

2021

MCTR 701_1

Master Advanced Mechatronics

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**Mechatronics
common framework
Lecture 2**

Contents

Lecture 2

IMPLEMENTATION OF THE MECHATRONIC SYSTEMS RELIABILITY PREDICTION

PROCESS

- Implementation of a specific approach for mechatronic systems
- Application to the two industrial examples previously described

Contents

- Objectives
- Issues
- Preliminary steps to the implementation of the approach
- Mechatronic system
- Bibliographic review (state of the art)
- Proposed approach: 10 steps
- Consolidation of the proposed approach
- Descriptions of the steps' approach and illustrations
- Conclusions
- Improvement areas

Definitions

Quality = Conformance to specifications or requirements defined by customer at time $t = 0$

Improvement of the quality can be improved by different methods and techniques:

- ISO 9004:2008
- Total Quality Management (TQM)
- Statistical
- Process control
- Six Sigma
- Quality Function Deployment (QFD)
- Quality Circle,
- Taguchi method
-

Definitions

Reliability = ability of a system or component to perform its required functions under stated conditions for a specified period of time

Definitions

Maintainability = ability of an item, under stated conditions of use, to be retained in, or restored to, a state in which it can perform its required functions, when maintenance is performed under stated conditions and using prescribed procedures and resources

- To reduce the chance of failures, **maintenance can be preventive or predictive**:
 - **Corrective Maintenance**: carried out after fault recognition to put an entity into a state in which it can perform a required function.
 - **Preventive Maintenance**: carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an entity.
 - **Predictive Maintenance**: performed continuously or at intervals governed by observed condition to monitor, diagnose or trend a structure, system or components' condition indicators.

Definitions

Availability = probability that a product or system is in operation at a specified time

The simplest representation of availability (A) is:

$$A = \frac{\text{Uptime of system}}{\text{Uptime of system} + \text{Downtime of system}}$$

Uptime depends on reliability of the system whereas downtime depends on maintainability of the system.

Thus availability is function of both reliability and maintainability.

Definitions

Failure = is the opposite ability of reliability, it corresponds to the "cessation of the ability of an entity to perform a required function"

The faulty (failed) state corresponds to an unacceptable state (loss of function)

Failures

Failure is inevitable for engineering systems.

Impact of failures :

- minor inconvenience and costs
- personal injury
- significant economic loss
- environmental impact
- deaths

Cause of failure :

- bad engineering design
- faulty manufacturing
- inadequate testing
- human error
- poor maintenance
- lack of protection against excessive stress



Fukushima
Space X
Chernobyl accident
Bhopal gas tragedy
space shuttle Columbia disaster



Classification of failures

- Amplitude: Partial, Complete or Total
- Speed of manifestation: Progressive or Sudden
- Amplitude and speed of manifestation: By degradation, Catalectic
- Date of appearance: Early or Youth, Random or Mature, Aging
- Causes: First, Second, By control
- Effects: Minor, Significant, Critical, Catastrophic

Need for Reliability and Safety Engineering

Reliability deals with the failure concept

Safety deals with the consequences after the failure

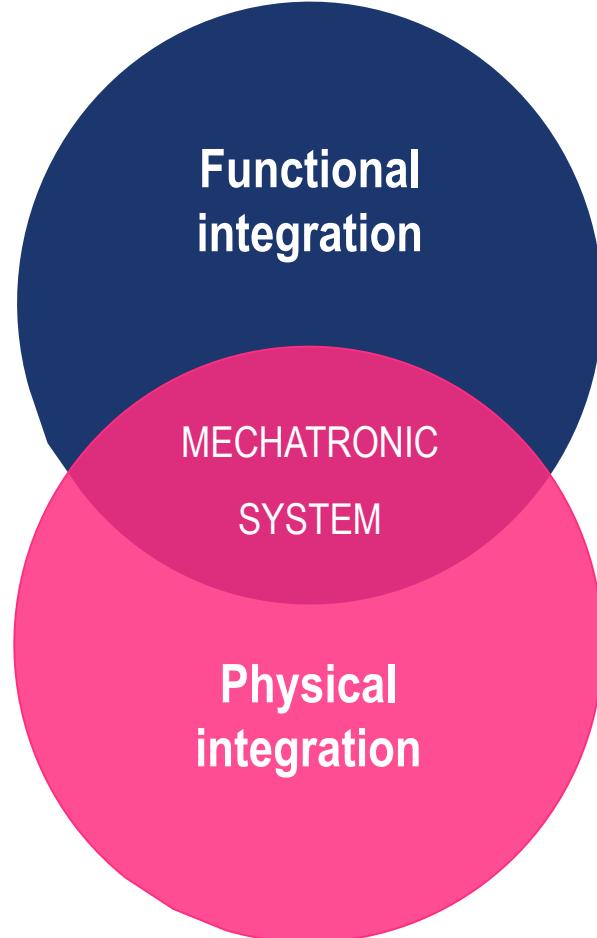
It is essential :

- to understand ‘why’ and ‘how’ failures occur to minimize them
- to know how often such failures may occur

Reliability and safety engineering are improved by the following factors:

- Design evaluation;
- Identification of critical components/events;
- Redundancy requirements;
- Burn-In/Accelerated life tests
- Establishment of preventive maintenance programs;
- Life cycle cost analysis

Issues



Mechatronics

multiple technologies

- Reliability is traditionally studied by technology
 - partitioning and analysis by technical department (electronics, mechanics, software ...)
- Reliability is studied phase by phase_(design, manufacturing,...)
 - *numerous dedicated methods exist with drawbacks, advantages and limitations*

Need for a interdisciplinary
and overall approach

Objectives of reliability prediction of mechatronic systems

To propose an approach able to estimate the predictive reliability of a mechatronic system during the design phase, that can take into account:

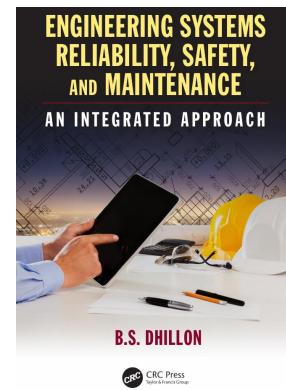
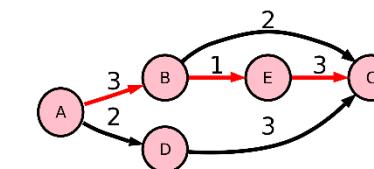
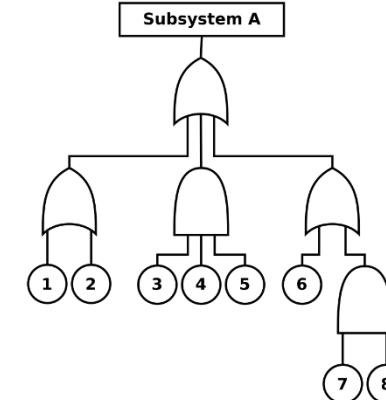
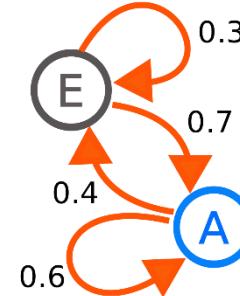
- the **intrinsic characteristics** of mechatronic systems
- the different **components and functions** of the system
- the **relations** between these components and functions
- the **mission profile**



Innovative
approach

Methods for performing Reliability, Safety, and Maintenance Analysis

- Markov
- FTA (*Fault Tree Analysis*)
- TOR (*Technique of Operation Review*)
- **FMEA (*Failure Mode Effect Analysis*)**



Bibliographic review / State of the art

Identification and analysis of the **state of the art** of the different **approaches** to study the reliability of mechatronic systems



Identification and analysis of the **deficiencies and gaps** in terms of reliability estimation for mechatronic systems

Keywords	Ziegler 1996	Moncelet 1998	Khalfaoui 2003	Schoenig 2004	Mihalache 2007	Demri 2009
reliability	-	-	-	-	+	+
mechatronic system	-	+	+	+	+	+
modeling	+	+	+	+	+	+
simulation	-	+	-	+	+	+
interdisciplinary dimension	-	-	-	-	-	-
vertical dimension	-	-	-	-	+	-
qualitative study	-	+	+	-	-	+
quantitative study	+	+	-	+	+	+
technological interdependences	-	-	-	-	-	-

- Neither **different functioning phases**, nor the **mission profile** and the **influent factors** are taken into account
- The **physical and functional interactions** created between the different technological parts are not studied
- No estimation of the **global reliability**

An innovative approach designed at SYMME lab - USMB



Contents lists available at [ScienceDirect](#)

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/reess



An overall methodology for reliability prediction of mechatronic systems design with industrial application

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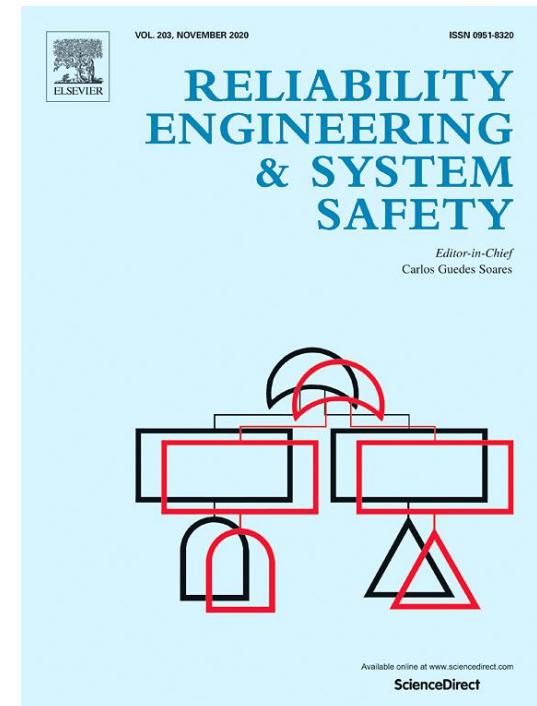
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ABSTRACT

We propose in this paper an overall ten-step methodology dedicated to the analysis and quantification of reliability during the design phase of a mechatronic system, considered as a complex system. The ten steps of the methodology are detailed according to the downward side of the V-development cycle usually used for the design of complex systems. Two main phases of analysis are complementary and cover the ten steps, qualitative analysis and quantitative analysis. The qualitative phase proposes to analyze the functional and dysfunctional behavior of the system and then determine its different failure modes and degradation states, based on external and internal functional analysis, organic and physical implementation, and dependencies between components, with consideration of customer specifications and mission profile. The quantitative phase is used to calculate the reliability of the system and its components, based on the qualitative behavior patterns, and considering data gathering and processing and reliability targets. Systemic approach is used to calculate the reliability of the system taking into account: the different technologies of a mechatronic system (mechanics, electronics, electrical ...), dependencies and interactions between components and external influencing factors. To validate the methodology, the ten steps are applied to an industrial system, the smart actuator of Pack'Aero Company.

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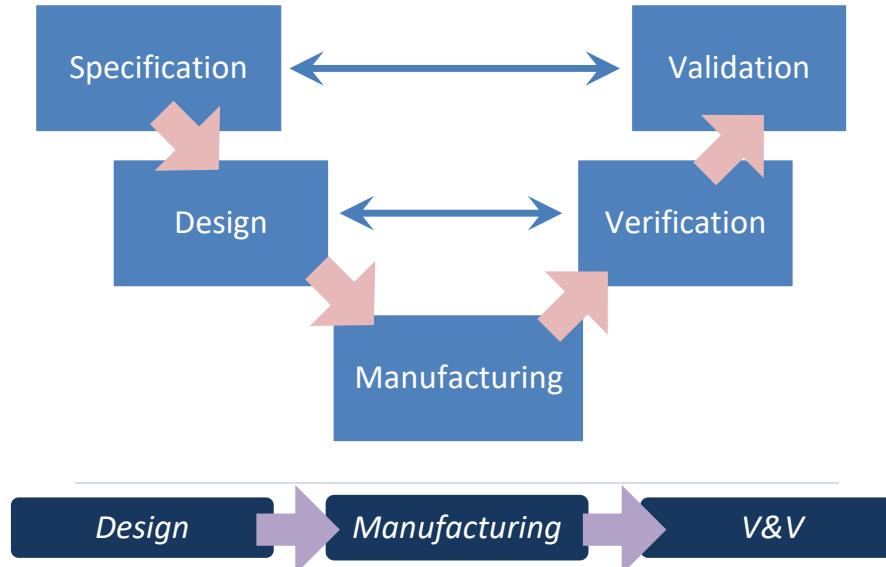


SYMME

Proposed approach: initial considerations

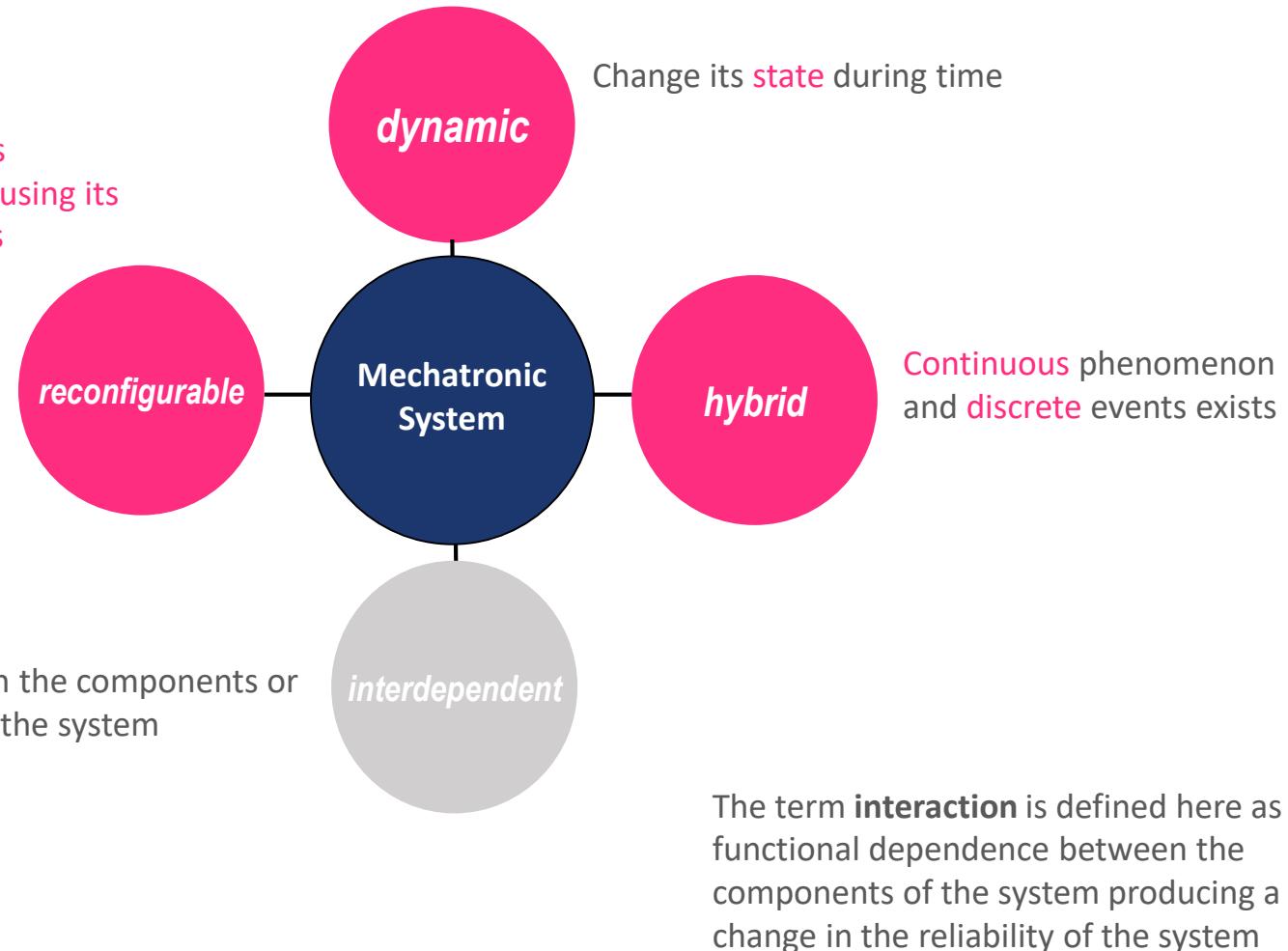
Development model

- Based on the **V- cycle**
- Interdisciplinary and overall approach
- Qualitative and quantitative analysis
- **Intrinsic characteristics** taken into account at each step
- Under a defined **mission profile**
- **Interactions** considered



Proposed approach: initial considerations

Assume **different functions**
alternatively or a **function using its
resources in different ways**



Proposed approach: 10 steps

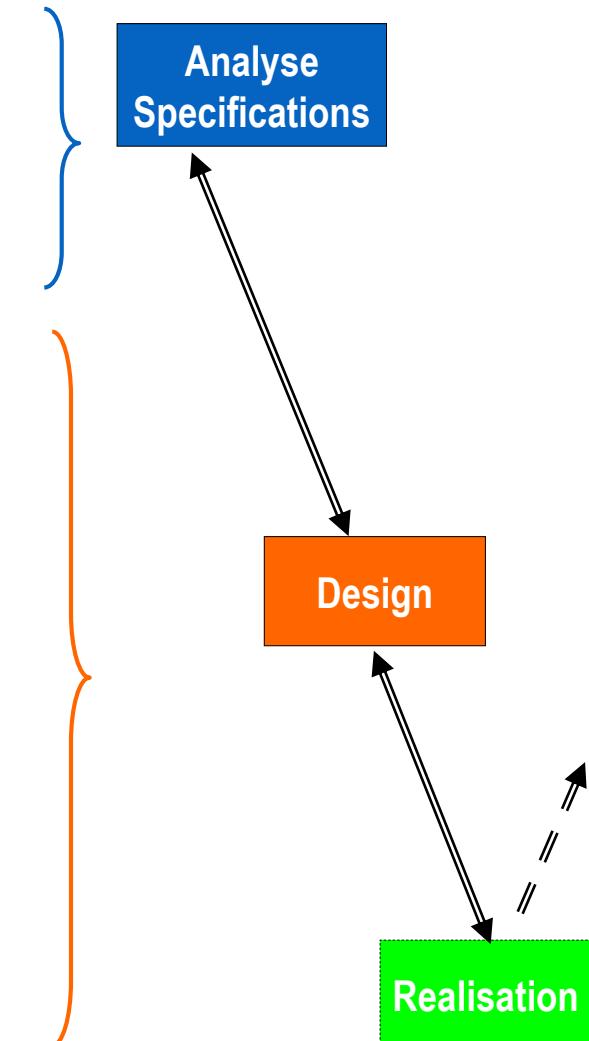
Qualitative analysis



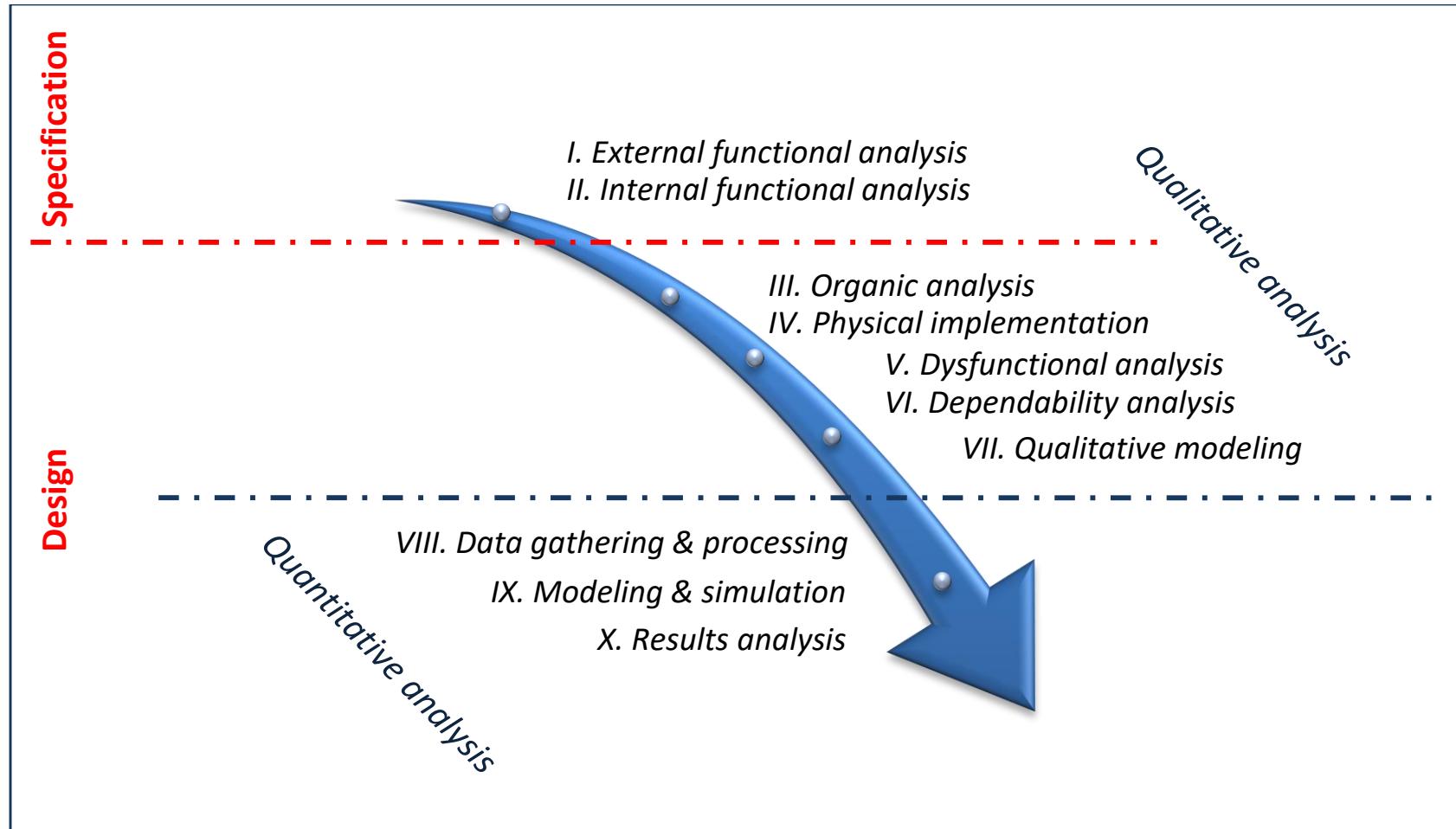
Quantitative analysis

1. External functional analysis (APTE)
2. Internal functional analysis (Bloc Diagrams)
3. Organic analysis (Bloc Diagrams)
4. Analysis of the physical place of the components
5. Dysfunctional analysis (enriched FMEA)
6. Interactions analysis (Interactions matrix)
7. Qualitative modeling (RdP)

8. Data gathering and processing (FIDES, tests, feedback...)
9. Modeling and simulation taking into account the mission profile and the interactions (RdP + Monte-Carlo, DF)
10. Analysis of simulation results



Proposed approach: 10 steps



Preliminary steps to the implementation of the approach

- The estimation of forecast reliability needs to provide the following informations :
 - Complete specifications
 - Reliability objectives
 - **Reliability data** concerning the components of the system and that are not available in database



A strong involvement of the company is needed in the implementation of the approach

Consolidation of the approach

Examples of industrial systems

Choice of 2 examples in order to run through the approach to realise it and consolidate it:

- Simple mechatronic systems
- Principal data available
- Industrial experimented in reliability
- Geographic proximity



Example to illustrate

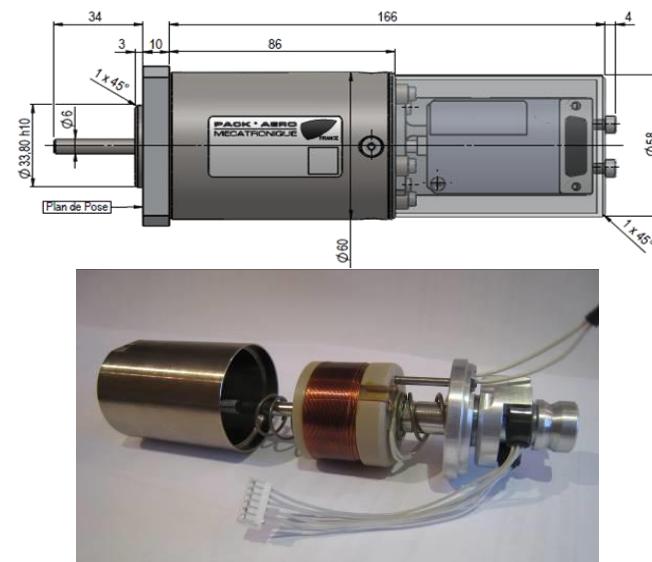
Smart actuator



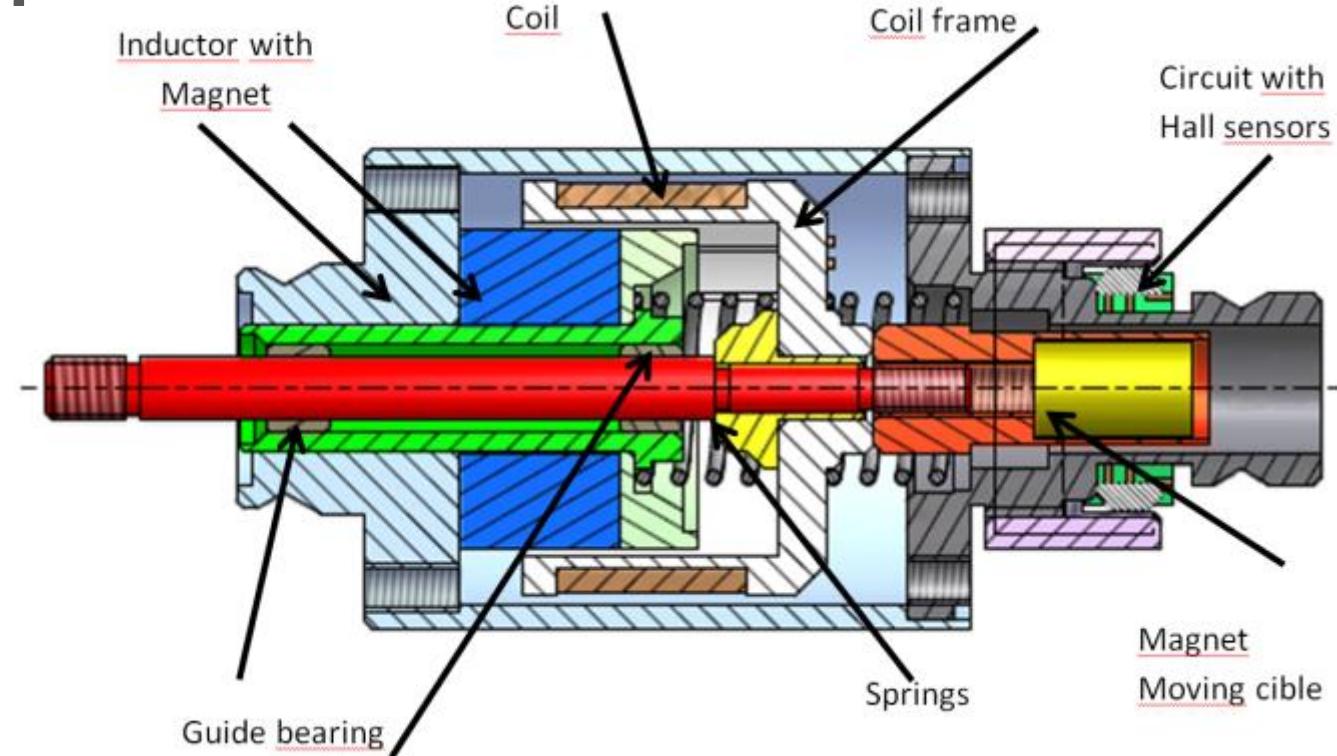
■ Specifications

In addition to be a classical actuator, the smart actuator assume additional functions such as operating, monitoring, communicating, data processing, etc.

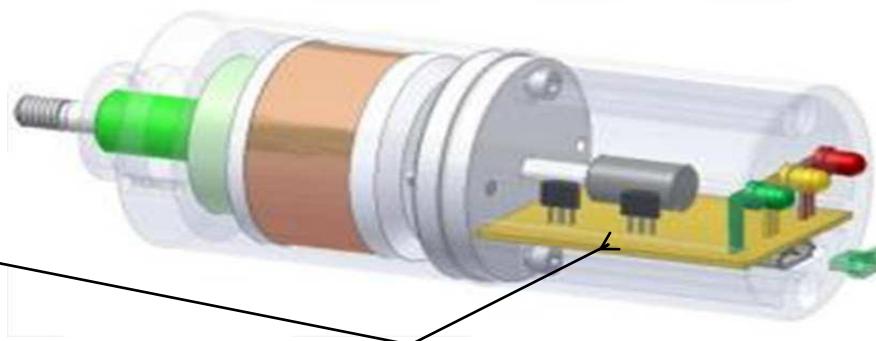
- > Transition from passive state to **active** state
- > Using a linear direct action instead of a linear indirect one
- > **Optimisation of the immediate answer** according to the needs
- > Integration of **electrical locking functions** with or without electricity consumption



Overall plan



Physical implementation
of the circuit board



Example to illustrate

■ Using context

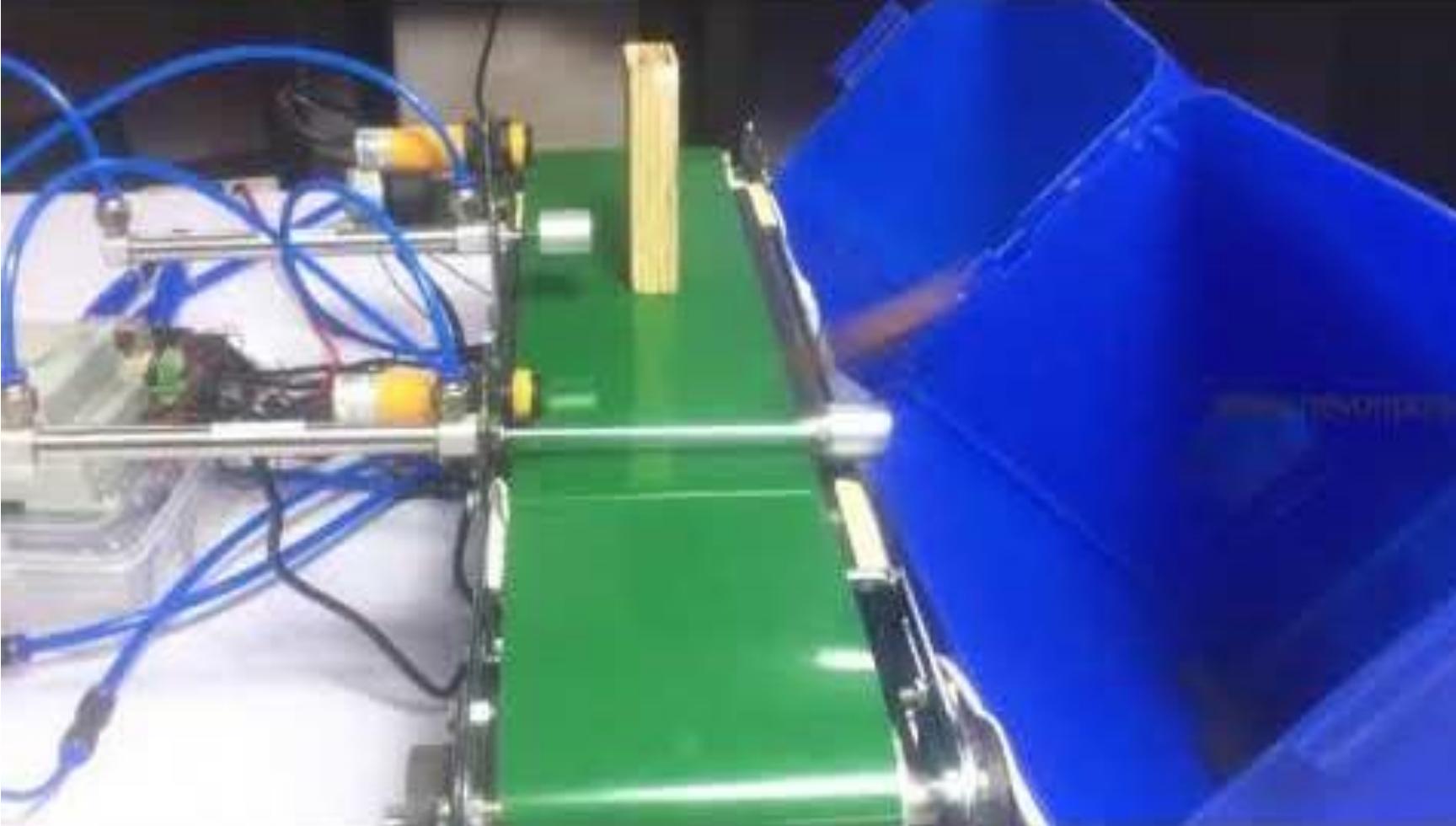
Continuous sorting line including 200 to 1000 wagons.

- The wagons carry parts from a station to another of the chain in continuous motion
- The actuator contributes to the realization of the function of wagons unloading

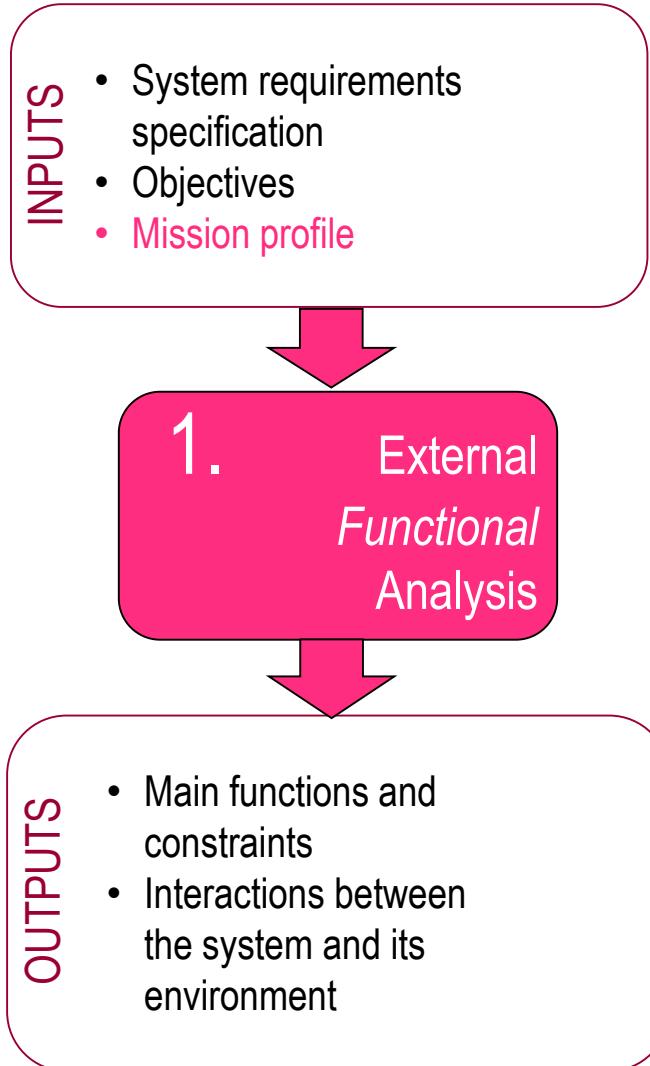
The finger of the smart actuator is used as a stop to open the shutter and release (let go) the load of wagon without stopping



Example to illustrate



1. External functional analysis



Describes:

- The expected function for **each phasis of the profile**
 - The reactive functions to take into account the environment
 - The **constraints** imposed by the users
- To write the Functional Specification

Mission profile

Component failure rates are very sensitive to the stresses applied.

Stresses, which can be classified as environmental or self-generated, include:

Temperature Shock Vibration Humidity Ingress of foreign bodies	Environmental
Power dissipation Applied voltage and current Self-generated vibration Wear	Self-generated

The intended use and environment of a system must be accurately stated in order to realistically measure Reliability.

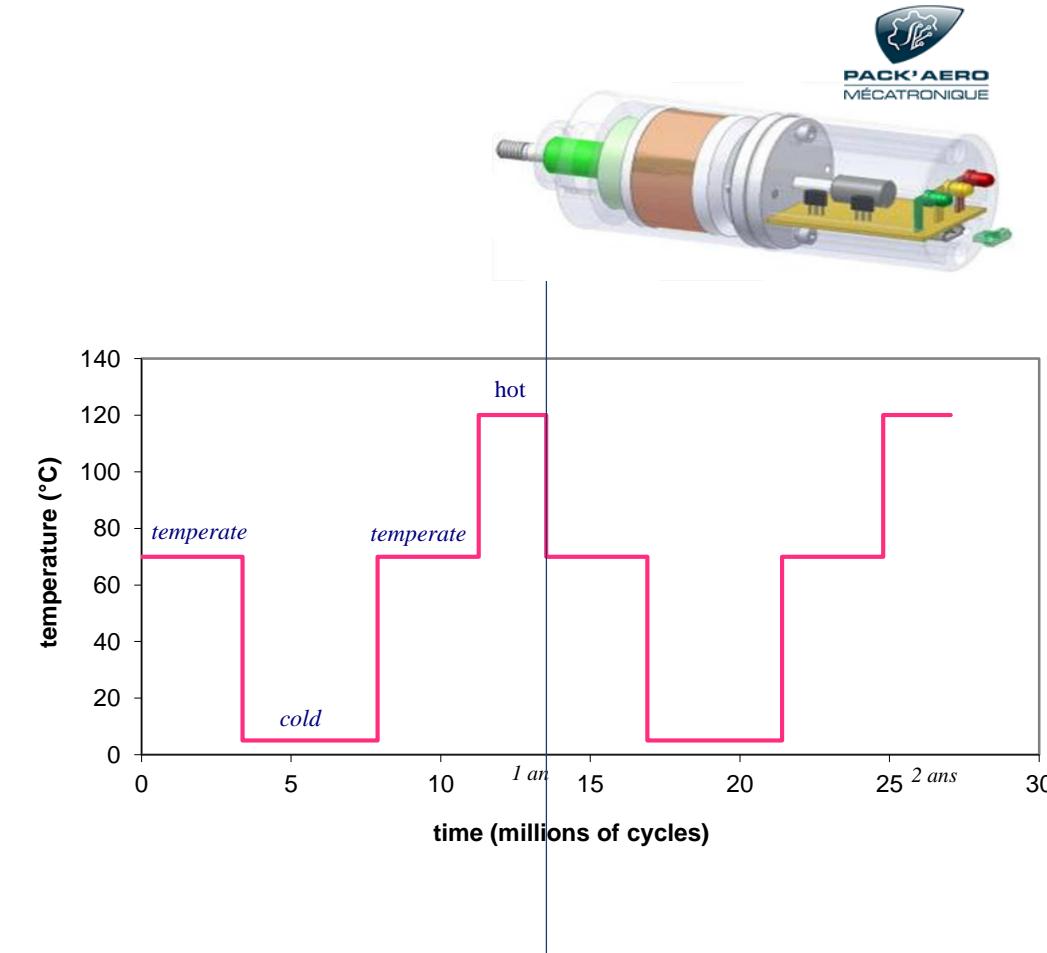
Mission profiles is an effective tool for that purpose

Mission profile

- The mission profile will be taken into account in the estimation of the predictive reliability.

Example of a mission profile for the actuator

- An influent factor : temperature
- Three different functioning phases: cold, temperate, hot

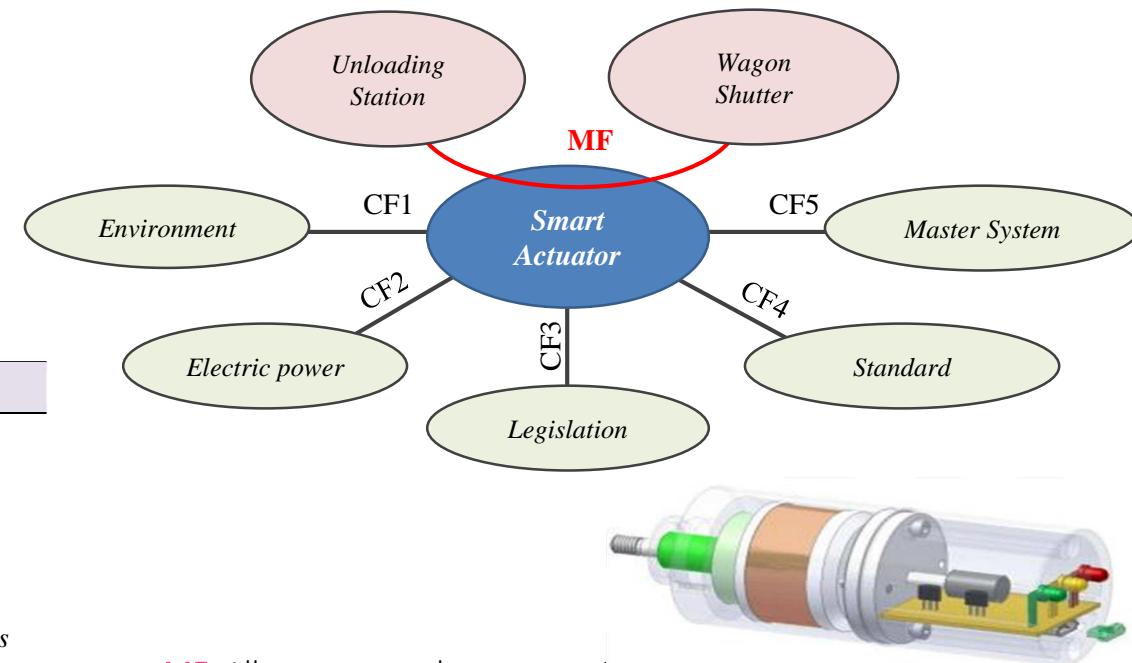


Functional Specification

APTE : Application of Corporation (Professional) Methods

Characteristics of the main function and constraint functions

Function	Criteria/Target	Value/Information
MF	Average number of opening/closing cycles before the occurrence of a first failure (MTTF)	10 million of cycles
	Desired lifetime	10 years
	Operating information	Intermittent operation Electric power: 1 slot ON-OFF/60 ms Duration of an opening/closing cycle: 40 ms Time between two cycles: 1.67 s Operation time 20 h/24, 6 days/7
CF1	Temperature and duration of the hot phase	120°C for 2/12 of cycles
	Temperature and duration of the cold phase	5°C for 4/12 of cycles
	Temperature and duration of the temperate phase	70°C for 2 times 3/12 of cycles
CF2	Electric power and voltage	10 W and 24 V +/- 5%
CF3	Meet the legislation requirements	Low Voltage Directive: NSC 20-030 Directive clean machine (Example: Noise emitted by equipment NFEN 11201)
CF4	Meet the normative standard requirements	Degree of electrical protection: NFEN60529 Noise emitted by equipment: NFEN 11201
CF5	Working order Stop order	TOR function (1) TOR function (0)



MF: Allows wagon shutter opening when the wagon arrives at the unloading station,

CF1: Withstands the thermal environment,

CF2: Works with the installed electrical power,

CF3: Meets the requirements of legislation,

CF4: Meets the normative standards requirements,

CF5: Allows the master system to order operating (ON/OFF).

2. Internal functional analysis

INPUTS

- System requirements specification, objectives, mission profile
- Main functions and constraints,
- Interactions between the system & its environment



To I/O of the External Functional Analysis

2. Internal Functional Analysis

OUTPUTS

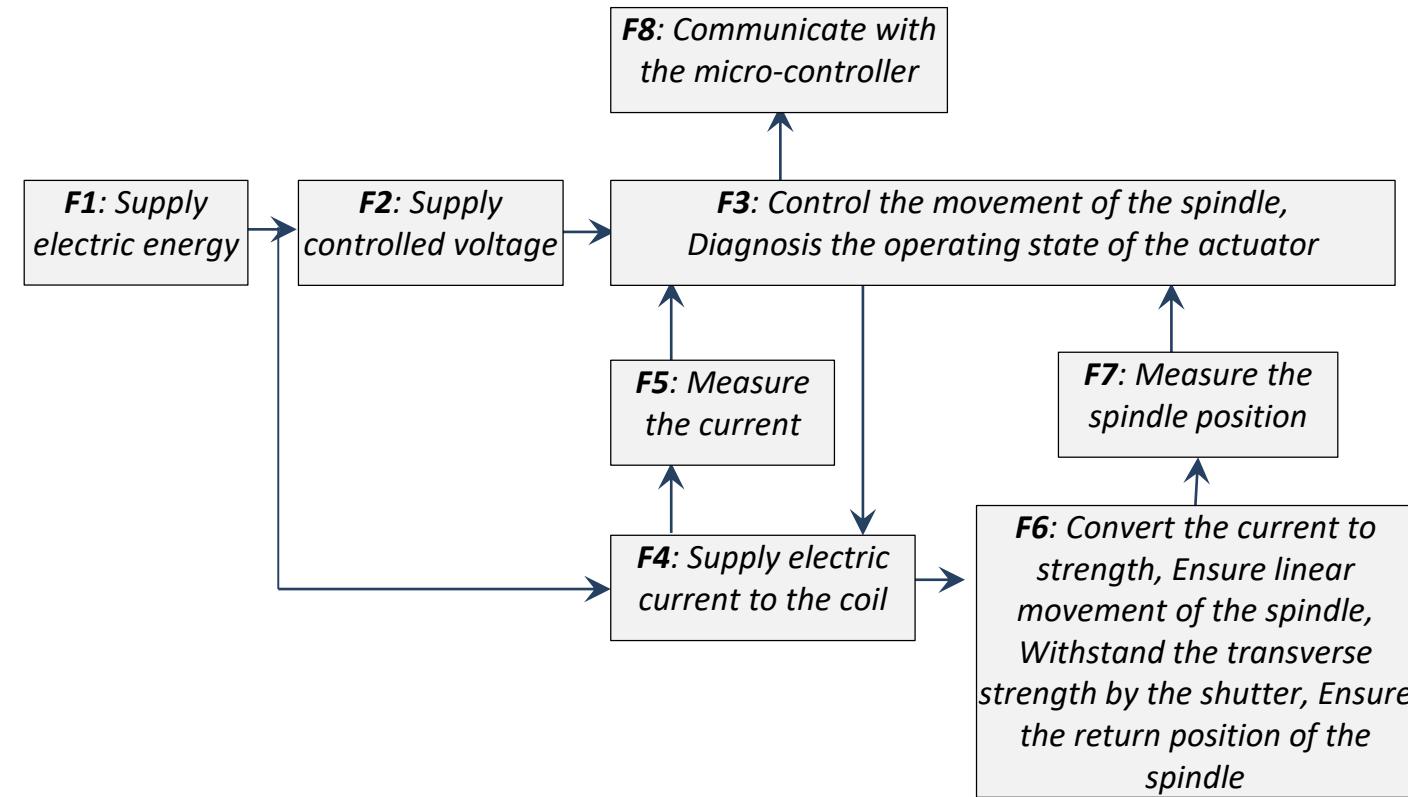
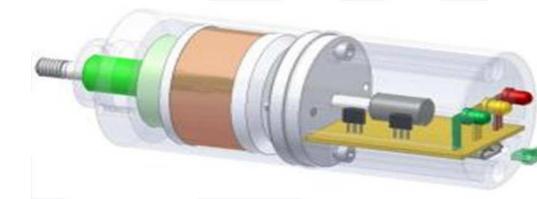
- Functional architecture,
- Choice criterion of the proposed technical solutions
- Description of the internal system & the relationships between internal functions

- establishes relationships between the external functional analysis and **possible solutions** to meet the need.
- allows the definition of the functions identified into **internal technical functions**

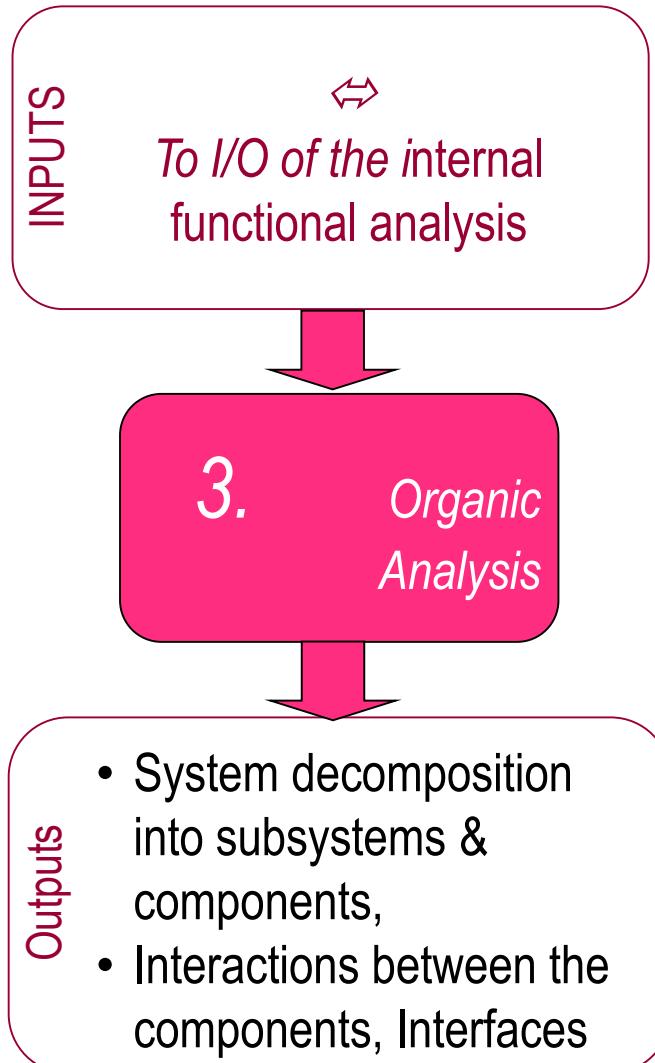
→ To make available some elements to compare objectives between different solutions

Functional Block Diagram (FBD)

FBD is a tool used to map the key internal functions and the relationships between these functions.

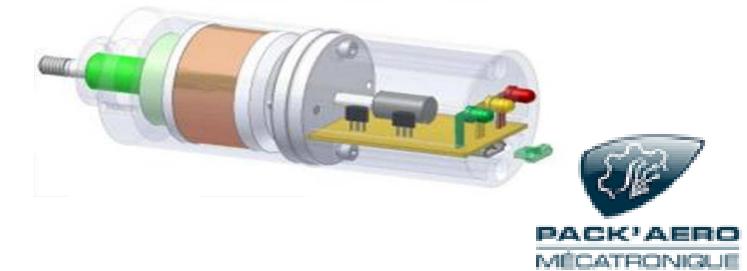
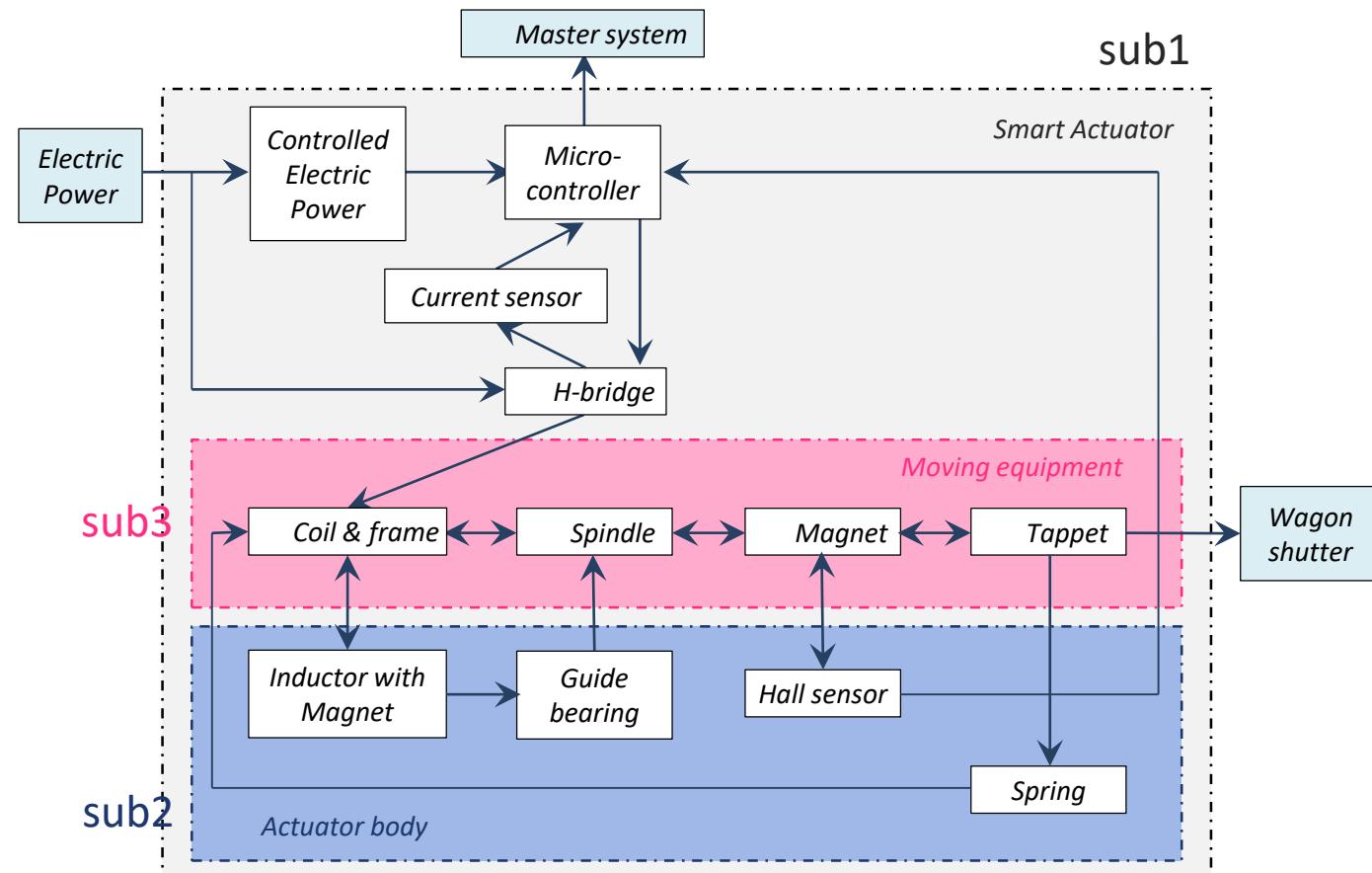


3. Organic Analysis



- Defines the **architecture of the system**, the decomposition into **sub-systems and components**
- Identifies the **functional interactions** between the different elements of the system to fit with the expected functions

Organic system architecture



3 sub-systems:

- Sub1= electrodynamic linear actuator with a mobile coil
- Sub2= contactless displacement sensor combining Hall probes and a mobile magnet
- Sub3= conditioning circuit board

4. Physical Implementation

- INPUTS
- Sub-systems
 - Components
 - Interactions
 - Interfaces

4. Physical implementation

- OUTPUTS

- Overall plan of the system
- Collateral interactions identification

Supplementary step proposed compared to
a conventional design approach



Innovative
approach

- Optimises the **locations** of the parts or organs
 - Highlights the **physical proximity** of components
- To minimise the collateral interactions' effects on the reliability of the system

5. Dysfunctional Analysis

- INPUTS**
- Specifications
 - Failure history
 - System internal functions
 - Interactions between the system and its environment
 - System architecture
 - **Physical implementation**
 - Preliminary Analyze of Risk

- Identifies failure modes and rank them according to their effects on the product performance:
 - > **Intrinsic** failures
 - > **Functional** failures identified thanks to the organic architecture
 - > **Collateral failure issued from the physical implementation analysis**
- **FMEA (Failure Modes and Effects Analysis)** → inductive approach to analyze the failure modes and their effects to order them (according to their criticity) to master them.

- OUTPUTS**
- Identification of potential damage, their causes & their effects on the system
 - Action plan

FMEA (Failure Mode Effect Analysis)

- FMEA is a widely used method for analyzing the reliability of engineering systems
- It involves studying a circuit or mechanical assembly to decide how its component parts contribute to the overall failure mode in question.
- The method consists of assessing the effect of each component part failing in each possible mode.
 - Step 1: Define system boundaries and its associated requirements.
 - Step 2: List system subsystems and components.
 - Step 3: List each component's failure modes, the description, and the identification.
 - Step 4: Assign failure occurrence probability/rate to each component failure mode.
 - Step 5: List each failure mode effect/effects on subsystem(s), system, and plant.
 - Step 6: Enter necessary remarks for each failure mode.
 - Step 7: Review each critical failure mode and take necessary actions.

FMEA (*Failure Mode Effect Analysis*)

- **Description**

- describes inherent causes of **events** that lead to system failure,
- determines their **consequences**
- formulates methods to minimize their occurrence or recurrence.
- allows identifying the **critical** elements of security and dormant faults.

- **Advantages**

- **Simple** approach
- Large application domains: design and exploitation
- Analysis table giving a good **traceability** and **decision support**

- **Drawbacks / limitations**

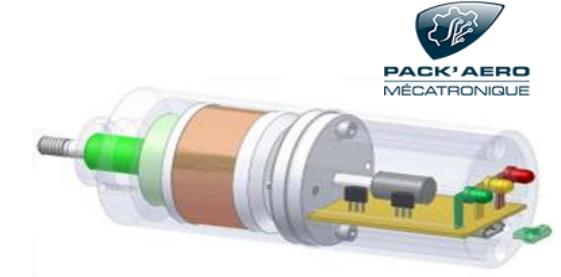
- Considered only one failure at a time
- Limited insight into the functional relationships between components,
- Time element in system operation cannot be represented.
- Limited insight into probabilistic system behavior,
- Better-adapted for mechanical or analog systems than digital ones

FMEA (Failure Mode Effect Analysis)

Enriched method

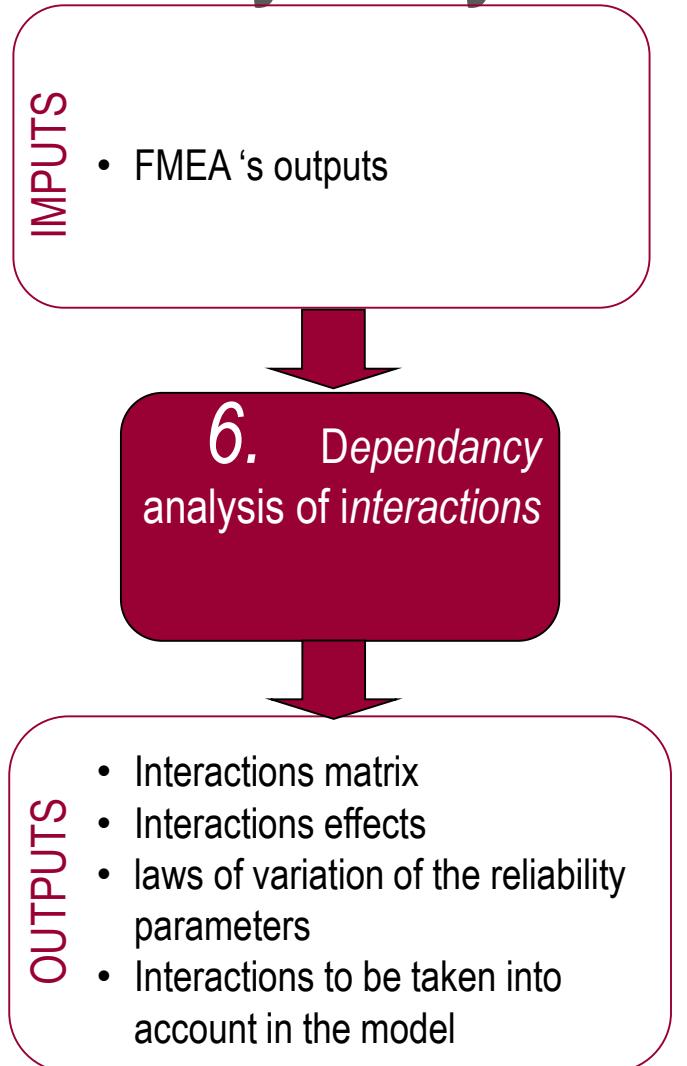
Classification of the failures according the damage's origin (intrinsic, collateral, and functional) and giving:

- its nature (first or second or by command)
- its event speed (sudden or progressive)
- its amplitude (partial or complete)



Sub-system	component	Function	Failure mode	Cause	Effects	Damage's origin	Classification : nature / event speed / amplitude
mobile	Coil + frame	F6	<ul style="list-style-type: none"> - Swelling of the cuivre wire [8]. - Swelling of the frame - Breakdown of the material - Breakdown of the wire [8] - Wrong value of the current on the coil - Wrong position of the frame 	Thermal heating, vibration, impact	No opening of the shutter	Collateral	Second, progressive, partial
				Excessive pressure or excessive translation speed	No opening of the shutter	Collateral	Second, progressive, partial
				Material fatigue [8]	No opening of the shutter	Intrinsic	First, progressive, complete
				Damage of inductor with magnet	No opening of the shutter	Fonctional (Inductor → Coil)	First, sudden, complete
				Damage of H Bridge	No opening of the shutter	Fonctional (H-Bridge → Coil)	First, sudden, complete
				Decentering of the rod	No opening of the shutter	Fonctional (Rod → coil frame)	First, sudden, complete

6. Dependency analysis of interactions



Additional analysis compared to
a conventional design approach

Innovative approach

- Identifies interactions defined and classified in the **enriched FMEA** (a criticality analysis will be necessary).
- Allows to make the **choice of the interactions to be considered** in modeling the system in terms of reliability.

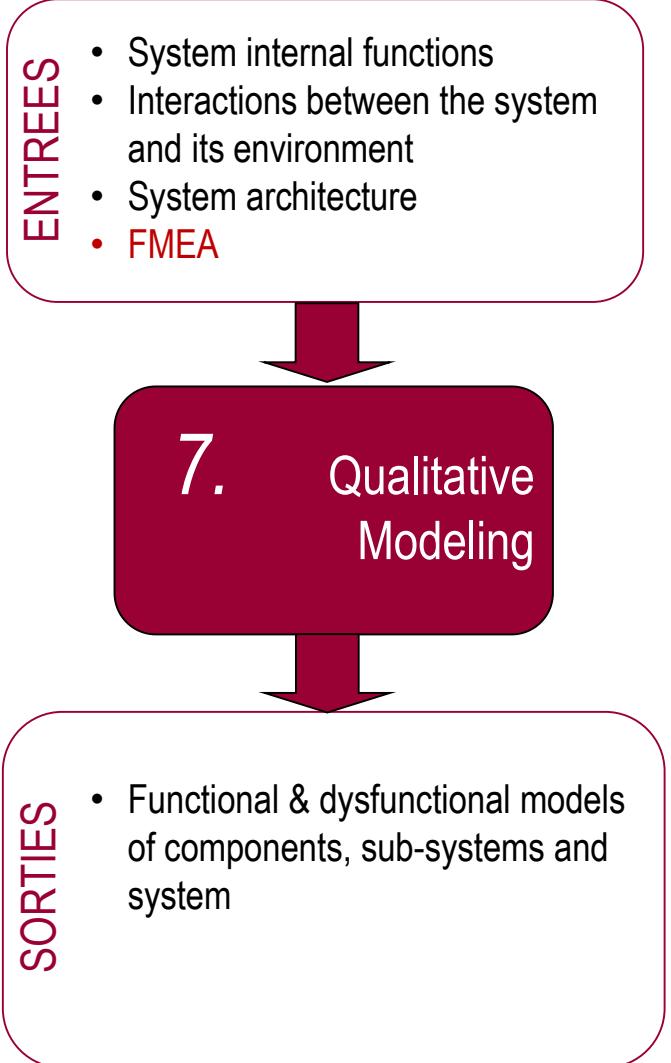
Interactions matrix

Acts on		Subsystem 1			Subsystem 2		
		Comp 1	Comp 2	Comp 3	Comp <i>i</i>	Comp <i>k</i>	Comp <i>n</i>
Subsystem 1	Comp 1	UF		BF			
	Comp 2						
	Comp 3						
Subsystem 2	Comp <i>i</i>					UC	
	Comp <i>k</i>	BC		UF			
	Comp <i>n</i>						

UF for unidirectional functional interaction
BF for bidirectional functional interaction
UC for unidirectional collateral interaction
BC for bidirectional collateral interaction

- Power supply acts on controlled power and on H-bridge,
- Controlled power acts on micro-controller,
- H-bridge acts on current sensor and on coil,
- Micro-controller acts on H-bridge and on master system,
- Current sensor acts on micro-controller,
- Coil acts on shutter,
- Magnet acts on tappet and on Hall sensor,
- Coil acts on inductor & magnet / inductor & magnet acts on coil,
- Magnet acts on shutter / Shutter acts on magnet.

7. Qualitative Modeling

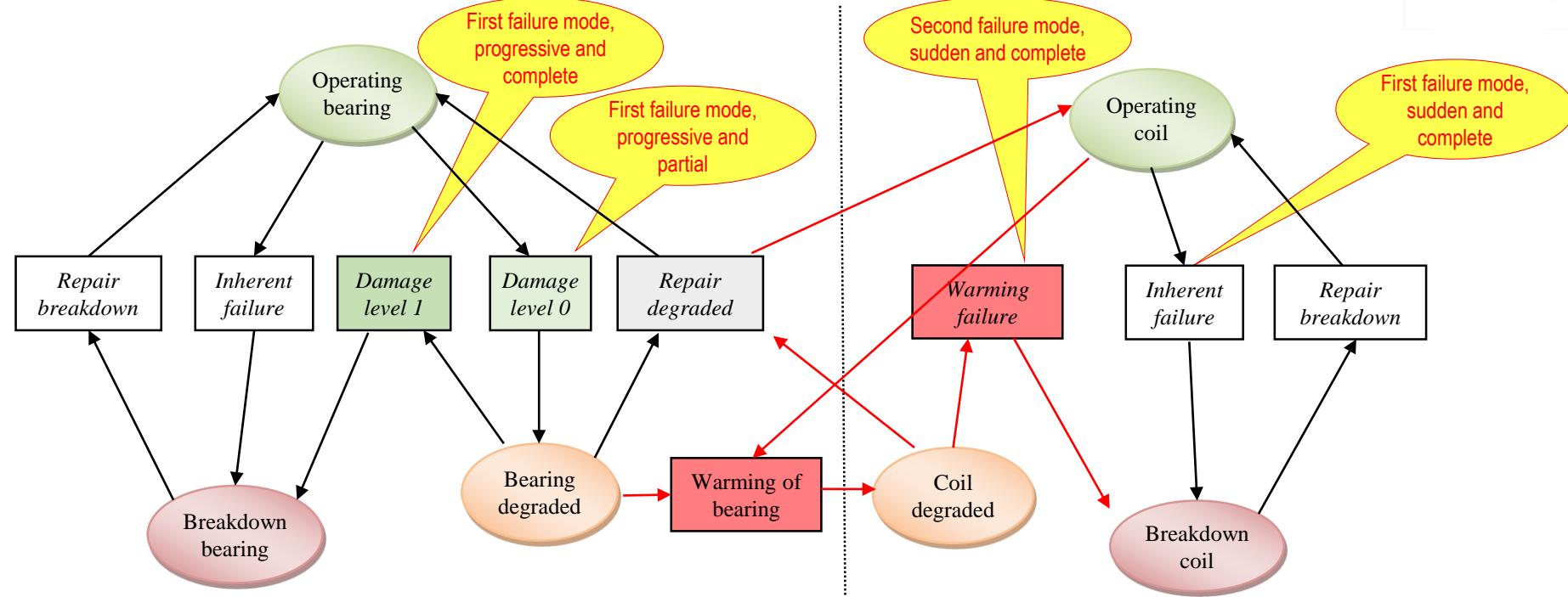
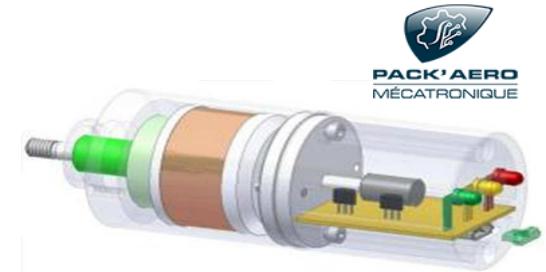


Models the functional and dysfunctional behavior of the system and its components, taking into account the interactions

- **States:** idle, operating, breakdown (whatever the mission profile phase), repair and degraded,
- **Transitions between states:** failure modes, events, repair modes

7. Qualitative modeling

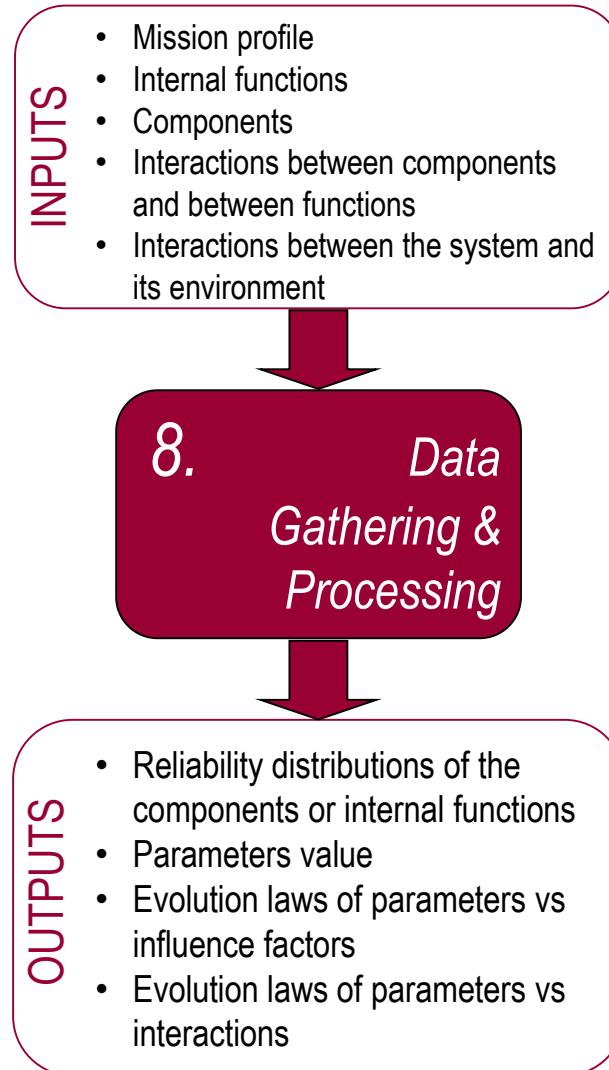
- Modeling of both components: guide bearing / coil
 - Bearing wear
 - Collateral interaction linked to the physical implementation guide bearing / coil



- Interactions modeled by implemented new states and modes:

- > 5 states for each component: idle, operating, breakdown, repair and **degraded**
- > 3 failure modes for the bearing, 2 failure modes for the coil
- > 2 repair modes for the bearing, 1 repair mode for the coil

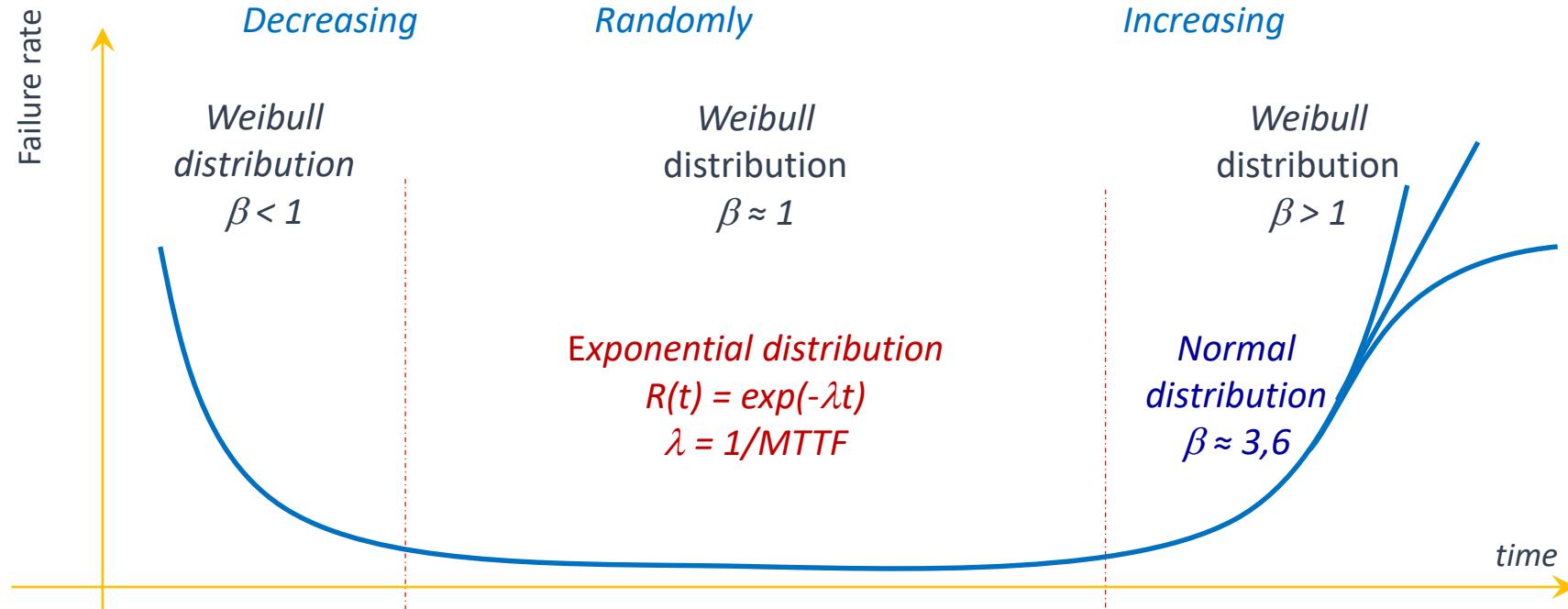
8. Components Data Gathering & Processing



Consists to :

- **Gather the reliability** data available on components (database, experiment, simulation, expertise...)
- **Process the data** (statistic analysis, influence of influential factors, influence of interactions...)
- **Identify relevant distributions** of reliability and the associated parameters for each component

Reliability distribution and parameters



Exponential distribution
 $R(t) = \exp(-\lambda t)$
 $\lambda = 1/\text{MTTF}$

$$\text{Weibull Distribution : } R(t) = \exp \left[- \left(\frac{t-\gamma}{\eta} \right)^\beta \right]$$

β : shape parameter ; η : scale parameter ; γ : position parameter

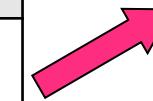
Reliability distribution and parameters

Technology	Comments	Reliability distribution and parameters
Electronics	Known distribution and parameters available in Database	Exponential : MTTF* or λ (failure rate)
Mechanics	<ul style="list-style-type: none">Distribution are known for few standard elementsTo find for most of specific components	Weibull : <ul style="list-style-type: none">β (shape parameter)η (scale parameter)

*MTTF : Mean Time To Failure



FIDES 2009
(reliability database for electronic components)



Feedback or estimation of reliability parameters for mechanical components

FIDES database

The expression of the failure rate or the MTTF of electronic components depends on several factors that themselves depend on 3 steps:

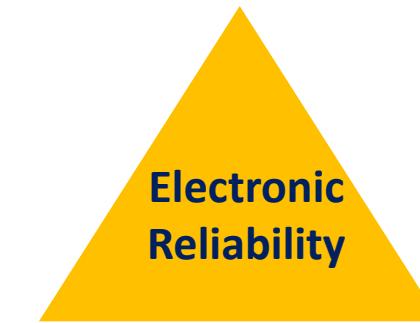
- design technology
- manufacturing process
- environmental operation



Design Technology



Manufacturing Process



*Environment
Conditions of use*



FIDES

- Objectives
 - To evaluate the **reliability parameters of electronic components** taking into account their using conditions (**exponential distribution**)
- Description
 - Developed, under the aegis of the DGA, by a consortium composed of AIRBUS, EUROCOPTER, NEXTER, MBDA and THALES
 - Includes failures relatives to specifications, design, manufacturing, except for software failures
 - Appropriate for components, electronic circuits or sub-systems (COTS - Commercial Off-The-Shelf)
- Relevant fields of study
 - All field using electronics

FIDES

- Approach management
 - Calculation of the predicted failure rate $\lambda = \lambda_{\text{physical}} \cdot \Pi_{\text{Part_manufacturing}} \cdot \Pi_{\text{Process}}$
 - The factor **physical** takes into account the **mission profile** of the COTS
 - The factor $\Pi_{\text{Part_manufacturing}}$ reflects the **quality and technical control of component manufacturing or of COTS** (depends on its nature, from 0.5 to 2 worst case)
 - The factor Π_{Process} reflects the **quality and technical control of the processes of developing, manufacturing and use of products** containing the COTS (evaluated thanks to an audit, from 1 to 8 worst case)
- Inputs
 - Mission profile information (phases, duration, temperature, humidity, vibration, etc..), life profile, environment and using conditions
 - Data concerning : suppliers of the used components, equipment definition, life cycle
- Outputs
 - Predicted failure rate or MTTF

FIDES

- Advantages
 - Takes into accounts the whole mission profile :
 - Phases and using cycles
 - Some influent factors
 - Include the complete product failures
- Drawbacks
 - The quality results depends on those of the different multiplying factors Π
 - Particular care for the audits used to quantify the quality Process
- References
 - FIDES Guide available on the Web :
<http://www.fides-reliability.org>

Taking into account the influent factors of the mission profile on FIDES

Two influent factors considered:

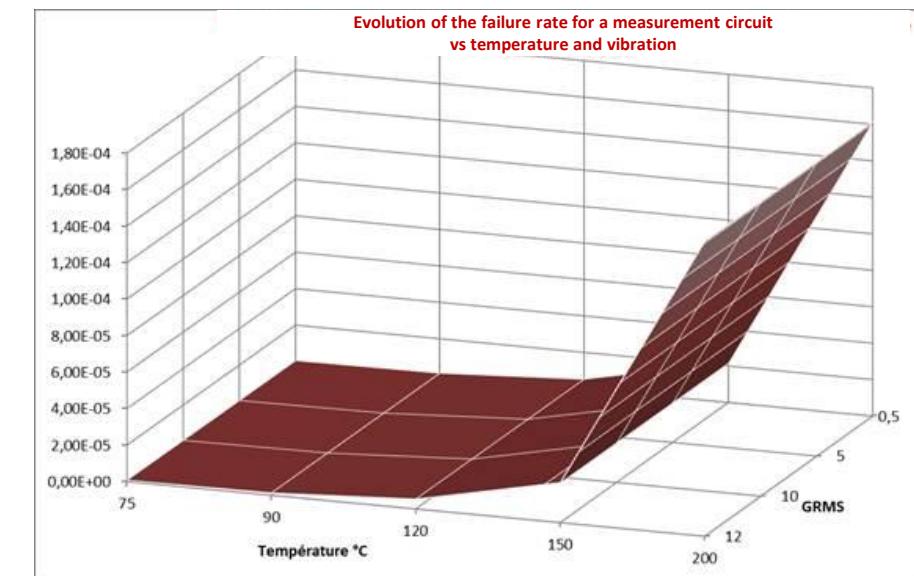
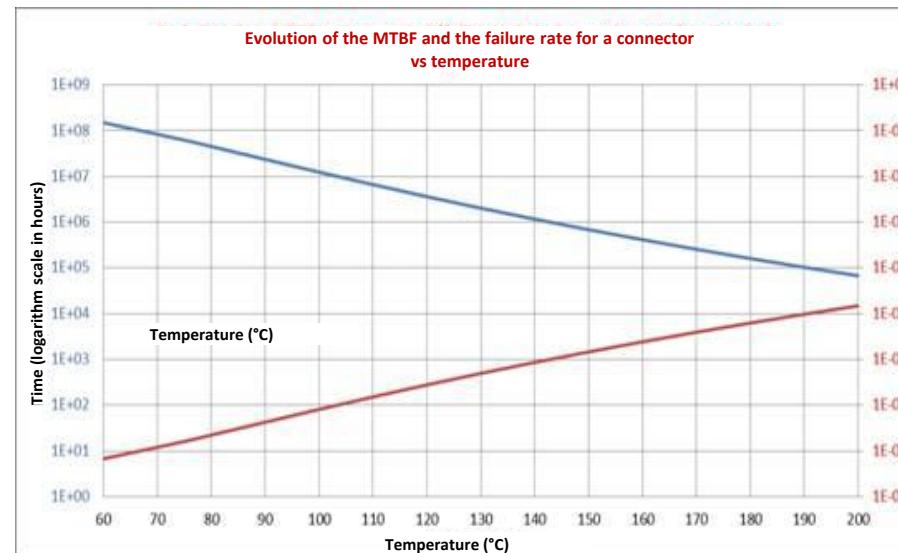
- Temperature
- Vibration

Vibration (Grms)	Temperature (°C)				
	75	90	120	150	200
0,5					
5					
12					



15 experiments have to be done

Influence of the temperature



Reliability estimation (1)

- Objective
 - Determine reliability laws (models) and their parameters from existing data (**tests or feedback**) to estimate experimental or operational reliability
- Description
 - Different laws (models) exist to express the reliability $R(t)$: **exponential**, **Weibull**, **normal**, **log-normal** ...
 - The **exponential** distribution is characterized by the **failure rate λ** or the **mean time to failure MTTF**
 - The **Weibull** law is characterized by three factors: the **form factor β** , the **scale factor η** , and the **position factor γ**
 - The **normal** and **log-normal** distributions are characterized by the **mean time to failure MTTF** or **MTBF** and the **standard deviation σ**

Reliability estimation (2)

- Process
 - Gathering of data (TTF or TBF) observed during tests or in use, selection and sorting in ascending chronological order
 - Non-parametric approach of the reliability law
 - Plotting of $F(t_i)$ as a function of t_i (median ranks, mean ranks, Kaplan-Meier...)
 - Calculation or graphical evaluation of the parameters of the laws (functional papers)
 - Calculation of confidence intervals
- Area of relevance
 - Structured tests and feedback to provide consistent data
 - Defined failure modes
 - Controlled test conditions (temperature, vibration...)
 - Similarity of mission profiles
 - Time characterization

Reliability estimation (3)

- Inputs
 - Reliability test results and conditions (TTF, TBF)
 - Events in operation over a period of time (failures)
- Outputs
 - Reliability models (laws, distributions) and their parameters
- Advantages
 - Data closest to reality
 - Simple calculations for the exponential distribution
 - Wealth of results
- Disadvantages
 - Limitations and assumptions for low data
 - Computational computations on Weibull parameter estimates
 - Need for consistent means for a rigorous and homogeneous gathering of data

Reliability estimation (4)

Example of data

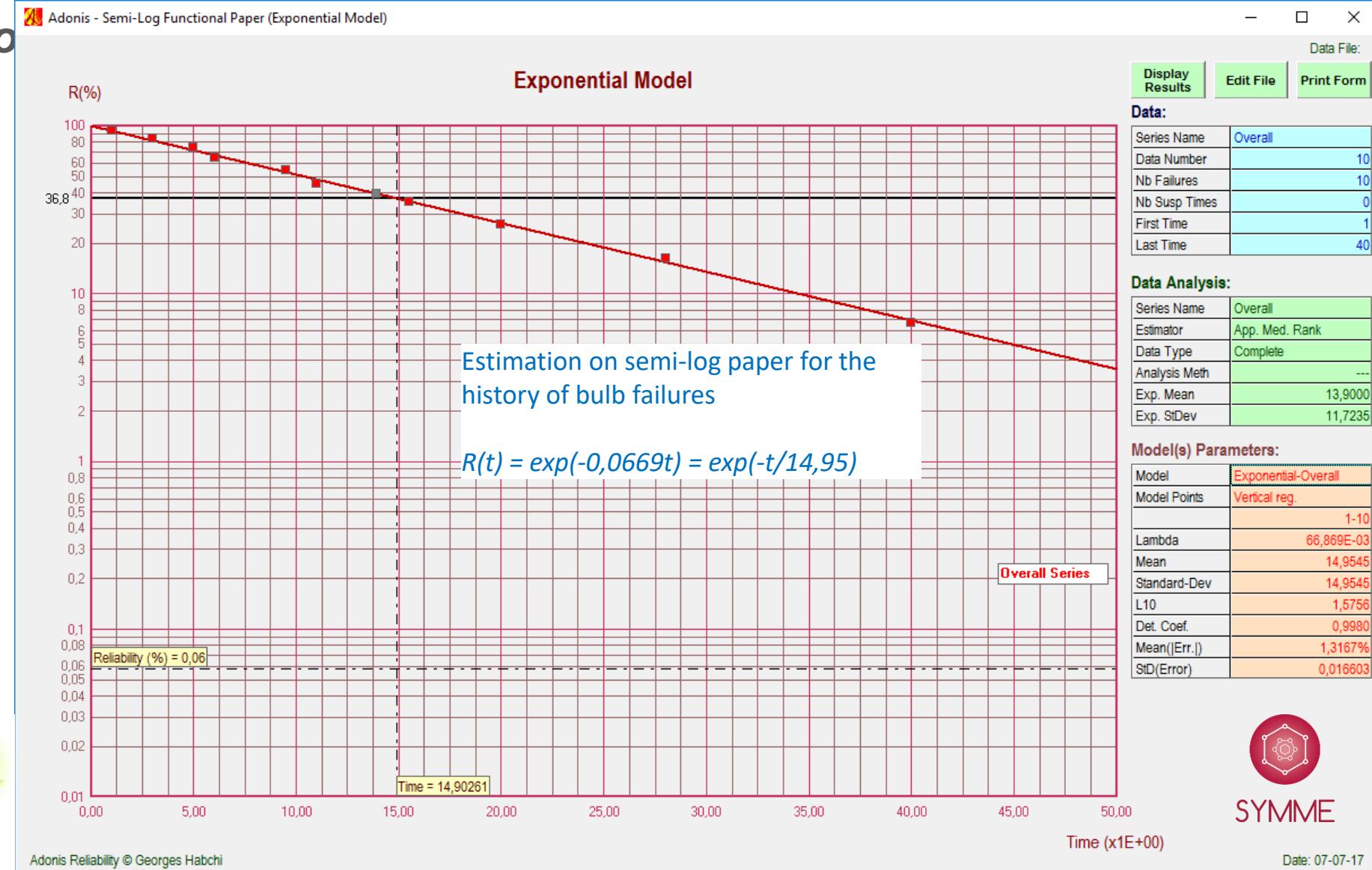
- Imagine that you have installed *10 identical light bulbs* (same brand, same power...) at the *same time* and that operate under *identical conditions*

- At 0 month, the 10 bulbs work
 - 1 month later, 1 bulb is out of service
 - 3 months later, another bulb is out of service
 - Etc.



Reliability estimation (5)

Use of exponential model



Reliability estimation (6)

Example of data

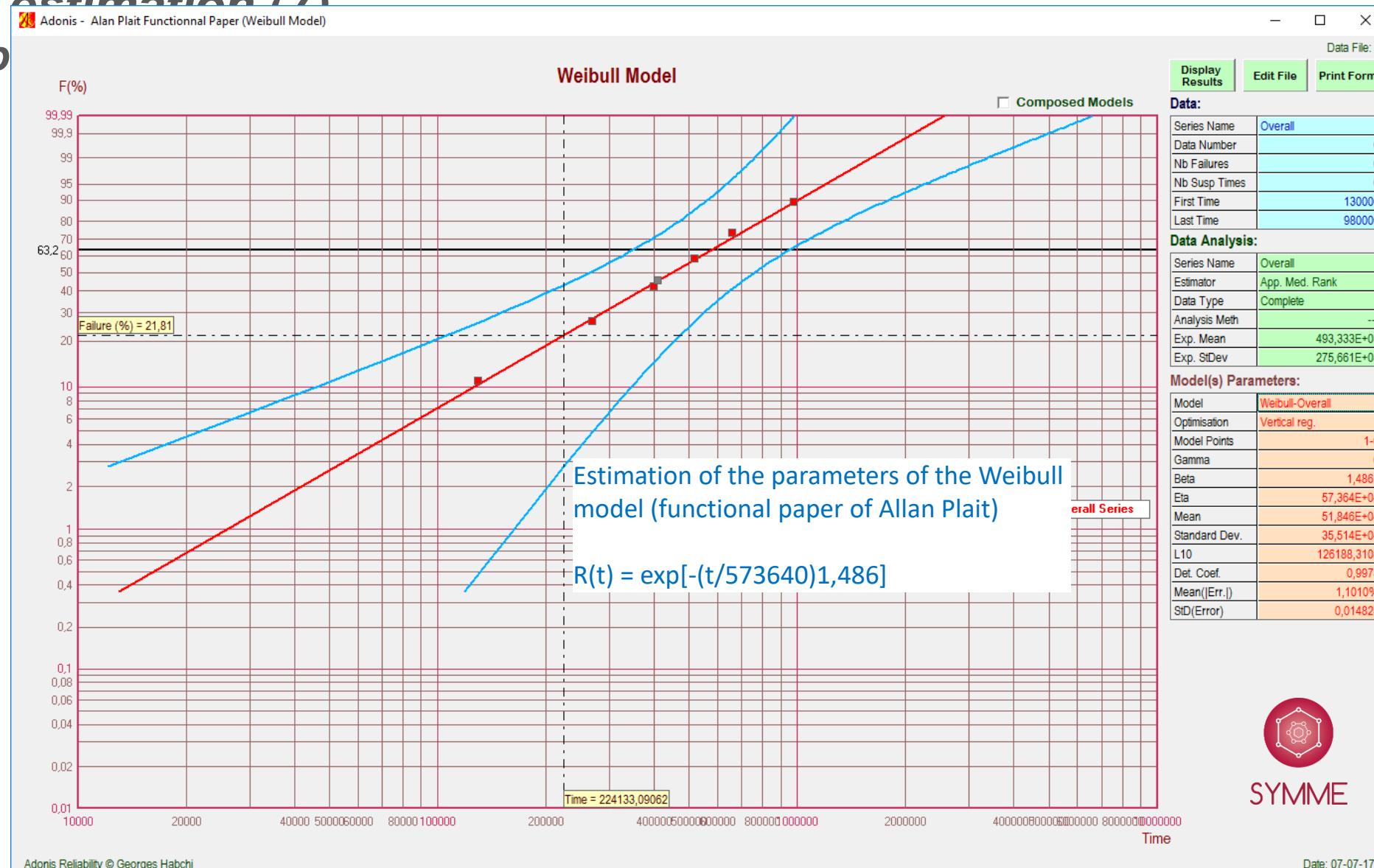
- A life test was performed on a lot of 6 loaded bearings under specific conditions and the following results were recorded



Bearing N°#	1	2	3	4	5	6
Number of cycles at break	400 000	130 000	980 000	270 000	660 000	520 000

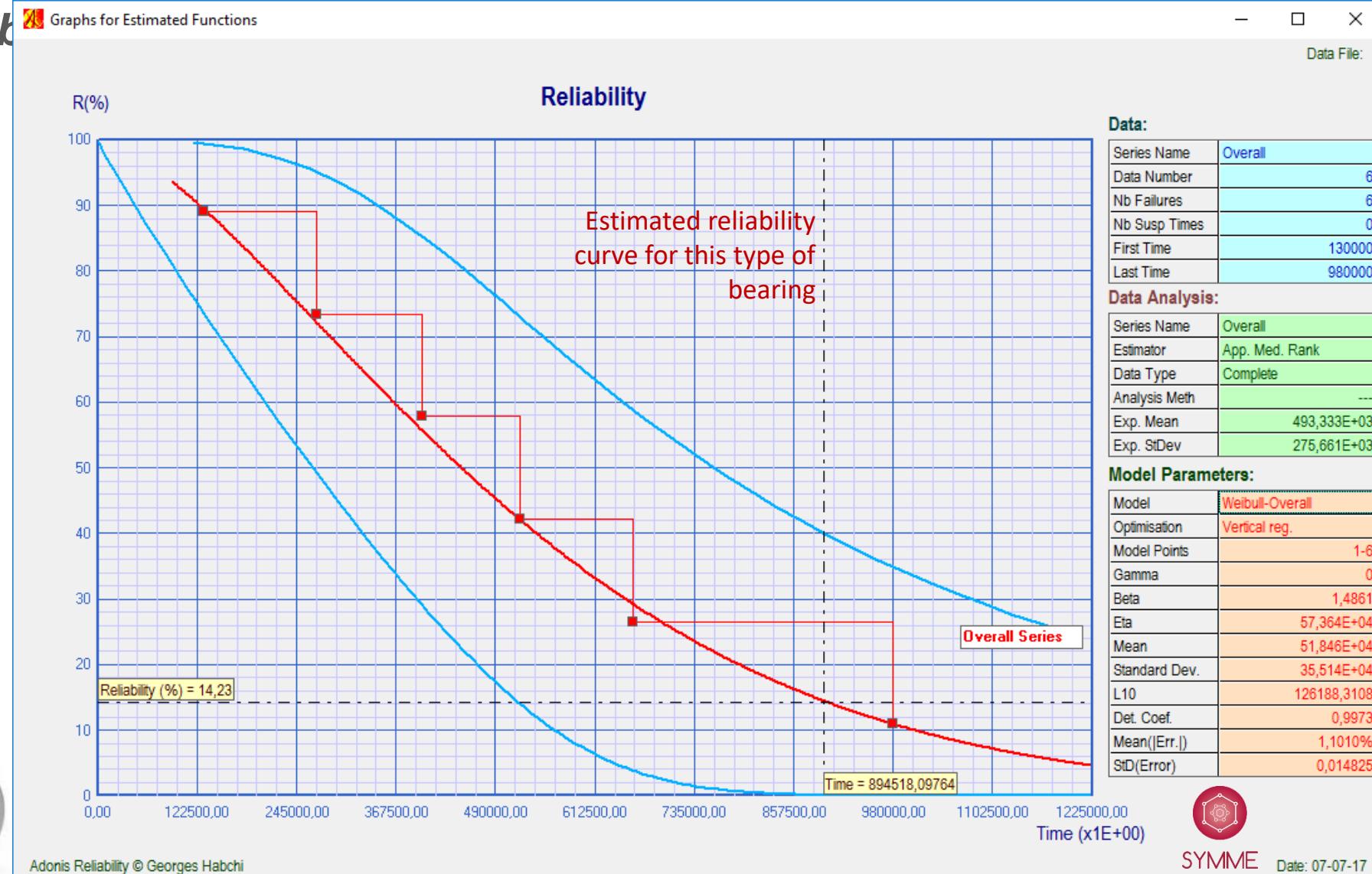
Reliability estimation (7)

Use of Weibull

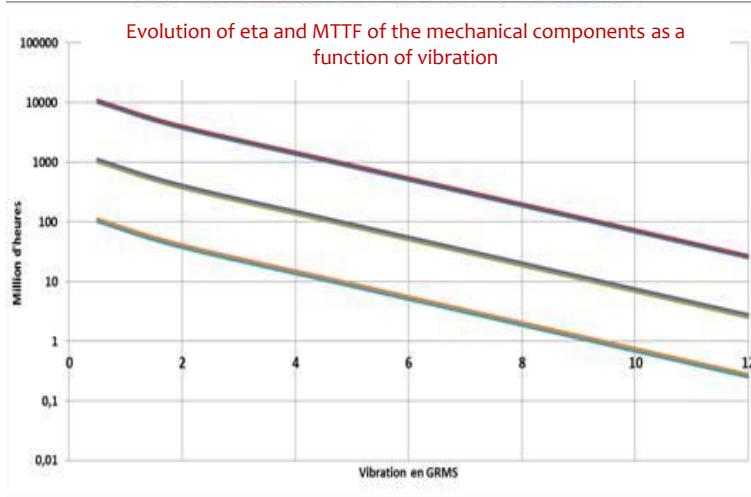
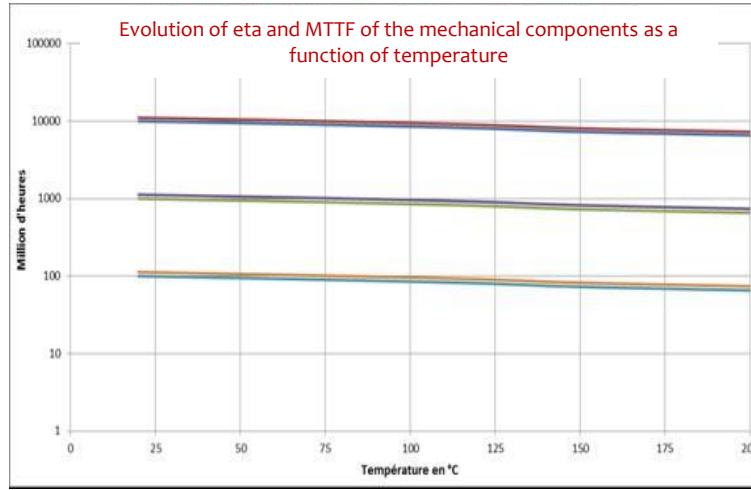


Reliability estimation (8)

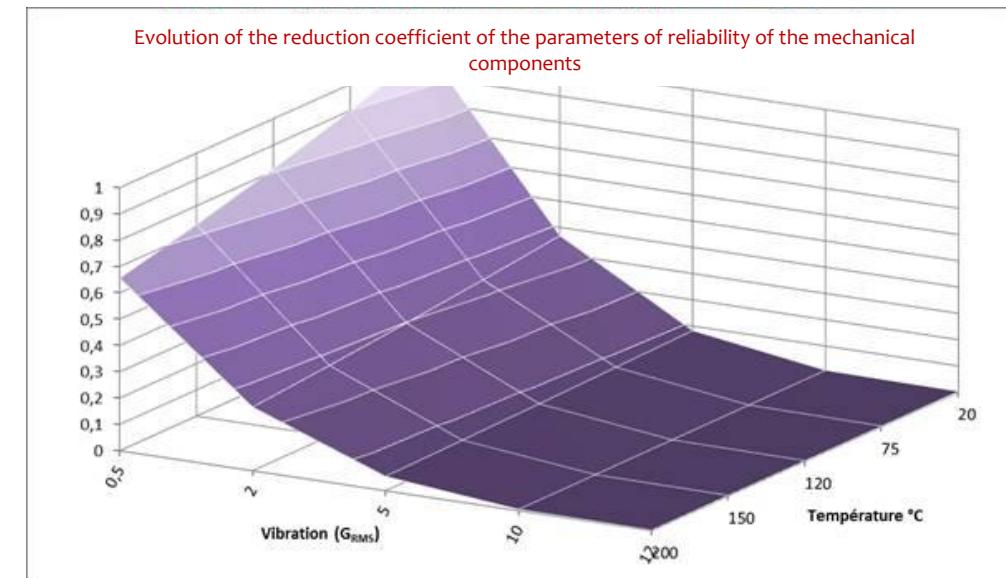
Use of Weibull



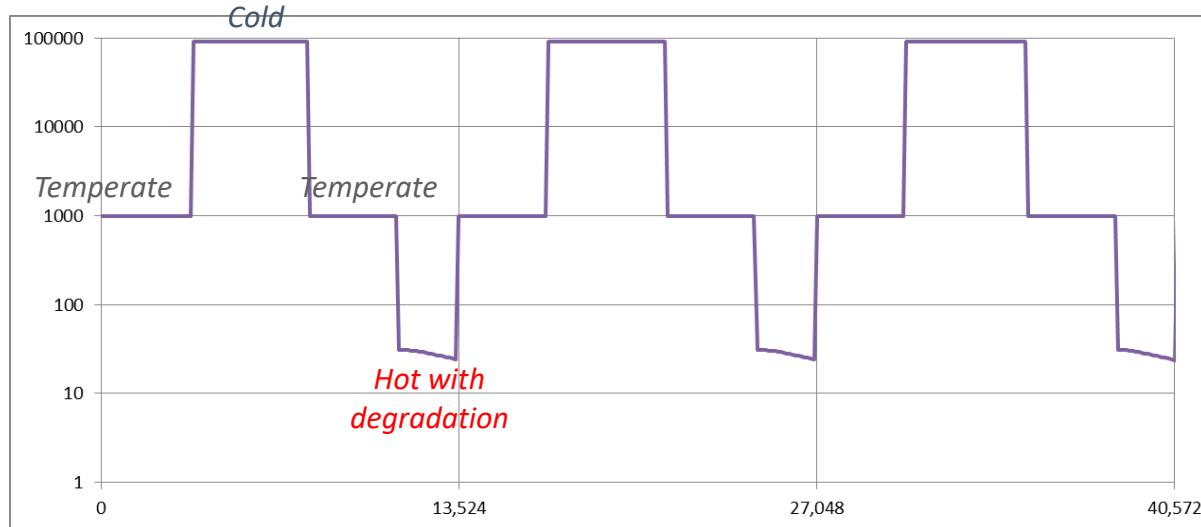
Influence of the environment on the degradation of mechanical components



- Law and values of the parameters chosen according to the experience of the manufacturer in the field of reliability (tests, feedback)
- Proposed evolution of parameters as a function of temperature and vibration



Influence of the mission profile on the parameters of reliability in the presence of interaction

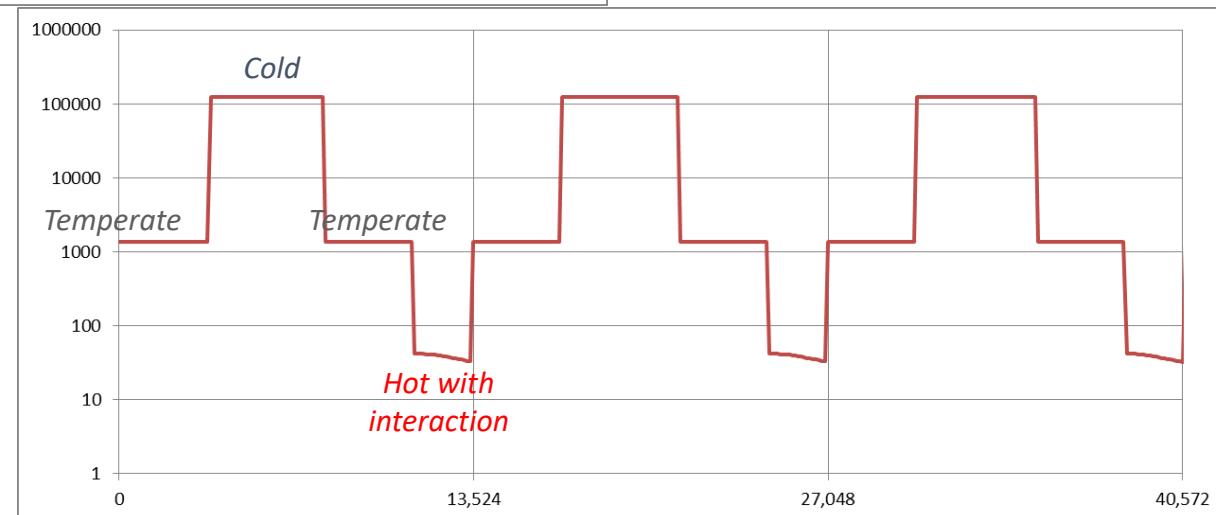


Evolution of the scale parameter η of the bearing according to:

- Mission profile phases
- Degradation in the “hot” phase

Evolution of the MTTF of the coil according to:

- Mission profile phases
- Interaction with the bearing in the “hot” phase



9. Modelling and Simulation

INPUTS

- Mission profile
- Functional and dysfunctional models
- Data and reliability models
- Behavior according to interactions
- Modelling method used
- Conditions of simulation, calculation...

9. Modelling & Simulation

OUTPUTS

- Reliability models according to the used method
- Types of results and desired shape in terms of reliability for the components and system
- Results

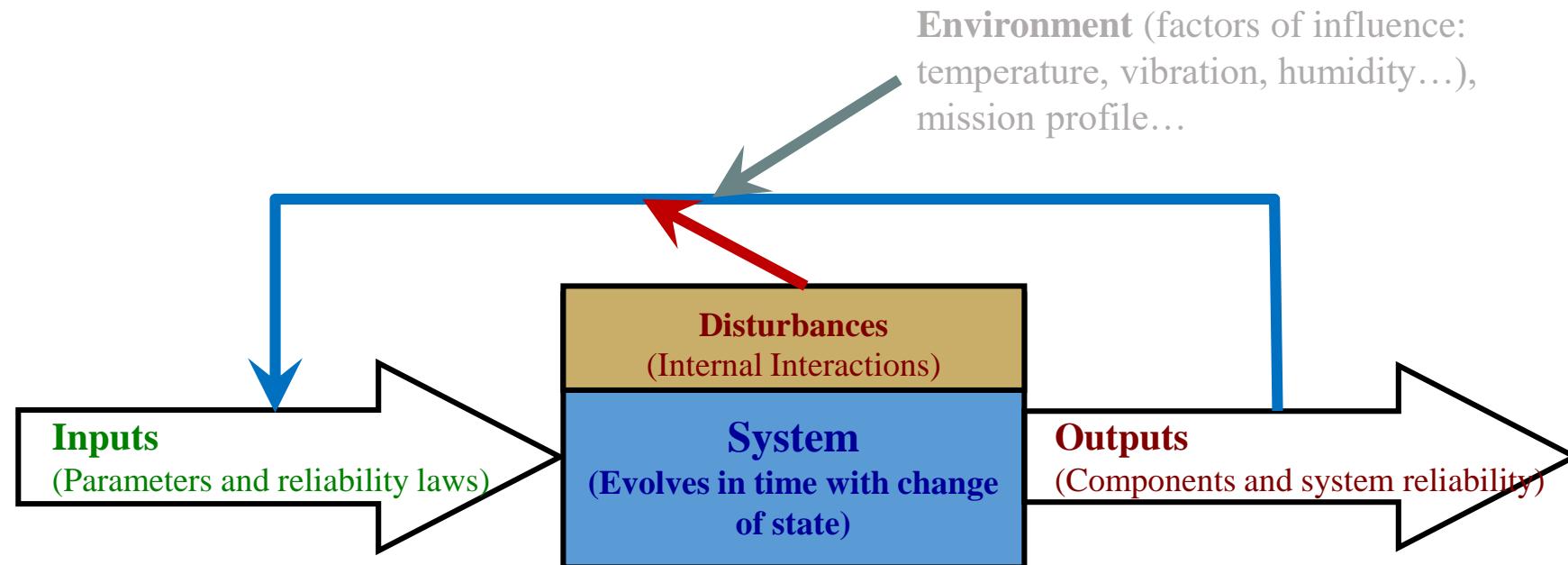
Implements the reliability models according to the chosen method, taking into account inputs and outputs and provides reliability results

Two methods are used:

1. **Petri nets** used for behavioral modeling of the different states of the system and **Monte Carlo** simulation for the quantification of the results of reliability
2. **Reliability Diagrams** used for block modeling of components and an analytical calculation of reliability

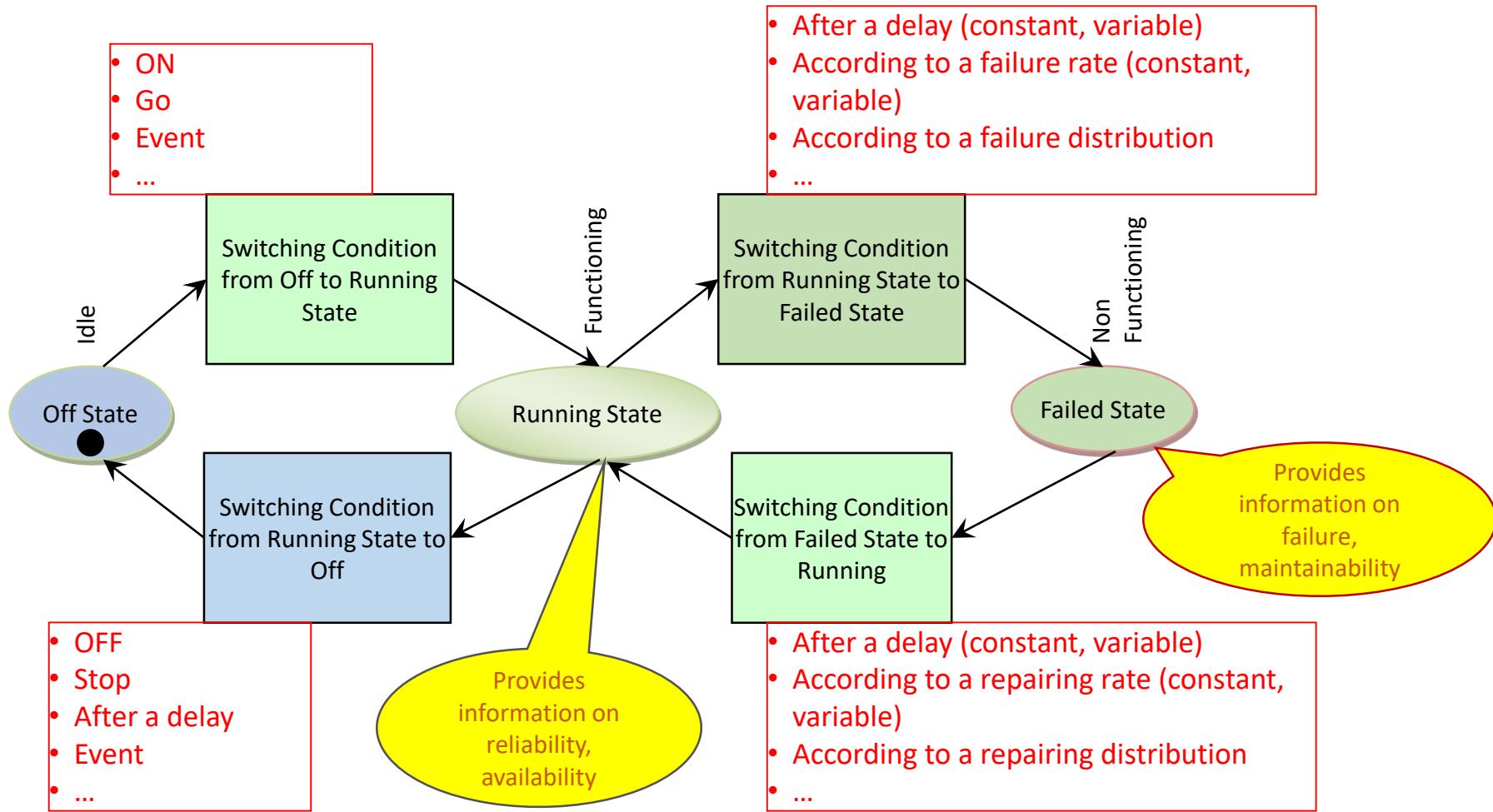
From the system to the reliability model

- Closed (elementary) system: the state of the inputs affects only the state of the outputs
- Open system (loop): the state of the inputs and some of the outputs affect the outputs
- Self-controlled system (self-adaptive): they react against the disturbances of the system, and against those of the environment (have the possibility of being modified)



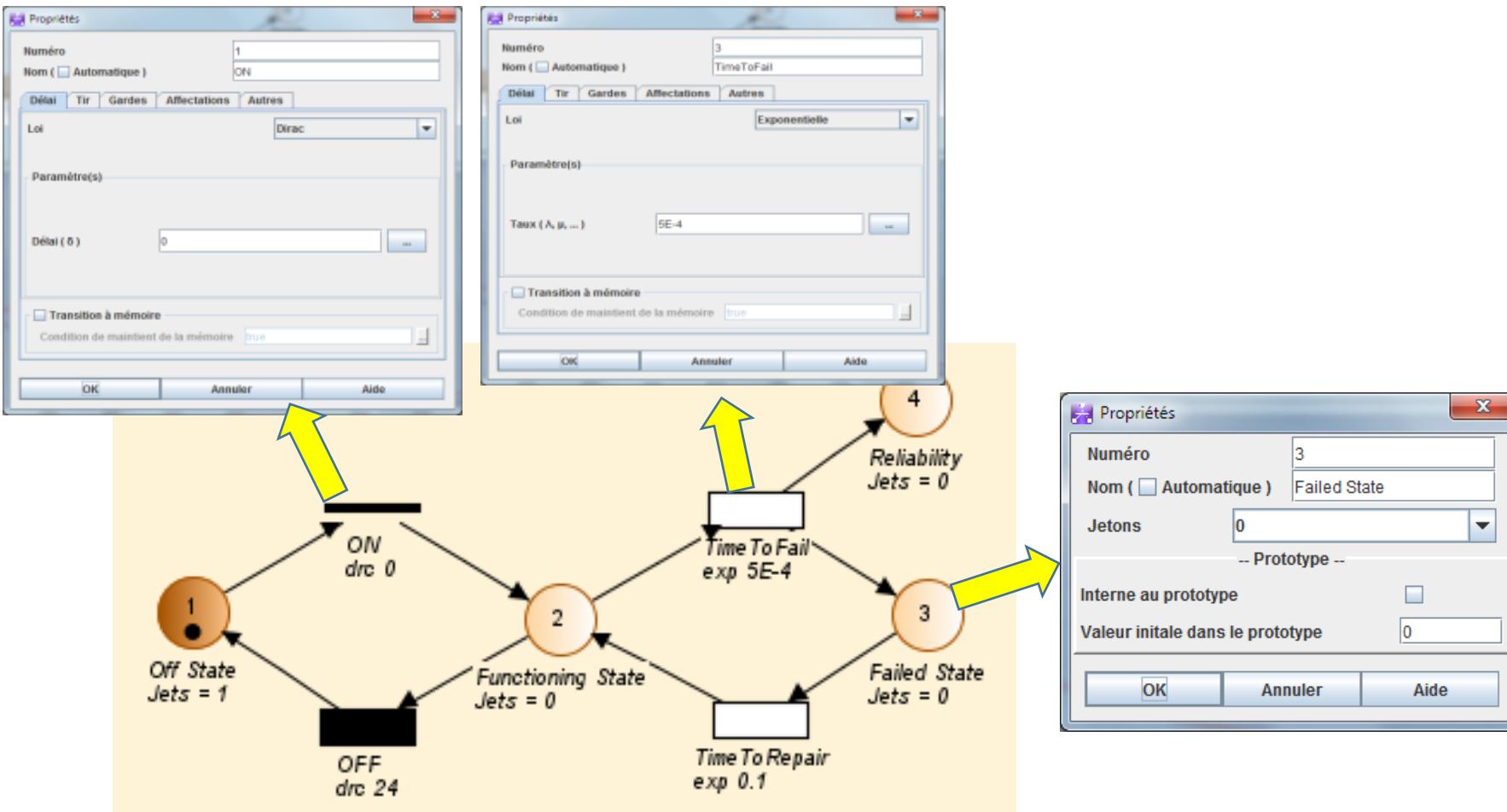
Elements of functioning of a Petri Net (1)

(places, transitions, arcs, tokens)



Elements of functioning of a Petri Net (2)

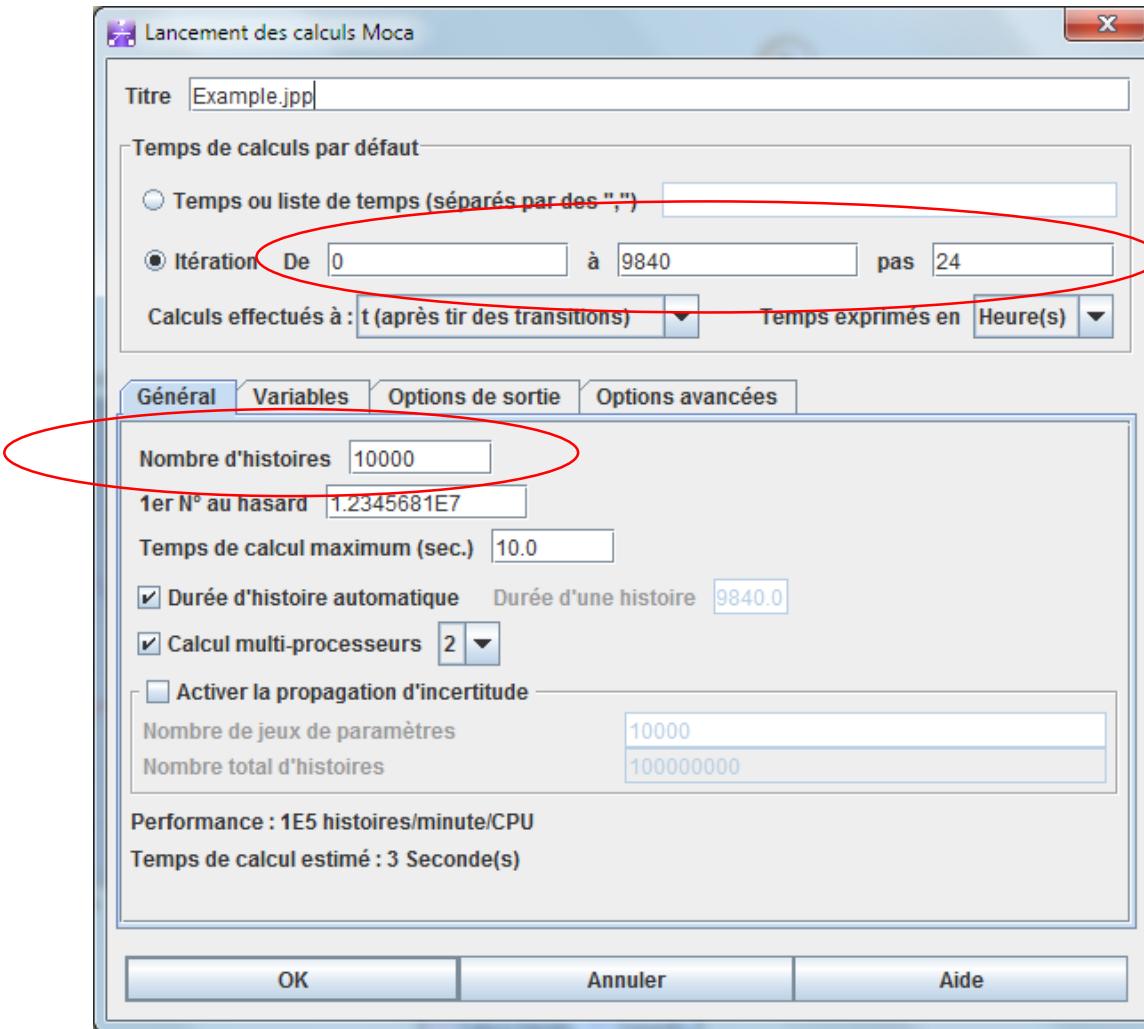
(places, transitions, arcs, tokens)



MOCA-RP software

Elements of functioning of a Petri Net (3)

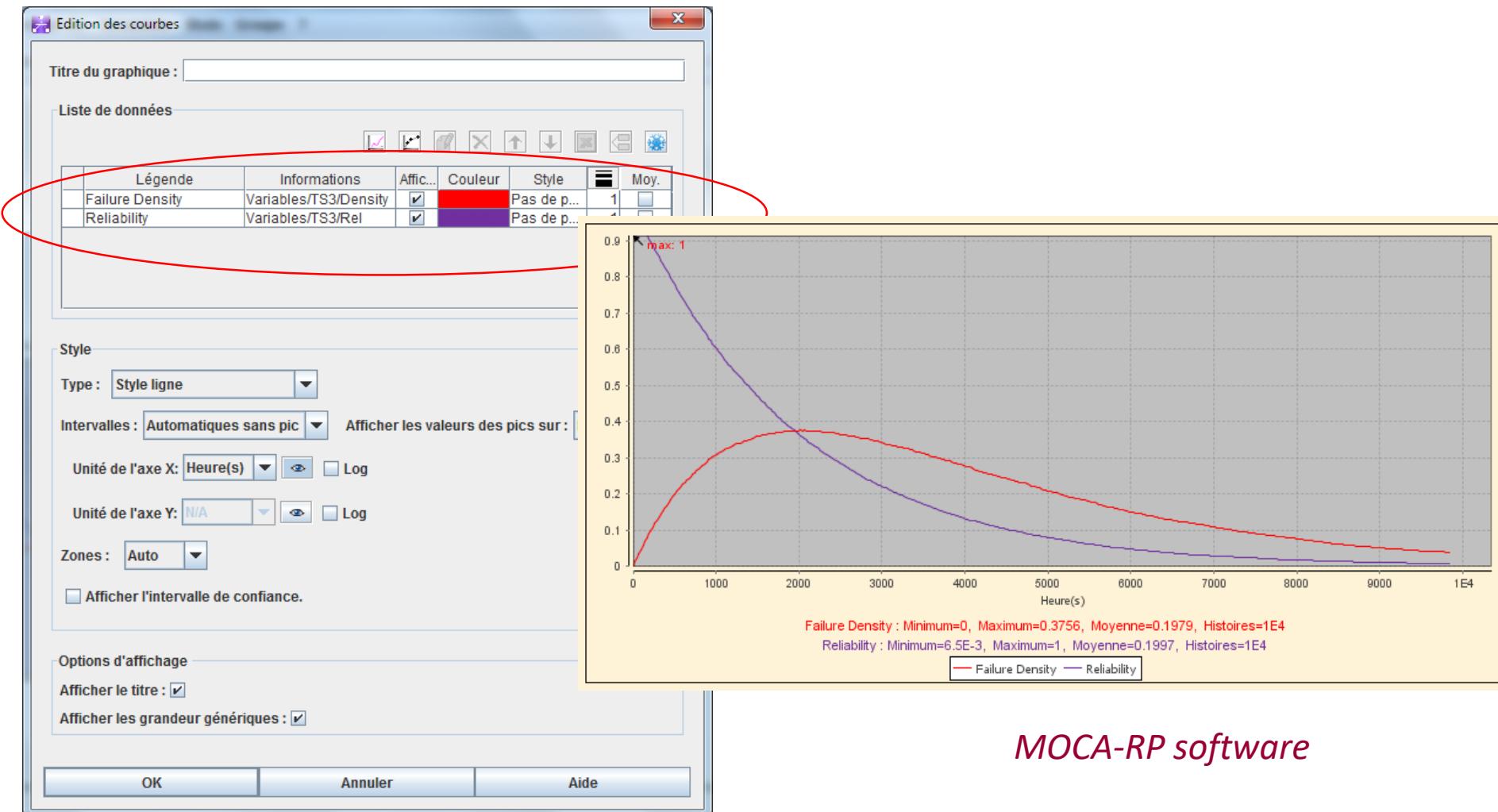
Simulation conditions



MOCA-RP software

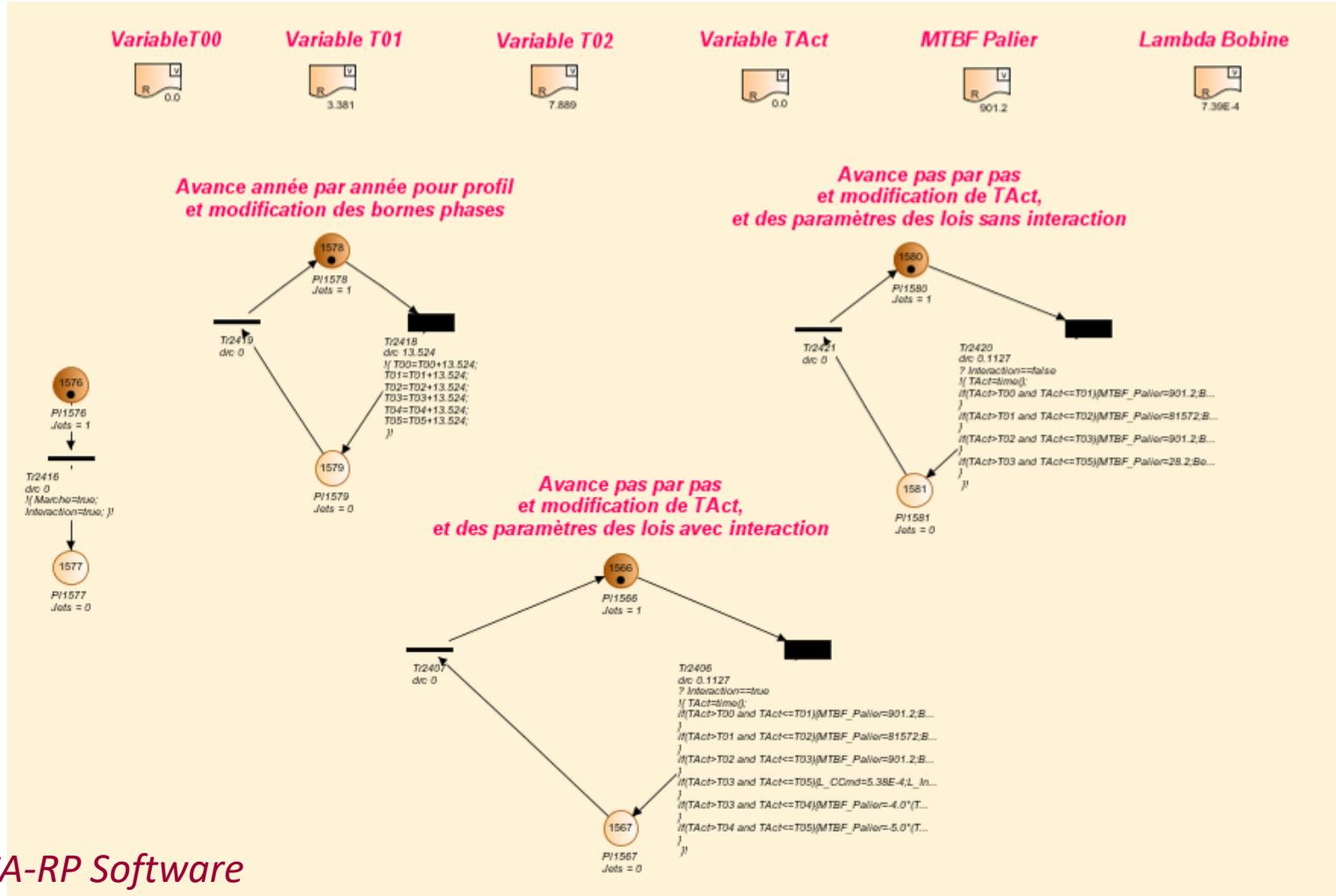
Elements of functioning of a Petri Net (4)

Results and curves



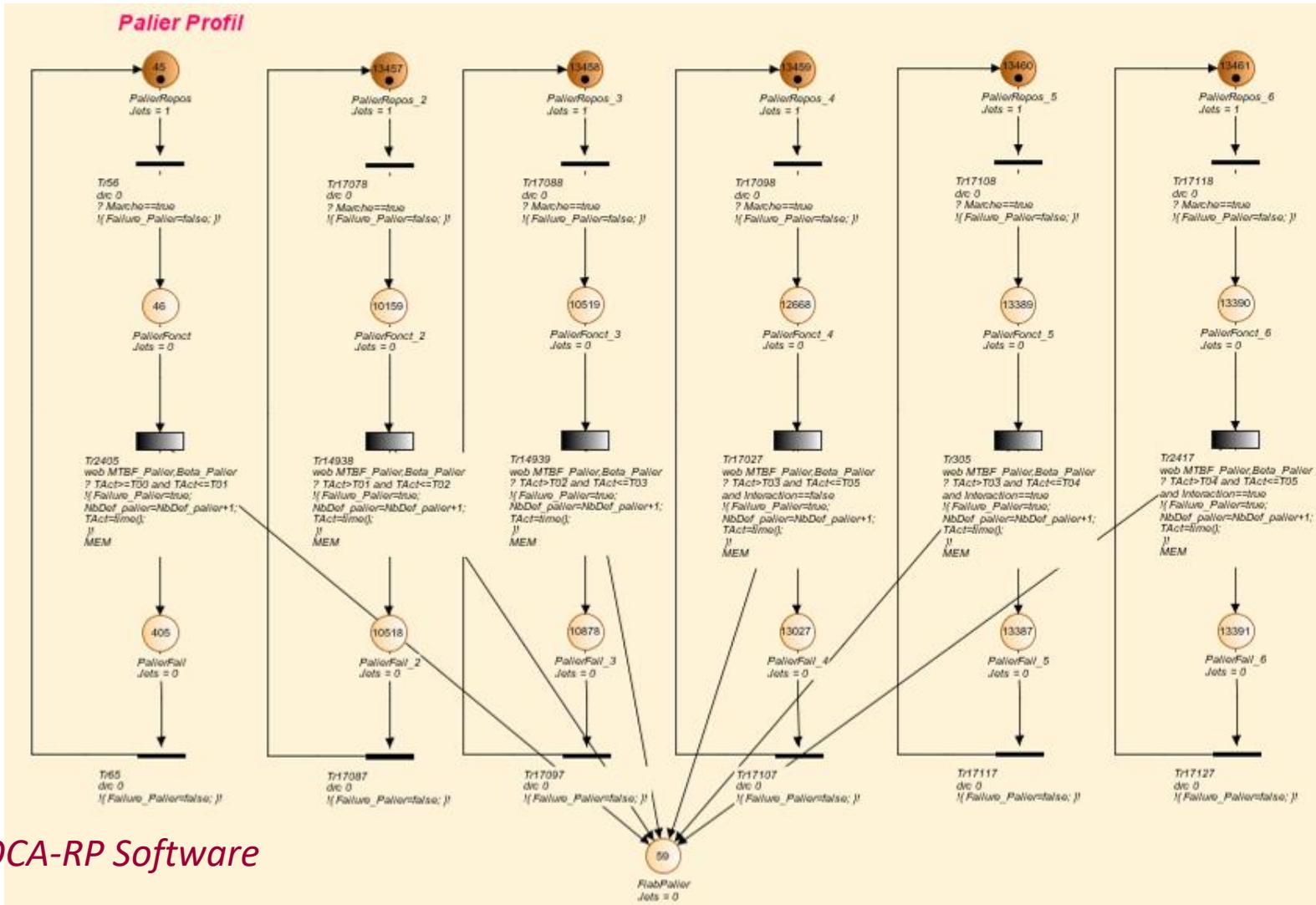
Petri Net of the Pack'Aero Smart Actuator (1)

(Mission profile and parameters evolution...)



Petri Net of the Pack'Aero Smart Actuator (2)

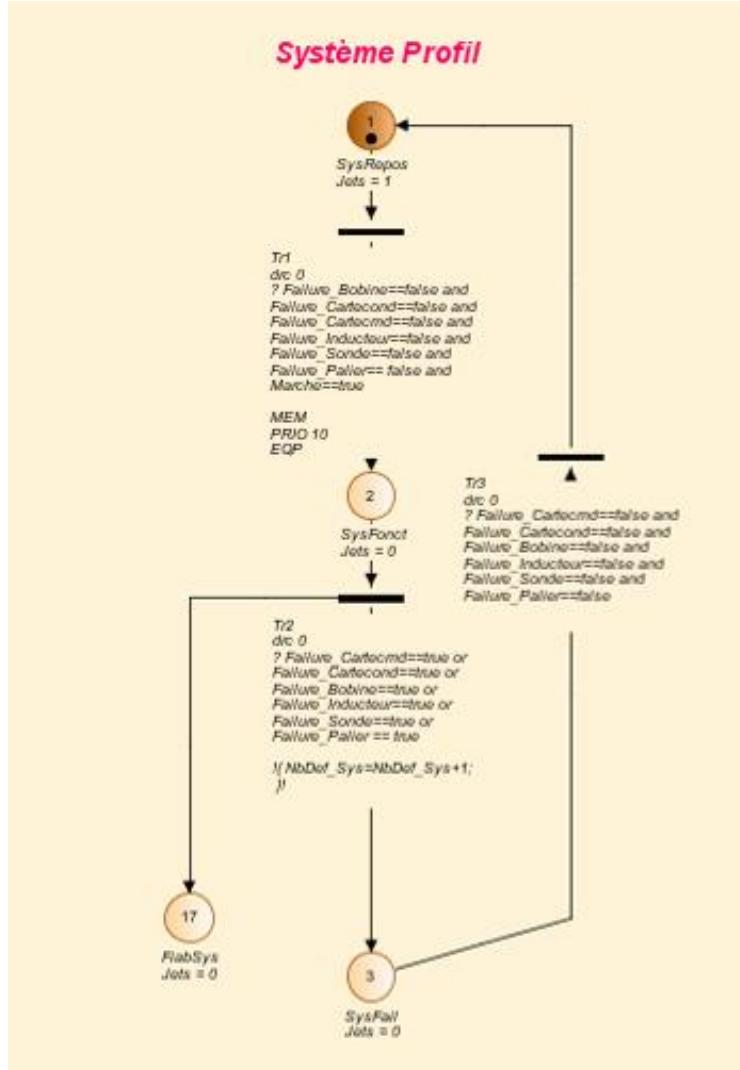
(Petri Net model of the bearing)



Petri Net of the Pack'Aero Smart Actuator (3)

(Petri Net model of the smart actuator)

MOCA-RP Software

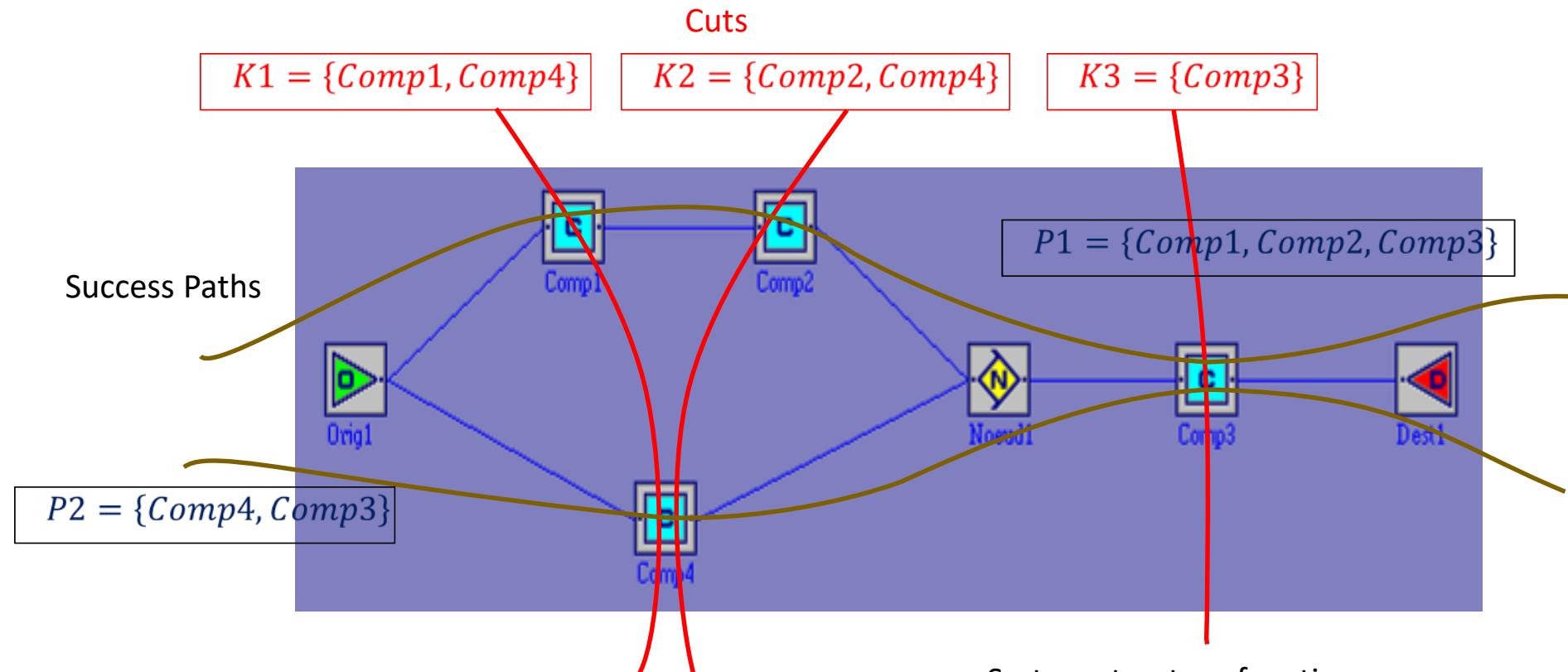


Petri Nets

- Advantages
 - **Visualization** of system behavior for qualitative analysis
 - Can be **detailed** according to the desired level
 - Can integrate **degraded** states
- Disadvantages
 - Need to **simulate** the network for quantitative results → use a **simulation method** (Monte Carlo) attached to the PN
 - Getting started and **calculation time** can be long
 - **Approximate results** when parameters change over time in a transition (interactions)
 - Difficulty of results in the presence of **shooting windows of short duration**

Elements of functioning of a Reliability Block Diagram

(Blocks, Nodes, Links, Cuts, Paths of Success)



System structure function

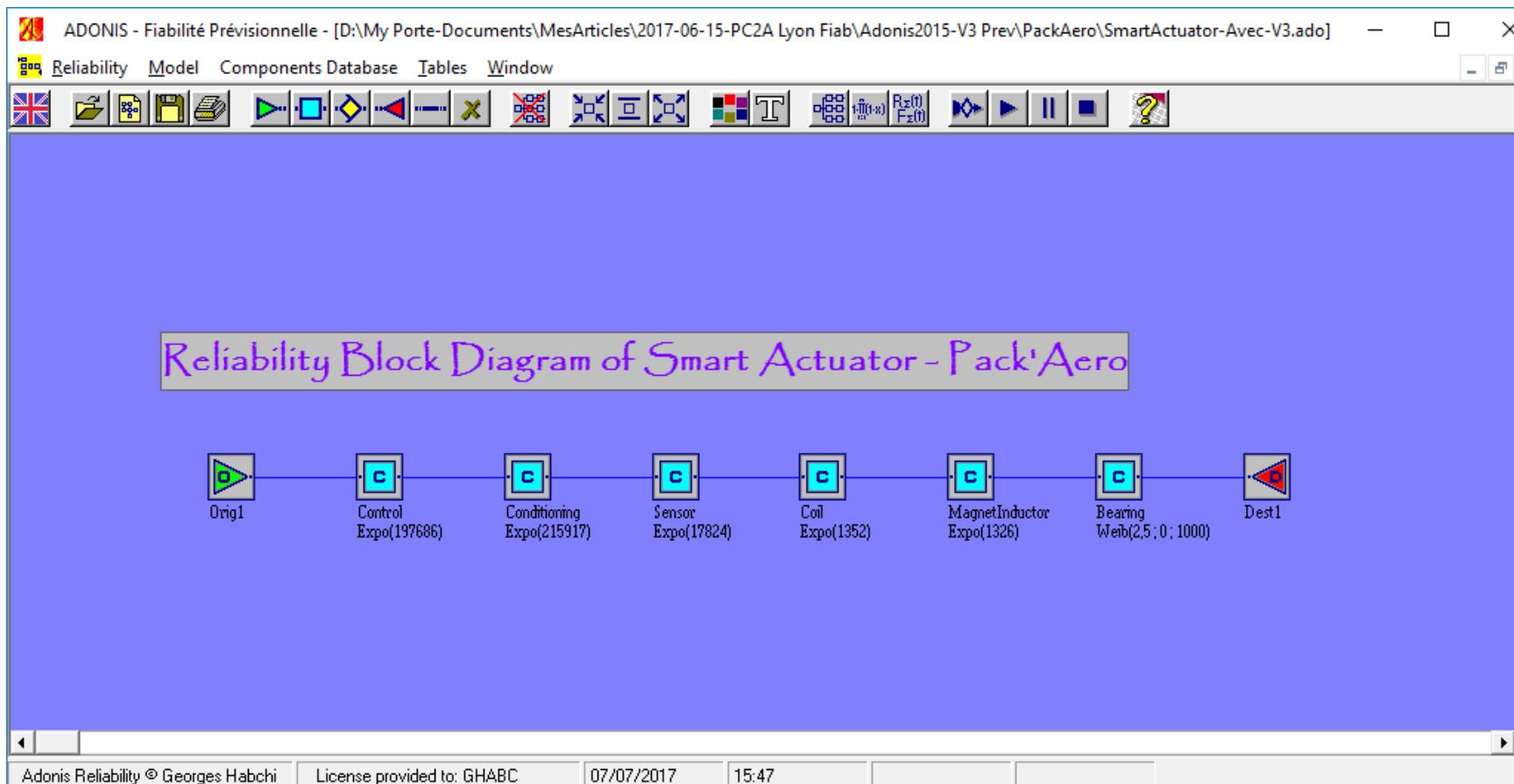
$$x = \emptyset(x_1, x_2, x_3, x_4)$$

$x = 1 \rightarrow$ the system is in a functional state

$x = 0 \rightarrow$ the system is in a dysfunctional state

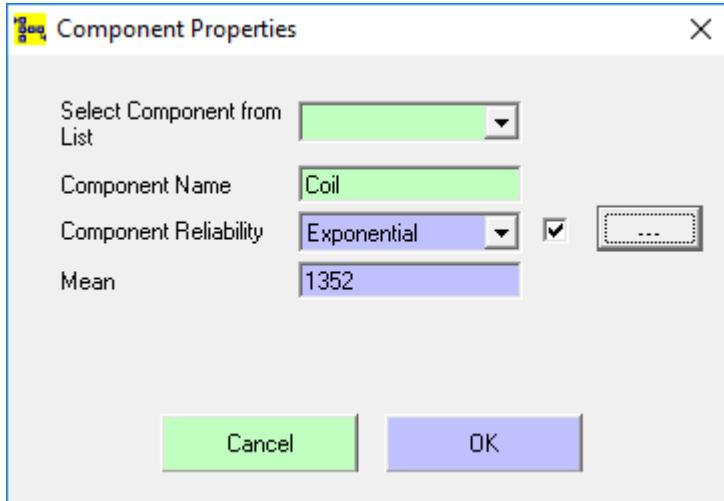
$$R = [1 - (1 - R_1 R_2)(1 - R_4)] \times R_3$$

Pack'Aero Smart Actuator RBD



ADONIS Reliability Software

Evolution of the MTTF of the coil as a function of the mission profile and the interaction



- *Coil*
- *Exponential distribution*
- *Parameter: MTTF = $1352 \cdot 10^6$ cycles (initial value)*



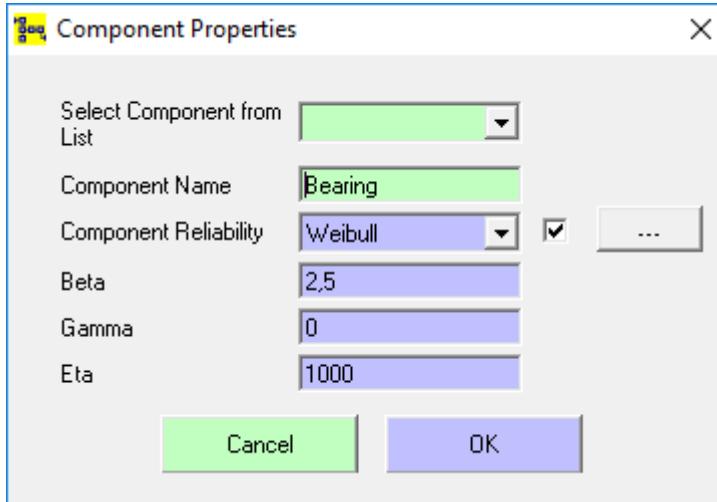
Table of mission profile

Phase Name	Cum Time	Mean Value
Temperate	3,381	cst(1352)
Cold	7,889	cst(122358)
Temperate	11,27	cst(1352)
Hot	12	Lin(42,3729;40,2542)
Hot	13,524	Lin(40,2542;31,7797)

Buttons: Cancel, OK, Help.

- *Mission profile phases*
- *Cumulated time*
- *Value of MTTF according to phases*
- *Laws of evolution for the interaction*

Evolution of the parameters of the bearing according to mission profile and interaction



- *Bearing*
- *Weibull distribution*
- *Parameters: $\beta = 2,5$; $\gamma = 0$; $\eta = 1000 \cdot 10^6$ cycles (initial values)*



Table of mission profile

Phase Name	Cum Time	Beta	Gamma	Eta
Temperate	3,381	cst(2,5)	cst(0)	cst(1000)
Cold	7,889	cst(2)	cst(0)	cst(92000)
Temperate	11,27	cst(2,5)	cst(0)	cst(1000)
Hot	12	cst(1,5)	cst(0)	Lin(31,24;29,6776)
Hot	13,524	cst(1,5)	cst(0)	lin(29,6776;23,4297)

Buttons: Cancel, OK, Help.

- *Mission profile phases*
- *Cumulated time*
- *Value of parameters according to phases*
- *Laws of evolution for the interaction*

Reliability Block Diagrams (RBD)

- Advantages
 - **Simple and logical** representation of how a system works
 - Taking into account the **mission profile** in the characteristics of the component
 - **Visualization** of the mission carried out by the system
 - Calculation time
- Disadvantages
 - Difficulty of taking into account **multifunction elements** (method must be carried out in conjunction with an FMEA)
 - Need to **adapt the tool** for a calculation of availability and maintainability (repair)

10. Analysis of Results

INPUTS

- Targets in terms of reliability
- Reliability results of components and system (tables, curves, histograms...)

10. *Analysis of
Results*

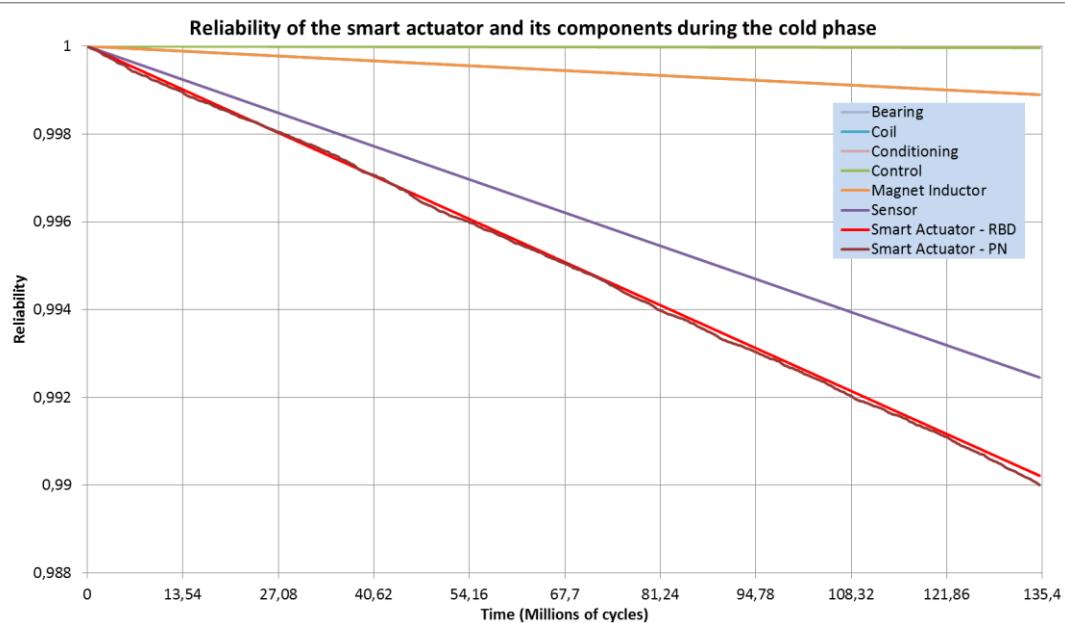
1. Evaluates the components and system reliability against targets
2. Evaluates the effect of influencing factors and interactions
3. Targets Critical Components
4. Proposes conclusions and improvement actions

OUTPUTS

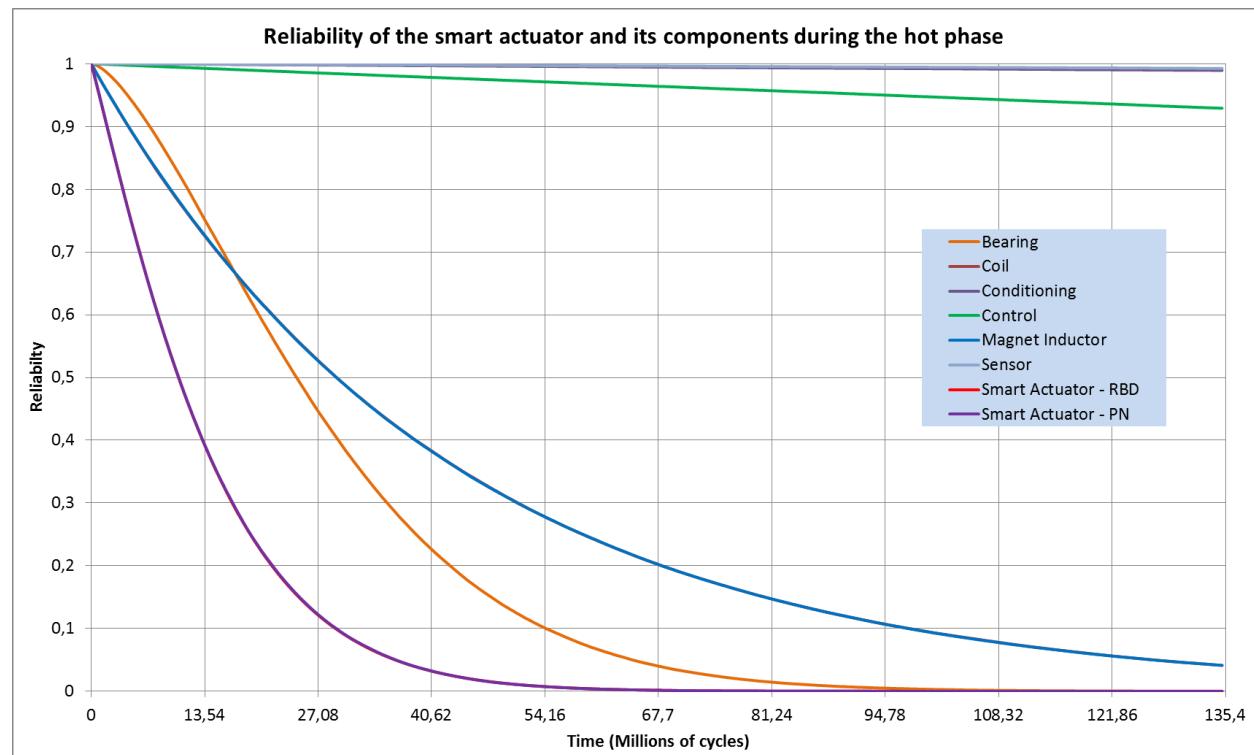
- Component by Component reliability analysis
- System reliability analysis
- Analysis of the effect of influencing factors and interactions
- Comparison of objectives and results
- Proposal for improvement actions

Results of reliability

Reliability of the smart actuator and components phase/phase



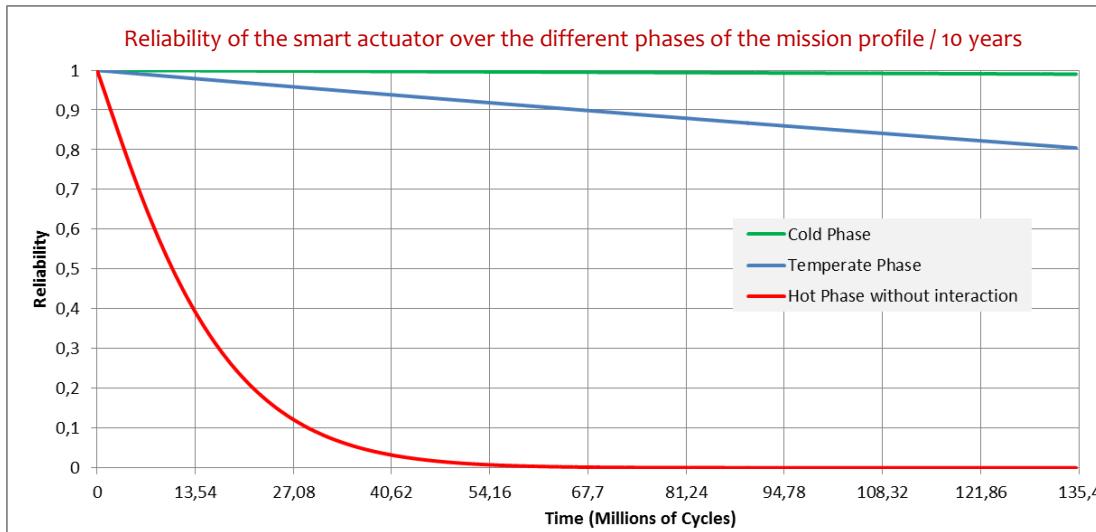
Reliability of the smart actuator and its components for the "cold" phase without bearing/coil interaction



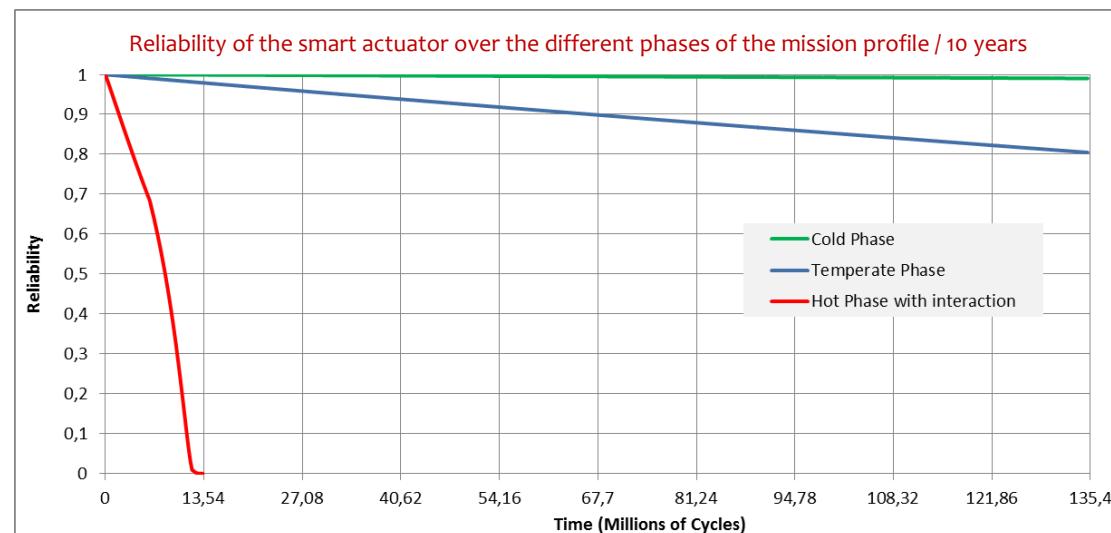
Reliability of the smart actuator and its components for the "hot" phase without bearing/coil interaction

Results of reliability

Reliability of the smart actuator without and with interaction (phase/phase)



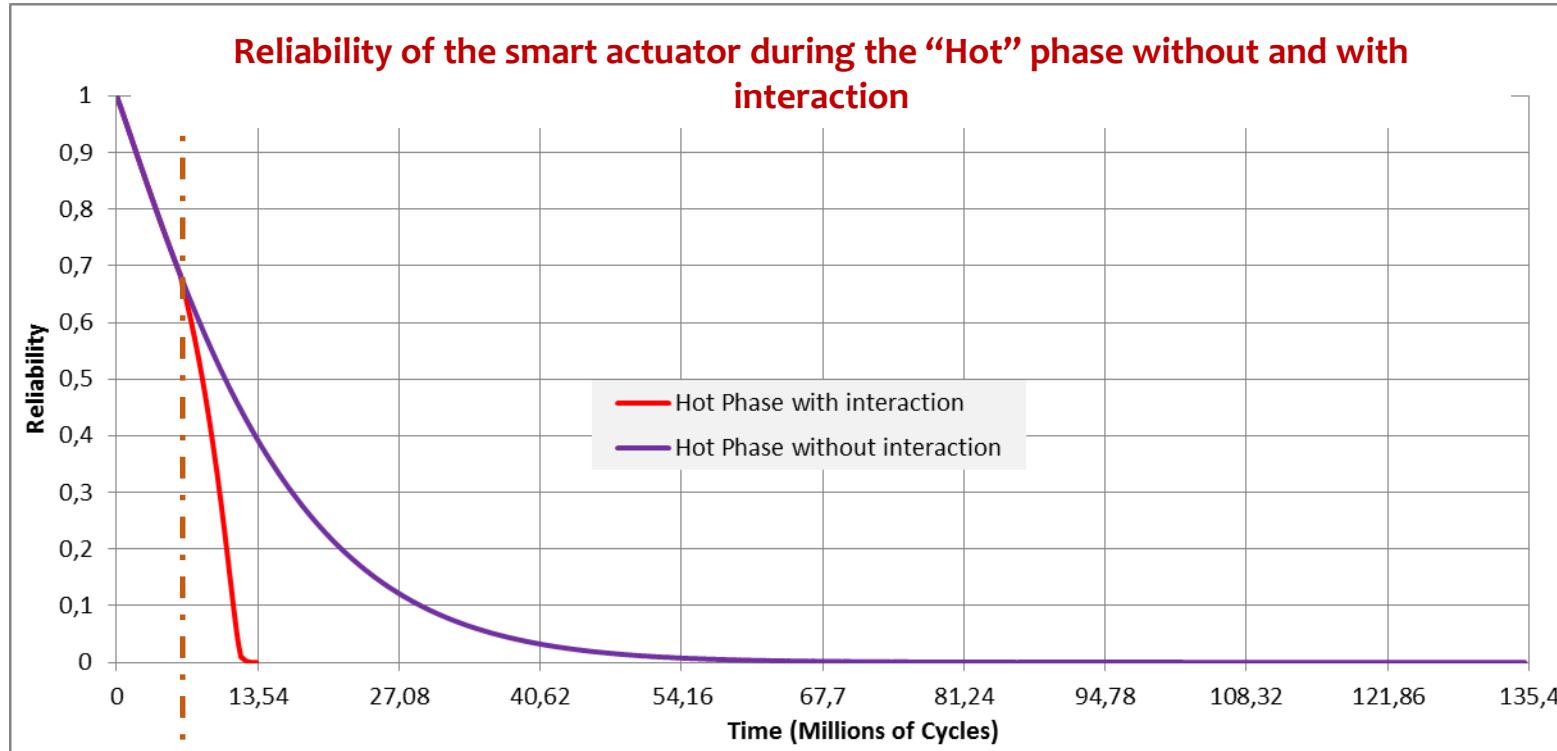
Reliability of the smart actuator phase/phase
without bearing/coil interaction



Reliability of the smart actuator phase/phase
with bearing/coil interaction

Results of reliability

Reliability of the smart actuator without and with interaction during the “Hot” phase

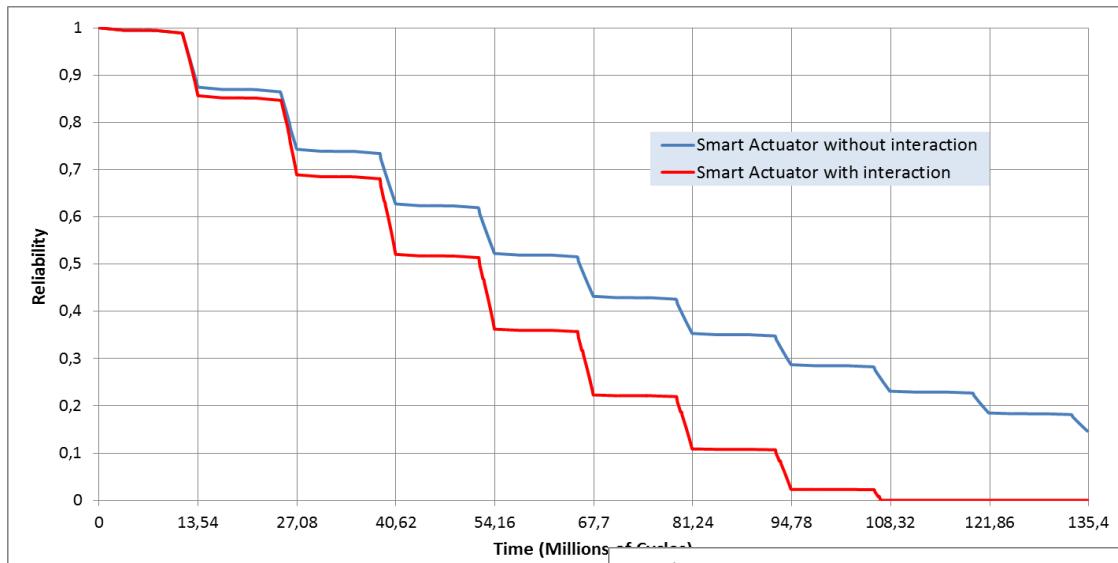


Influence of the bearing / coil interaction
from 6 million cycles



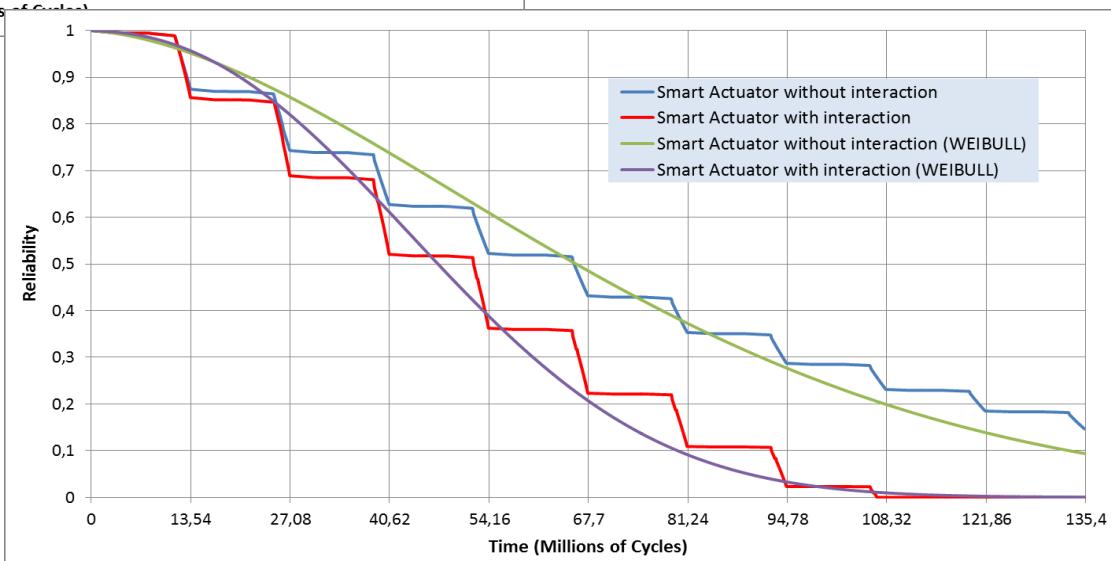
Results of reliability

Reliability of the smart actuator according to the mission profile



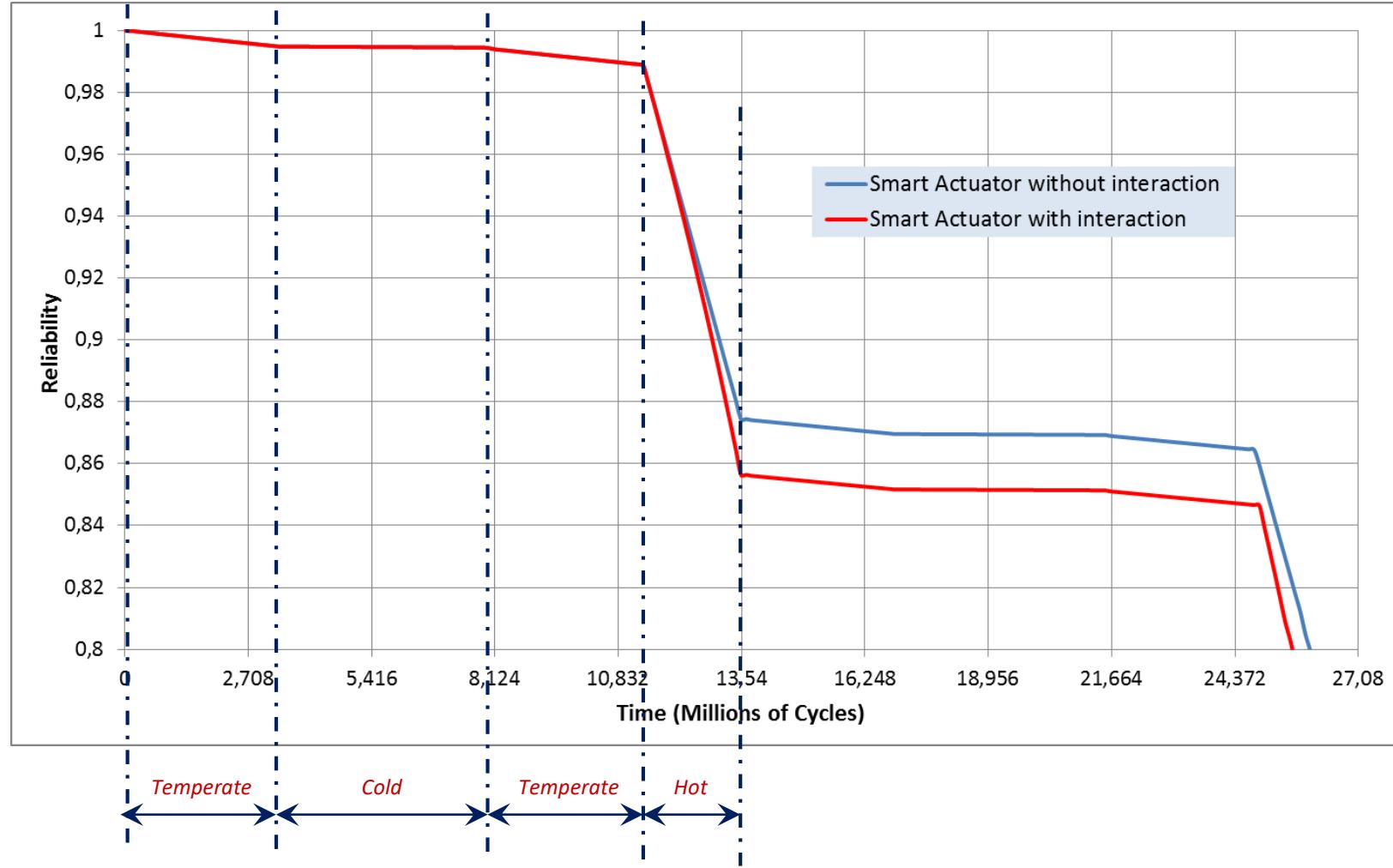
Reliability of the smart actuator **without** and **with bearing/coil interaction**

Search for reliability models **without** and **with bearing/coil interaction**



Results of reliability

Reliability of the smart actuator according to the mission profile (one-year zoom)

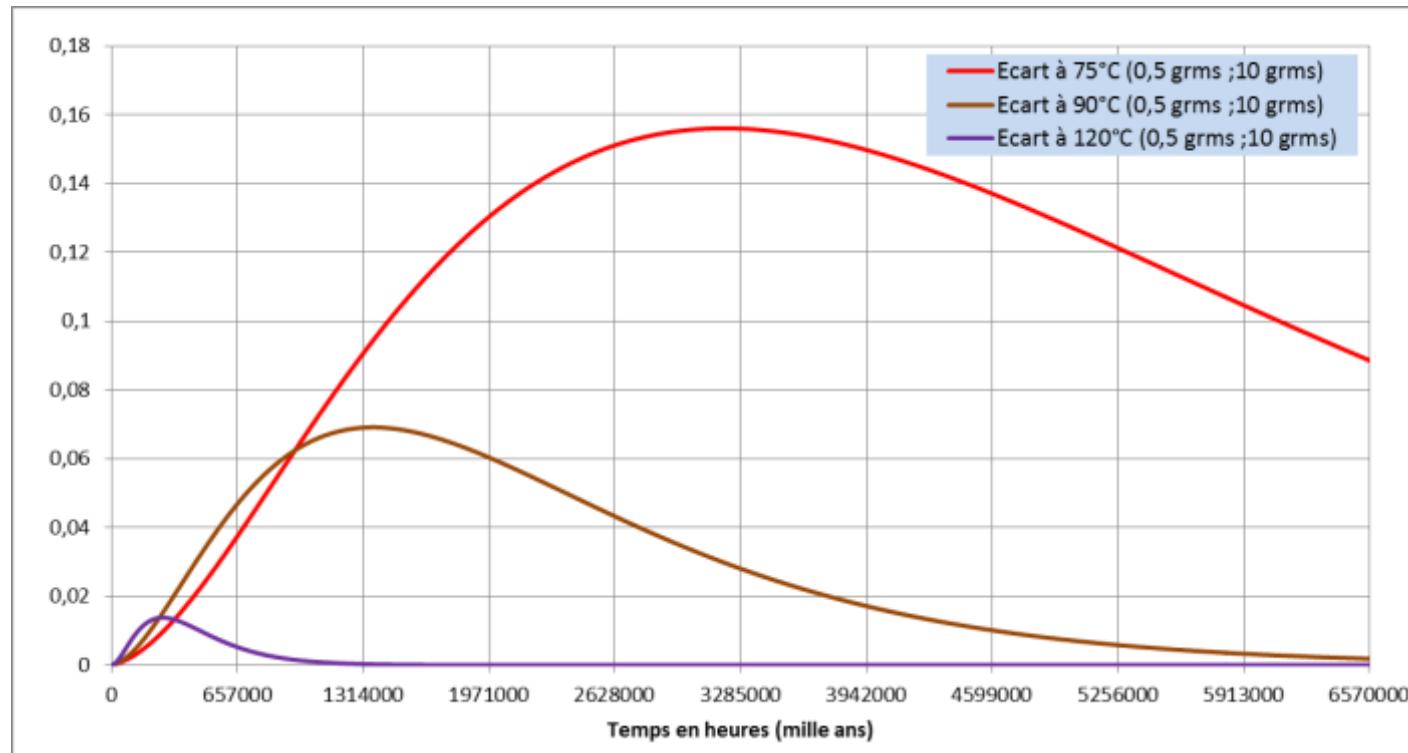


Results of reliability

Reliability of the electronic measuring circuit



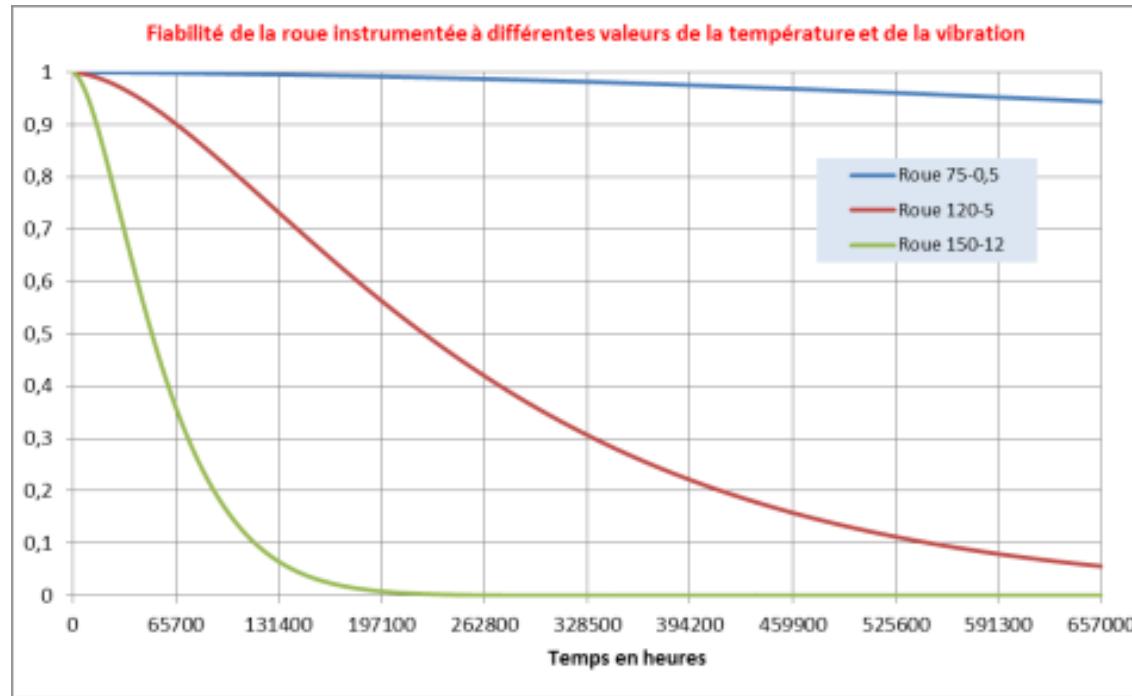
Evolution of the deviation of reliability as a function of temperature and vibration



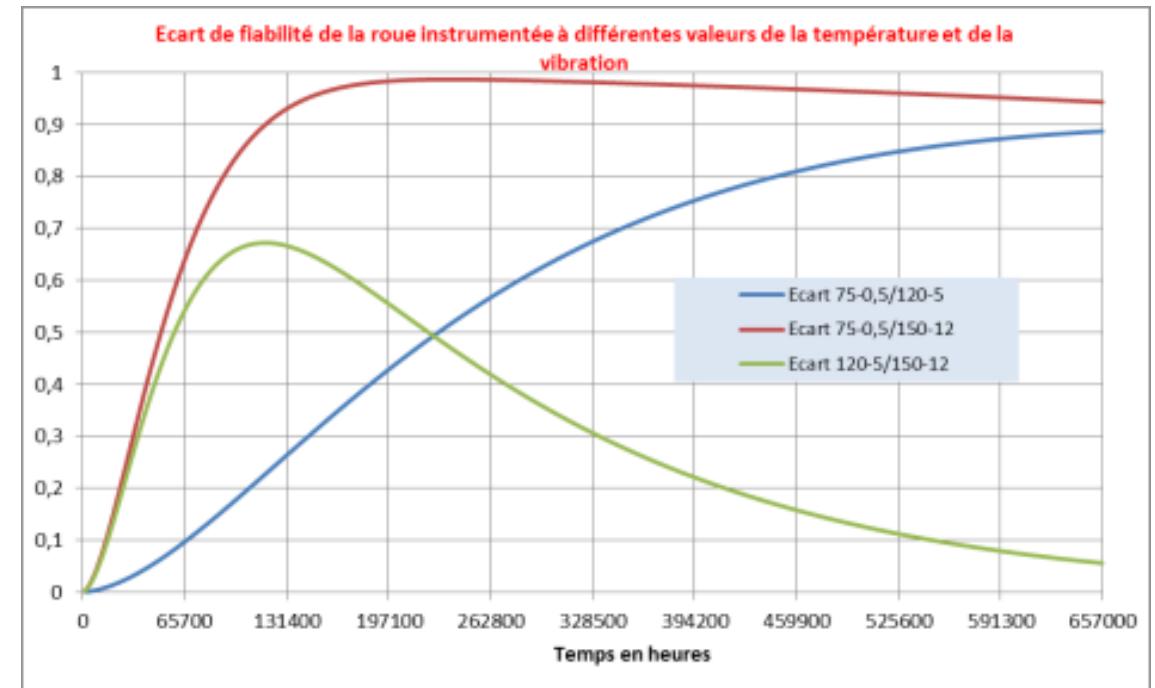
Results of reliability

Reliability of the instrumented wheel bearing

NTN SNR



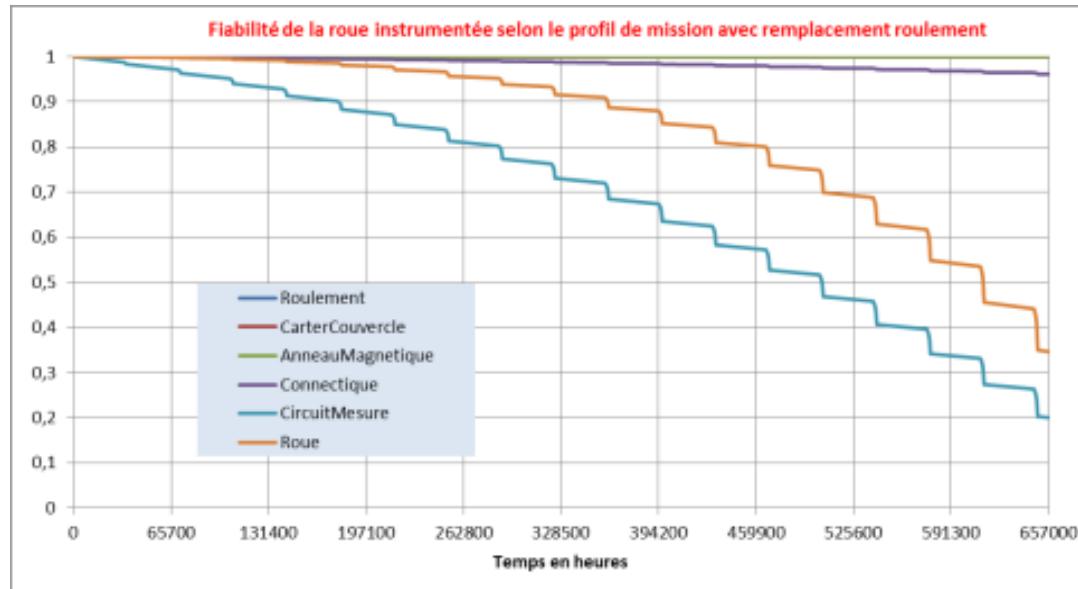
Reliability of the instrumented wheel bearing as a function of the **influence factors** (temperature, vibration)



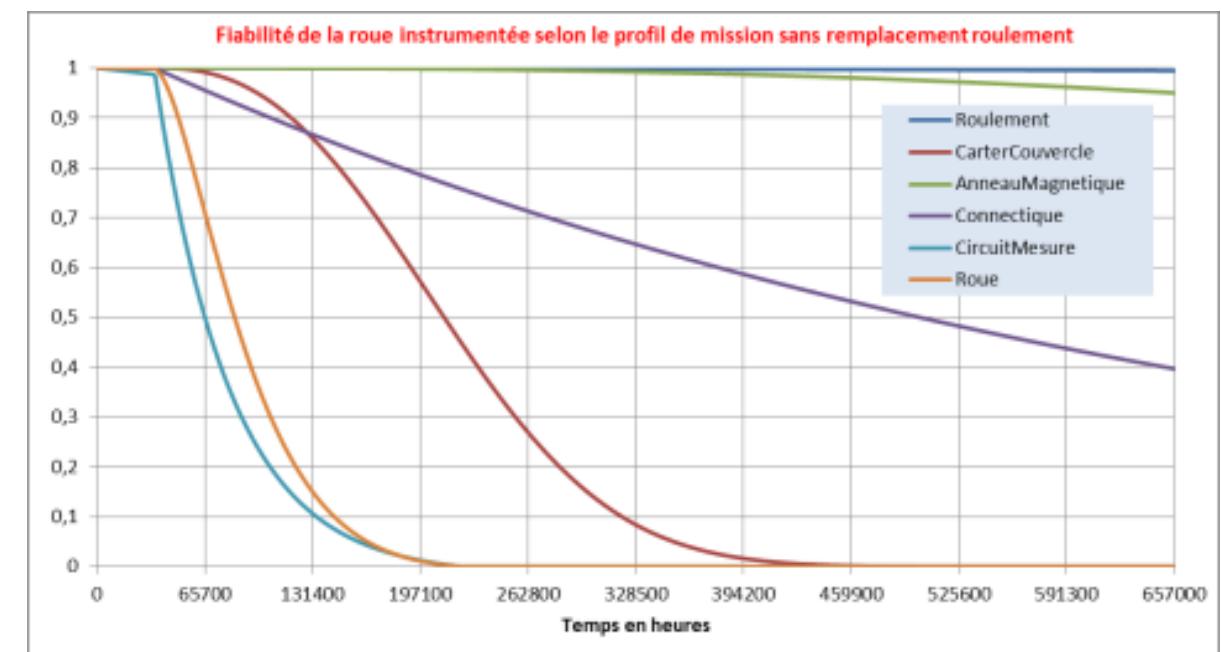
Deviation of reliability of the instrumented wheel bearing as a function of temperature and vibration

Results of reliability

Reliability of the instrumented wheel bearing



Reliability of the instrumented wheel bearing and its components **with bearing replacement due to flaking**

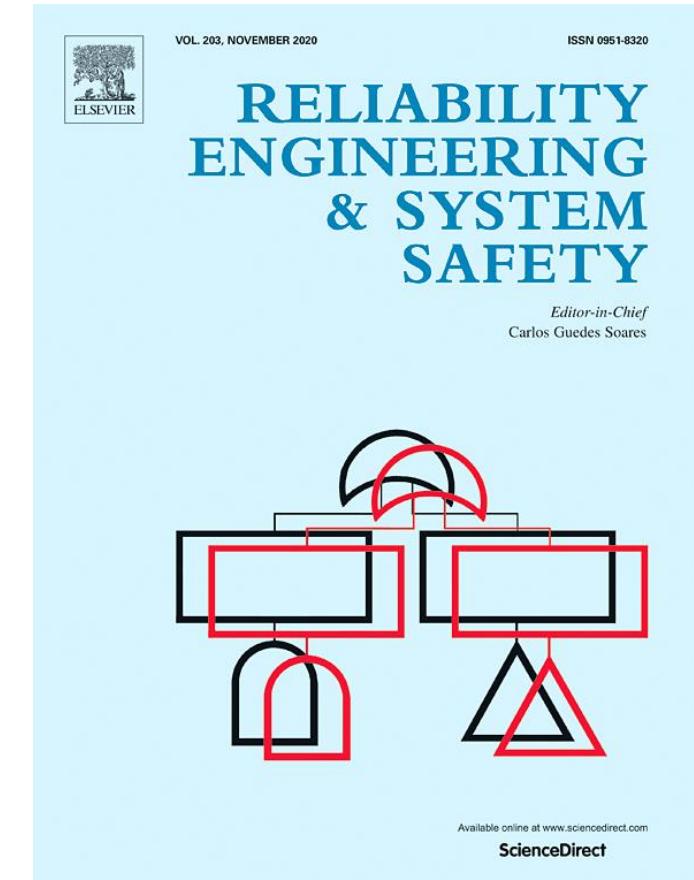
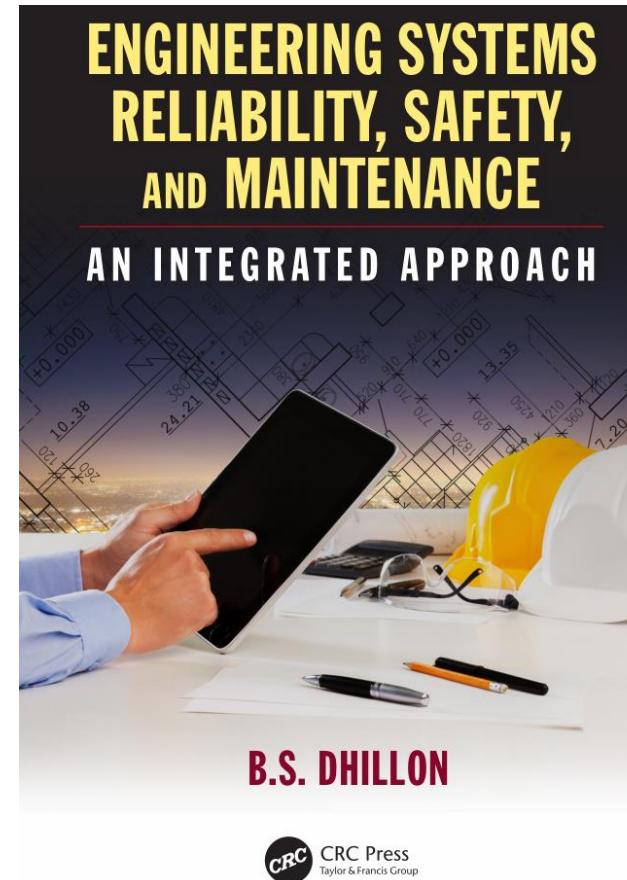
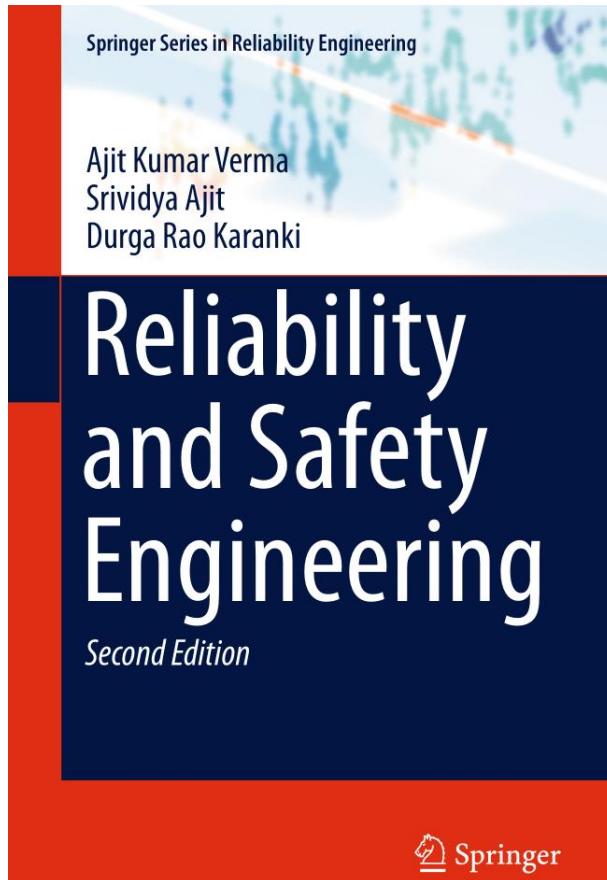


Reliability of the instrumented wheel bearing and its components **without bearing replacement due to flaking**

Conclusions

- Development of an approach to assess the predictive reliability of mechatronic systems
 - Structured and based on **the V-cycle**
 - Both **qualitative and quantitative**
 - Taking into account the characteristics of these systems: **dynamic, hybrid, reconfigurable, interactive (interdependent)**
 - Enabling to assess the **overall reliability** of the system in its multi-technology definition
 - Taking into account a **mission profile, influence factors** and **collateral and functional interactions** (interdependencies)
 - Allowing to evolve certain classical methods (FMEA: analysis with **classification of the modes of failure**, taking into account the **collateral interactions**, DF: taking into account the **mission profile** and the **interactions**)
 - Consolidated and validated on industrial **mechatronic products / systems**

Relevant books



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SYMME

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