7].
- The condition of the system is monitored continuously. The monitoring is perfect and has no effect on system reliability [7].
- The system hazard rate is a known function of the condition. This implies that the hazard rate function ca be monitored and predicted continuously through condition-based maintenance [7].
- A predictive maintenance action has a perfect effect on the system : the maintenance restores the system to as good as new as we consider only replacement [7].
- If the system fails before the scheduled predictive maintenance time, an unscheduled (corrective) maintenance has to be performed on the system. The cost for unscheduled maintenance is higher than the cost for scheduled(predictive) maintenance [7].

IV. Reliability-centered maintenance

2. Mathematical formulation

- Predictive maintenance is performed whenever the reliability of the system reaches the reliability threshold ***R***. This means that the system reliability at each predictive maintenance should be equal to ***R***.
- Considering $\mathbf{n_{in}}$ the total number of inspection and $\boldsymbol{h_i}$ the failure hazard rate of the system between inspection ***i*** and ***i+1***, the reliability ***R*** can be expressed as follow :

$$exp(\sum_{0}^{t_{nin}-1} -\int_{t_i}^{t_{i+1}} h_i(t).dt) = R$$

$$\sum_{0}^{t_{nin}-1} -\int_{t_i}^{t_{i+1}} h_i(t).dt = -lnR$$

IV. Reliability-centered maintenance

2. Mathematical formulation

- As the failure of the system follows the Weibull distribution, the hazard rate h_i can be expressed as follow :

$$h_i(t) = \frac{k_i}{\lambda_i}.(\frac{t}{\lambda_i})^{k_i-1}$$

Where λ_i and k_i are respectively the scale and shape paramters of failure distribution between inspection ***i*** and ***i+1***.

- At the n_{in}^{th} inspection, the probability of corrective maintenance is ***–lnR*** and the probability of predictive maintenance is ***1+lnR***.
- The expected total cost of maintenance ***EC*** at n_{in}^{th} inspection :

$$EC = c_c(-lnR) + c_p(1 + lnR) + c_i n_{in} + c_{dt}.D_c(-lnR) + c_{dt}.D_p(1 + lnR)$$

and the total cost rate c_{ER} during the cycle ***D*** :

$$c_{E_T} = \frac{EC}{D}.$$

IV. Reliability-centered maintenance

3. Main differences with RUL-based maintenance

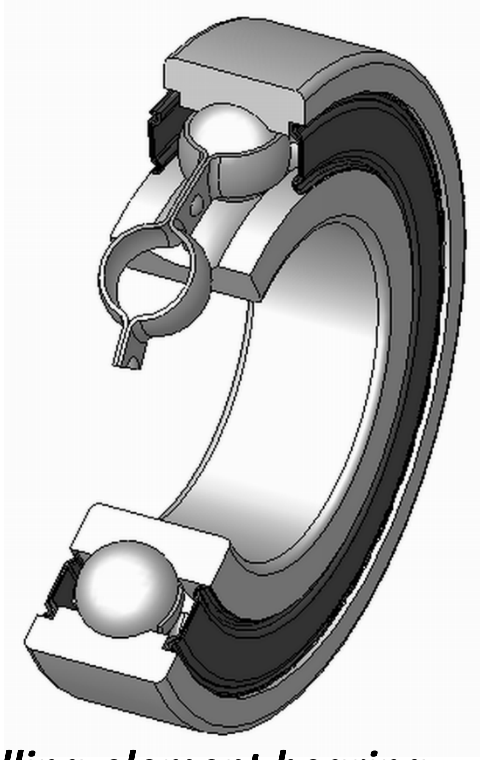
	RUL-based maintenance	Reliability-based maintenance
Optimization method	Reflection on an inspection interval and then optimization on cycle *D*	Reflection and optimization on cycle *D*
Health indicator	RUL (interval)	Reliability (value)
Predictive cost	Binary model	Probabilistic model

→ Both methods however agree on the objective results :
- Evaluation of the optimal health indicator for predictive maintenance
- Evaluation of the optimal number of inspections

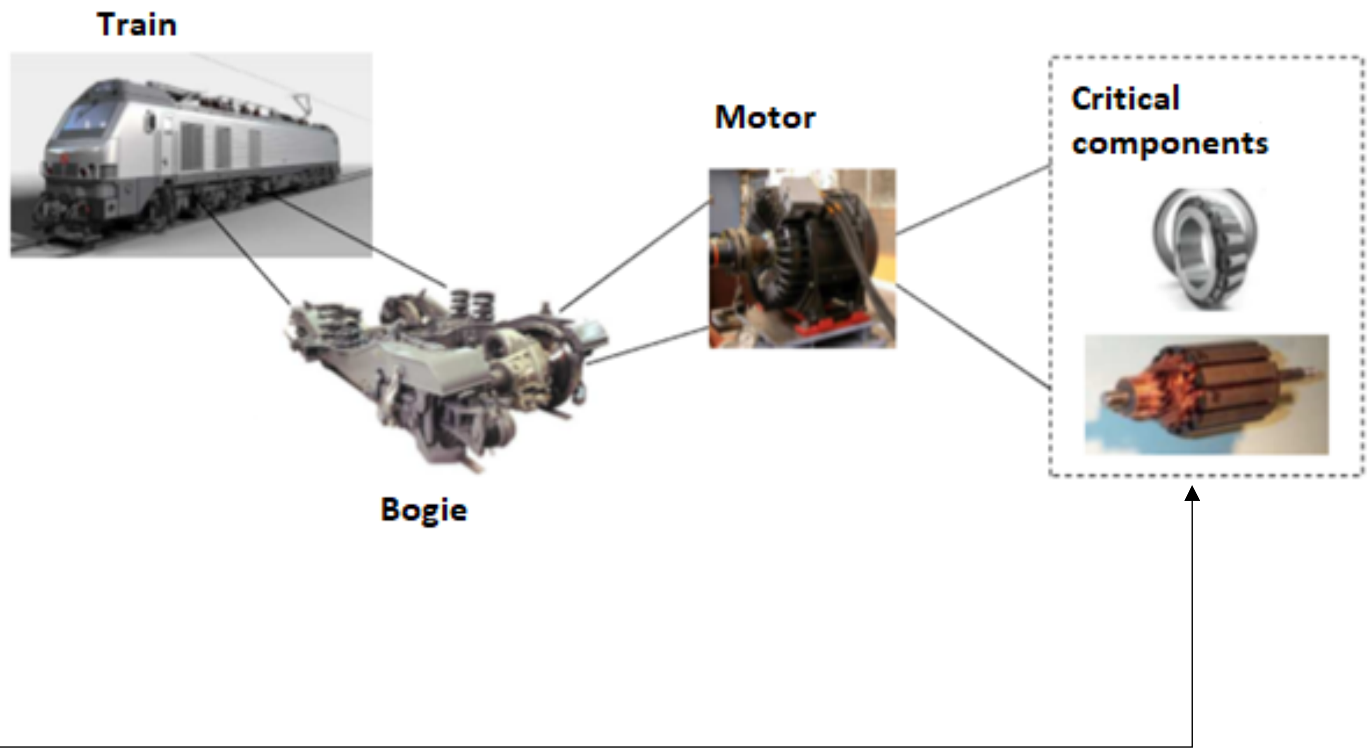
V. Application on a case-study : mechanical bearing system

1. System description

- 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.



rolling-element bearing



V. Application on a case-study : mechanical bearing system

1. System description

Characteristics of the system	*Value*	*Dimension*
Average lifetime of the global complex system D	25000	*hours (h)*
Cost of corrective replacement c_c	800	*euros*
Cost of predictive replacement c_p	200	*euros*
Cost of inspection c_i	150	*euros*
Cost of system down time for maintenance C_{dt}	1000	*euros/h*
Duration of a predictive replacement D_p	2	*hours (h)*
Duration of a corrective replacement D_c	10	*hours (h)*
Scale parameter of failure distribution λ	27000	/

V. Application on a case-study : mechanical bearing system

2. Impact of variation of input parameters on optimization results

- ***Variation of cost parameters***

Variation of c_i

c_i	RUL-based maintenance				Reliability-based maintenance				ΔN_{in}	ΔC_{tot}
	N_{in}	C_{tot}	RUL_{inf}	RUL_{sup}	N_{in}	c_{Er}	C_{tot}	R		
10	9	3994.56	4143.58	6675.40	9	0.15	3686.70	0.96	0	7.71%
20	9	4084.56	4143.58	6675.40	9	0.15	3776.70	0.96	0	7.54%
30	8	4168.40	4441.42	7326.17	8	0.15	3861.87	0.97	0	7.35%
40	8	4248.40	4441.42	7326.17	8	0.16	3941.87	0.97	0	7.22%
50	8	4328.40	4441.42	7326.17	8	0.16	4021.87	0.97	0	7.08%
60	7	4403.63	4827.33	8166.16	7	0.16	4096.11	0.98	0	6.98%
70	7	4473.63	4827,33	8166,16	7	0.17	4166.11	0.98	0	6.87%
80	7	4543.63	4827.33	8166.16	7	0.17	4236.11	0.98	0	6.77%
90	7	4613.63	4827.33	8166.16	7	0.17	4306.11	0.98	0	6.67%
100	7	4683.63	4827.33	8166.16	7	0,18	4376.11	0.98	0	6.57%
110	6	4748.71	5345.28	9287.76	6	0.18	4437.23	0.98	0	6.56%
120	6	4808.71	5345.28	9287.76	6	0.18	4497.23	0.98	0	6.48%
130	6	4868.71	5345.28	9287.76	6	0.18	4557.23	0.98	0	6.40%
140	6	4928.71	5345.28	9287.76	6	0.18	4617.23	0.98	0	6.32%
150	6	4988.71	5345.28	9287.76	6	0.19	4677.23	0.98	0	6.24%
160	6	5048.71	5345.28	9287.76	6	0.19	4737.23	0.98	0	6.17%
170	6	5108.71	5345.28	9287.76	6	0.19	4797.23	0.98	0	6.10%
180	6	5168.71	5345.28	9287.76	5	0.19	4856.98	0.99	1	6.03%
190	5	5225.30	6073,064935	10853.75	5	0.20	4906.98	0.99	0	6.09%
200	5	5275.30	6073.06	10853.75	5	0.20	4956.98	0.99	0	6.03%

V. Application on a case-study : mechanical bearing system

2. Impact of variation of input parameters on optimization results

- ***Variation of cost parameters***

Variation of c_p

c_p	RUL-based maintenance				Reliability-based maintenance				ΔN_{in}	ΔC_{tot}
	N_{in}	C_{tot}	RUL_{inf}	RUL_{sup}	N_{in}	c_{Er}	C_{tot}	R		
100	6	4888.71	5345.28	9287.76	6	0.18	4595.57	0.98	0	6%
200	6	4988.71	5345.28	9287.76	6	0.19	4677.23	0.98	0	6.24%
300	6	5088.71	5345.28	9287.76	6	0.19	4758.89	0.98	0	6.48%
400	6	5188.71	5345.28	9287.76	6	0.19	4840.55	0.98	0	6.71%
500	6	5288.71	5345.28	9287.76	6	0.20	4922.21	0.98	0	6.93%
600	6	5388.71	5345.28	9287.76	6	0.20	5003.87	0.98	0	7.14%
700	6	5488.71	5345.28	9287.76	6	0.20	5085.53	0.98	0	7.35%
800	6	5588.71	5345.28	9287.76	6	0.21	5167.19	0.98	0	7.54%
900	6	5688.71	5345.28	9287.76	6	0.21	5248.85	0.98	0	7.73%
1000	6	5788.71	5345.28	9287.76	6	0.21	5330.51	0.98	0	7.92%
1100	6	5888.71	8961.49	16916.07	6	0.22	5412.17	0.98	0	8.09%
1200	6	5988.71	8961.49	16916.07	6	0.22	5493.83	0.98	0	8.26%
1300	6	6088.71	8961.49	16916.07	6	0.22	5575.49	0.98	0	8.43%
1400	6	6188.71	24225.72	26052.64	6	0.23	5657.15	0.98	0	8.59%
1500	6	6288.71	24225.72	26052.64	6	0.23	5738.81	0.98	0	8.74%

V. Application on a case-study : mechanical bearing system

2. Impact of variation of input parameters on optimization results

- ***Variation of cost parameters***

Variation of c_c

c_c	RUL-based maintenance				Reliability-based maintenance				ΔN_{in}	ΔC_{tot}
	N_{in}	C_{tot}	RUL_{inf}	RUL_{sup}	N_{in}	c_{Er}	C_{tot}	R		
100	6	4866.29	5345.28	9287.76	6	0.18	4548.85	0.98	0	6.52%
200	6	4883.78	5345.28	9287.76	6	0.18	4567.19	0.98	0	6.48%
300	6	4901.27	5345.28	9287.76	6	0.18	4585.53	0.98	0	6.44%
400	6	4918.76	5345.28	9287.76	6	0.18	4603.87	0.98	0	6.40%
500	6	4936.25	5345.28	9287.76	6	0.18	4622.21	0.98	0	6.36%
600	6	4953.73	5345.28	9287.76	6	0.19	4640.55	0.98	0	6.32%
700	6	4971.22	5345.28	9287.76	6	0.19	4658.89	0.98	0	6.28%
800	6	4988.71	5345.28	9287.76	6	0.19	4677.23	0.98	0	6.24%
900	6	5006.20	5345.28	9287.76	6	0.19	4695.57	0.98	0	6.20%
1000	6	5023.69	5345.28	9287.76	6	0.19	4713.91	0.98	0	6.17%
1100	6	5041.17	5345.28	9287.76	6	0.19	4732.25	0.98	0	6.13%
1200	6	5058.66	5345.28	9287.76	6	0.19	4750.59	0.98	0	6.09%
1300	6	5076.15	5345.28	9287.76	6	0.19	4768.93	0.98	0	6.05%
1400	6	5093.64	5345.28	9287.76	6	0.19	4787.27	0.98	0	6.01%
1500	6	5111.13	5345.28	9287.76	6	0.19	4805.61	0.98	0	5.98%

V. Application on a case-study : mechanical bearing system

2. Impact of variation of input parameters on optimization results

- ***Variation of cost parameters***

Variation of c_{dt}

c_{dt}	RUL-based maintenance				Reliability-based maintenance				ΔN_{in}	ΔC_{tot}
	N_{in}	C_{tot}	RUL_{inf}	RUL_{sup}	N_{in}	c_{Er}	C_{tot}	R		
500	5	3064.51	6073.06	10853.75	5	0.12	2889.78	0.99	0	5.70%
600	5	3456.67	6073.06	10853.75	5	0.13	3253.22	0.99	0	5.89%
700	5	3848.83	6073.06	10853.75	5	0.14	3616.66	0.99	0	6.03%
800	6	4238.95	5345.28	9287.76	5	0.16	3980.10	0.99	1	6.11%
900	6	4613.83	5345.28	9287.76	6	0.17	4330.51	0.98	0	6.14%
1000	6	4988.71	5345.28	9287.76	6	0.19	4677.23	0.98	0	6.24%
1100	6	5363.59	5345.28	9287.76	6	0.20	5023.95	0.98	0	6.33%
1200	6	5738.47	5345.28	9287.76	6	0.21	5370.67	0.98	0	6.41%
1300	6	6113.35	5345.28	9287.76	6	0.23	5717.39	0.98	0	6.48%
1400	6	6488.23	4827.34	8166.16	6	0.24	6064.10	0.98	0	6.54%
1500	7	6859.39	4827.34	8166.16	6	0.26	6410.82	0.98	1	6.54%
1600	7	7224.54	4827.34	8166.16	7	0.27	6749.98	0.98	0	6.57%
1700	7	7589.69	4827.34	8166.16	7	0.28	7087.29	0.98	0	6.62%
1800	7	7954.84	4827.34	8166.16	7	0.30	7424.60	0.98	0	6.67%
1900	7	8320	4827.34	8166.16	7	0.31	7761.92	0.98	0	6.71%
2000	7	8685.15	4827.34	8166.16	7	0.32	8099.23	0.98	0	6.75%

→ The optimal number of inspections is similar for both methods for different values of cost parameters (***c_i***, ***c_p*** and ***c_{dt}***).

→ ΔC_{tot} is almost constant and close to ***6%***. This is due to the fact that in our approach we use a discrete model for predictive maintenance while in [7], we use a probability for predictive maintenance.

V. Application on a case-study : mechanical bearing system

2. Impact of variation of input parameters on optimization results

- ***Variation of time parameters***

Variation of D_p

D_p	RUL-based maintenance				Reliability-based maintenance				ΔN_{in}	ΔC_{tot}
	N_{in}	C_{tot}	RUL_{inf}	RUL_{sup}	N_{in}	c_{Er}	C_{tot}	R		
0.50	6	3488.71	5345.28	9287.76	6	0.14	3452.33	0.98	0	1.04%
1	6	3988.71	5345.28	9287.76	6	0.15	3860.63	0.98	0	3.21%
1.50	6	4488.71	5345.28	9287.76	6	0.17	4268.93	0.98	0	4.90%
2	6	4988.71	5345.28	9287.76	6	0.19	4677.23	0.98	0	6.24%
2.50	6	5488.71	6073.06	10853.75	6	0.20	5085.53	0.98	0	7.35%
3	6	5988.71	6073.06	10853.75	6	0.22	5493.83	0.98	0	8.26%
3.50	6	6488.71	6073.06	10853.75	5	0.24	5900.53	0.99	1	9.06%
4	6	6988.71	6073.06	10853.75	5	0.25	6298.38	0.99	1	9.88%
4.50	6	7488.71	6073.06	10853.75	5	0.27	6696.23	0.99	1	10.58%
5	6	7988.71	6073.06	10853.75	5	0.28	7094.08	0.99	1	11.20%
5.50	6	8488.71	6073.06	10853.75	5	0.30	7491.93	0.99	1	11.74%
6	6	8988.71	6073.06	10853.75	5	0.32	7889.78	0.99	1	12.23%
6.50	6	9488.71	6073.06	10853.75	5	0.33	8287.63	0.99	1	12.66%
7	6	9988.71	6073.06	10853.75	4	0.35	8669.17	0.99	2	13.21%
7.50	6	10488.71	6073.06	10853.75	4	0.36	9048.45	0.99	2	13.73%
8	1	10950			4	0.38	9427.73	0.99	-3	13.90%

V. Application on a case-study : mechanical bearing system

2. Impact of variation of input parameters on optimization results

- ***Variation of time parameters***

Variation of D_c

D_c	RUL-based maintenance				Reliability-based maintenance				ΔN_{in}	ΔC_{tot}
	N_{in}	C_{tot}	RUL_{inf}	RUL_{sup}	N_{in}	c_{Er}	C_{tot}	R		
1	1	1950			1	0.08	1950		0	0%
2	1	2950			2	0.11	2757.19	0.99	-1	6.54%
3	4	3644.53			3	0.13	3145.02	0.99	1	13.71%
4	4	3866.77	7161.83	13177.22	4	0.14	3427.73	0.99	0	11.35%
5	5	4064.51	6073.6	10853.75	4	0.15	3669.17	0.99	1	9.73%
6	5	4256.67	6073.6	10853.75	5	0.16	3889.78	0.99	0	8.62%
7	5	4448.83	6073.6	10853.75	5	0.16	4094.08	0.99	0	7.97%
8	5	4640.99	6073.06	10853.75	5	0.17	4298.38	0.99	0	7.38%
9	6	4813.83	5345.28	9287.76	6	0.18	4493.83	0.98	0	6.65%
10	6	4988.71	5345.28	9287.76	6	0.19	4677.23	0.98	0	6.24%

→ There is a slight difference in the results between both methods. The gap in results is more important as we get close to unrealistic configurations where D_p is close to D_c.

→ The impact of predictive maintenance cost and corrective maintenance cost on optimization results is seen through c_{dt}, D_p and D_c rather than c_c and c_p.

VI. Conclusion and future perspectives

- **Maintenance cost-optimization based on *RUL***
- **Application on a case-study : mechanical –bearing system**
- **Comparaison with reliability-centered maintenance by varying the input parameters and study their impact on optimization results**

Scientific publications :

(1) R. Louhichi, M. Sallak, and J. Pelletan. ”A cost model for predictive maintenance based on risk-assessment.” CIGI QUALITA, Canada, 2019.

(2) R. Louhichi, M. Sallak, and J. Pelletan. “A maintenance cost optimization approach : application on a mechanical bearing system”. **International Journal** of **Mechanical Engineering and Robotics** Research, 2020 (being published).

(3) A study of the impact of predictive maintenance parameters on the improvement of system monitoring. **Cognition, Technology and Work** revue, 2020 (submitted paper).

VI. Conclusion and future perspectives

Risk study → Decision maker's attitude to risks → Test and validation

How about a multi-component system ?

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