

2025

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

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

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**



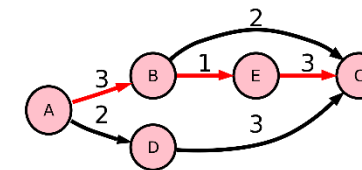
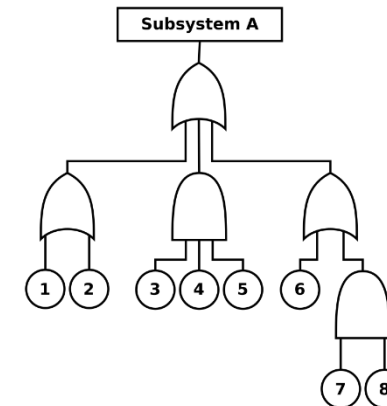
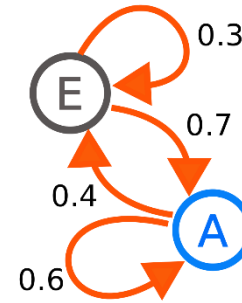
Innovative
approach



SYMME

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 phasis**, 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**

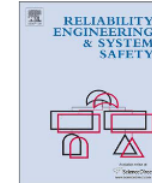
An innovative approach designed at SYMME lab - USMB



Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

Reliability Engineering and System Safety

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



SYMME

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

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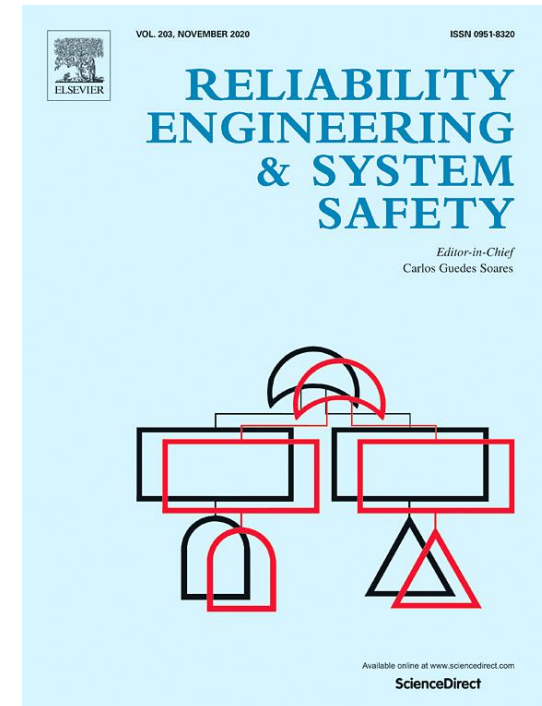
Modeling

Simulation

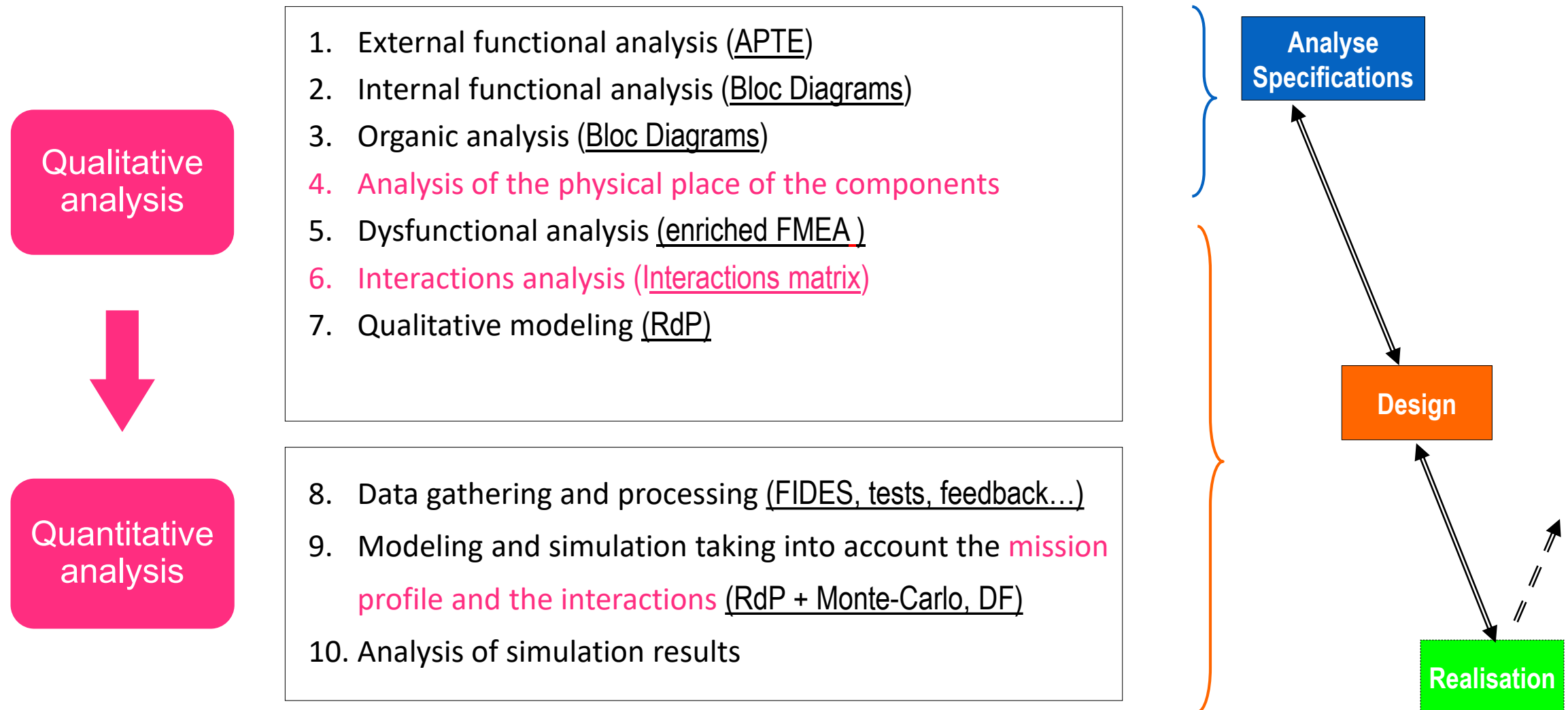
ABSTRACT

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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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**

Example to illustrate

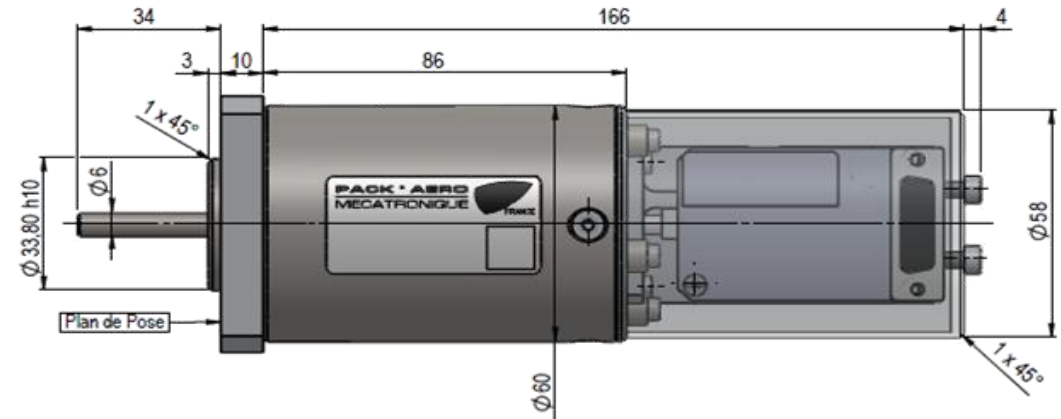
Smart actuator



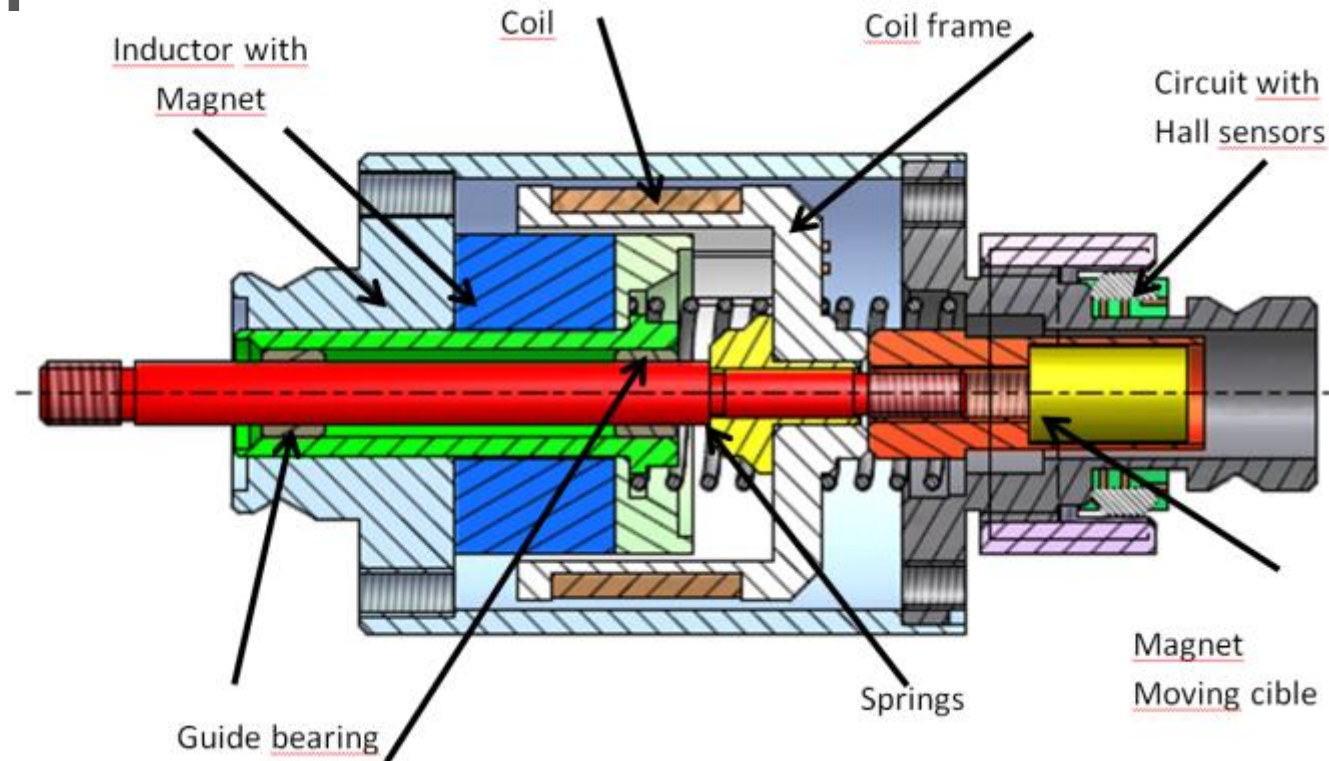
■ Specifications

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

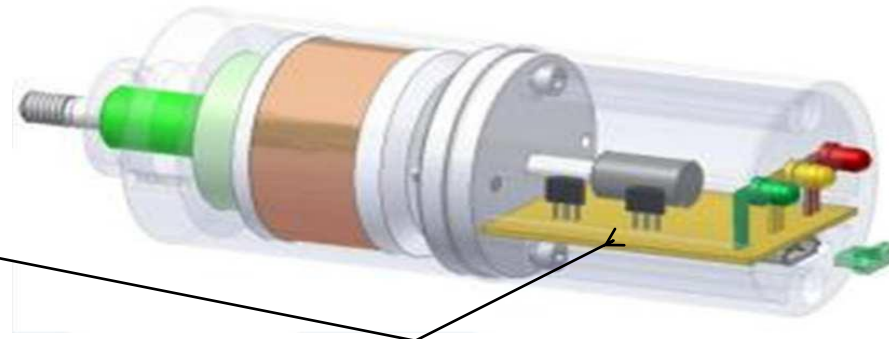
- > Transition from passive state to **active** state
- > Using a linear direct action instead of a linear indirect one
- > **Optimisation of the immediate answer** according to the needs
- > Integration of **electrical locking functions** with or without electricity consumption



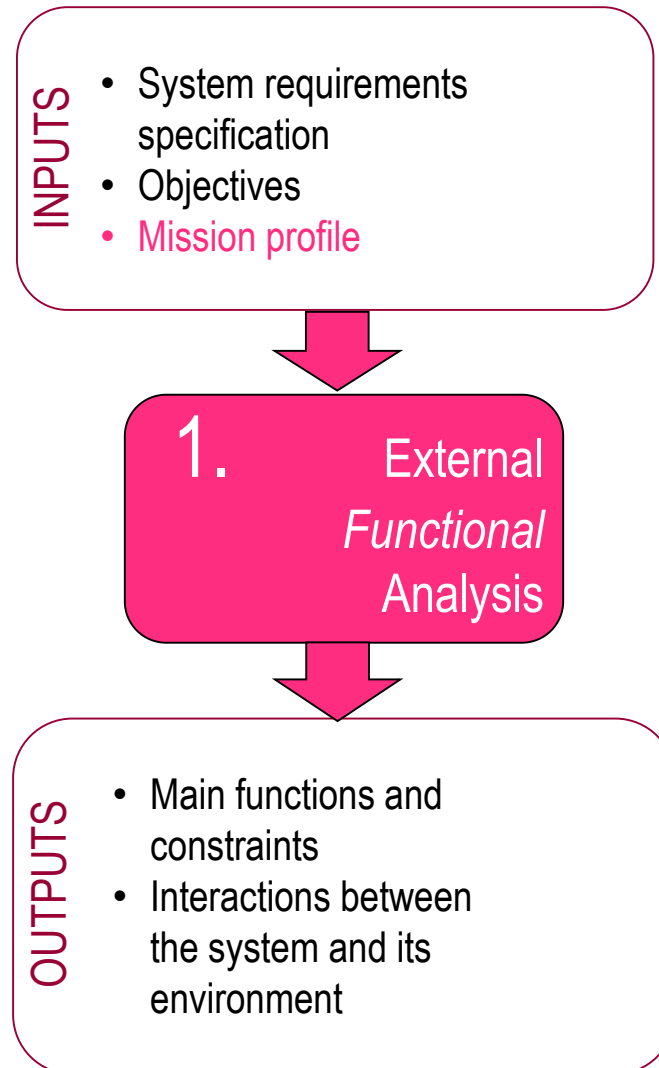
Overall plan



Physical implementation
of the circuit board



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.

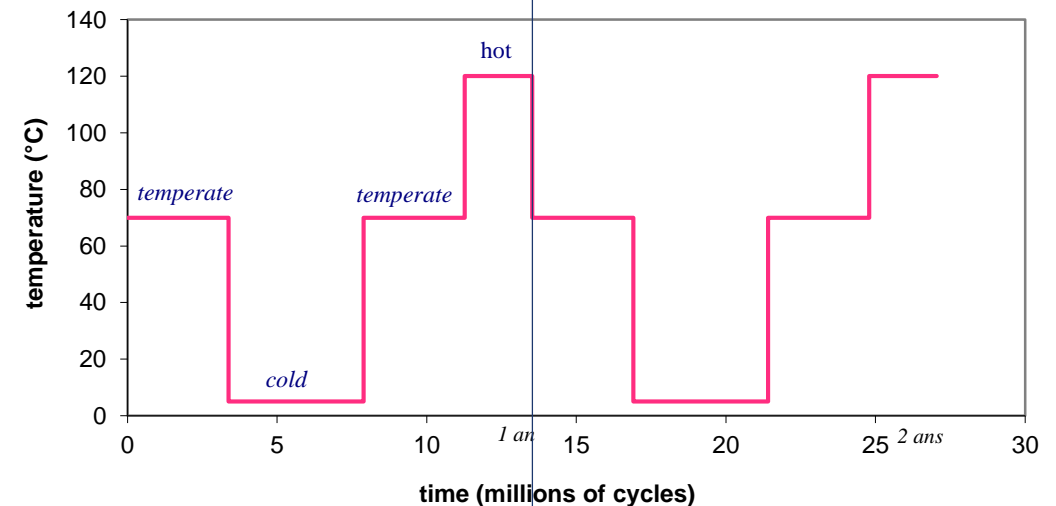
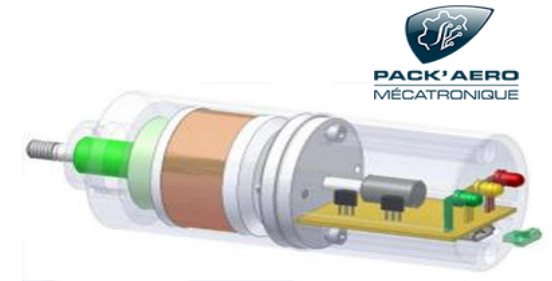
Mission profiles is an effective tool for that purpose

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

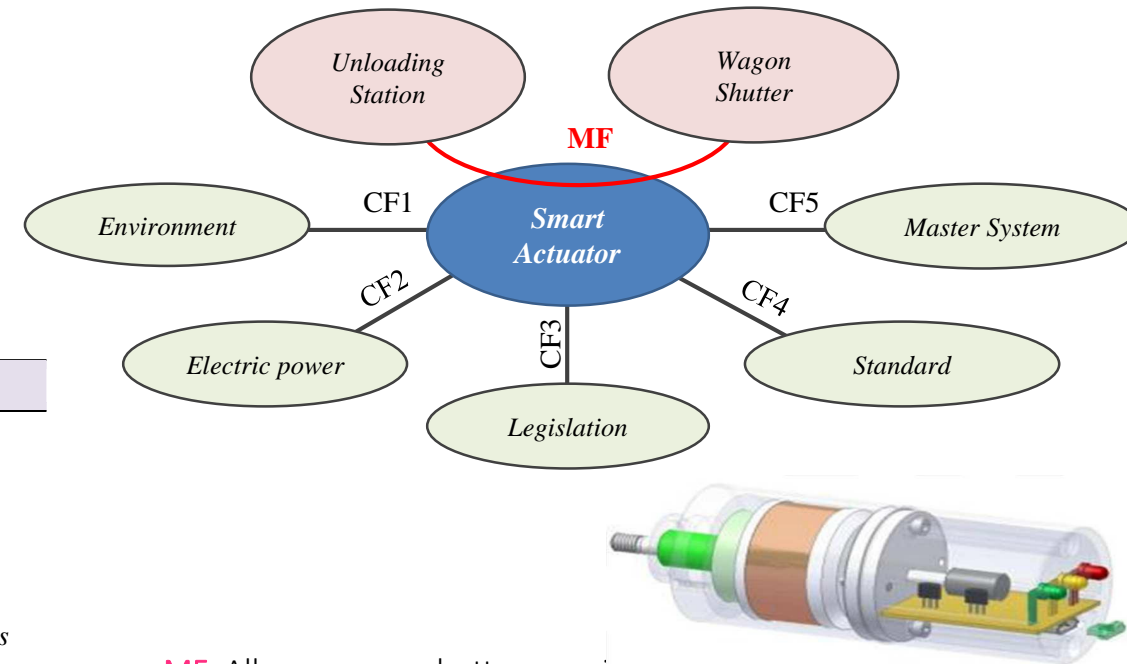


Functional Specification

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
	Intermittent operation	
	Electric power: 1 slot ON-OFF/60 ms	
	Duration of an opening/closing cycle: 40 ms	
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	TOR function (1)
	Stop order	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

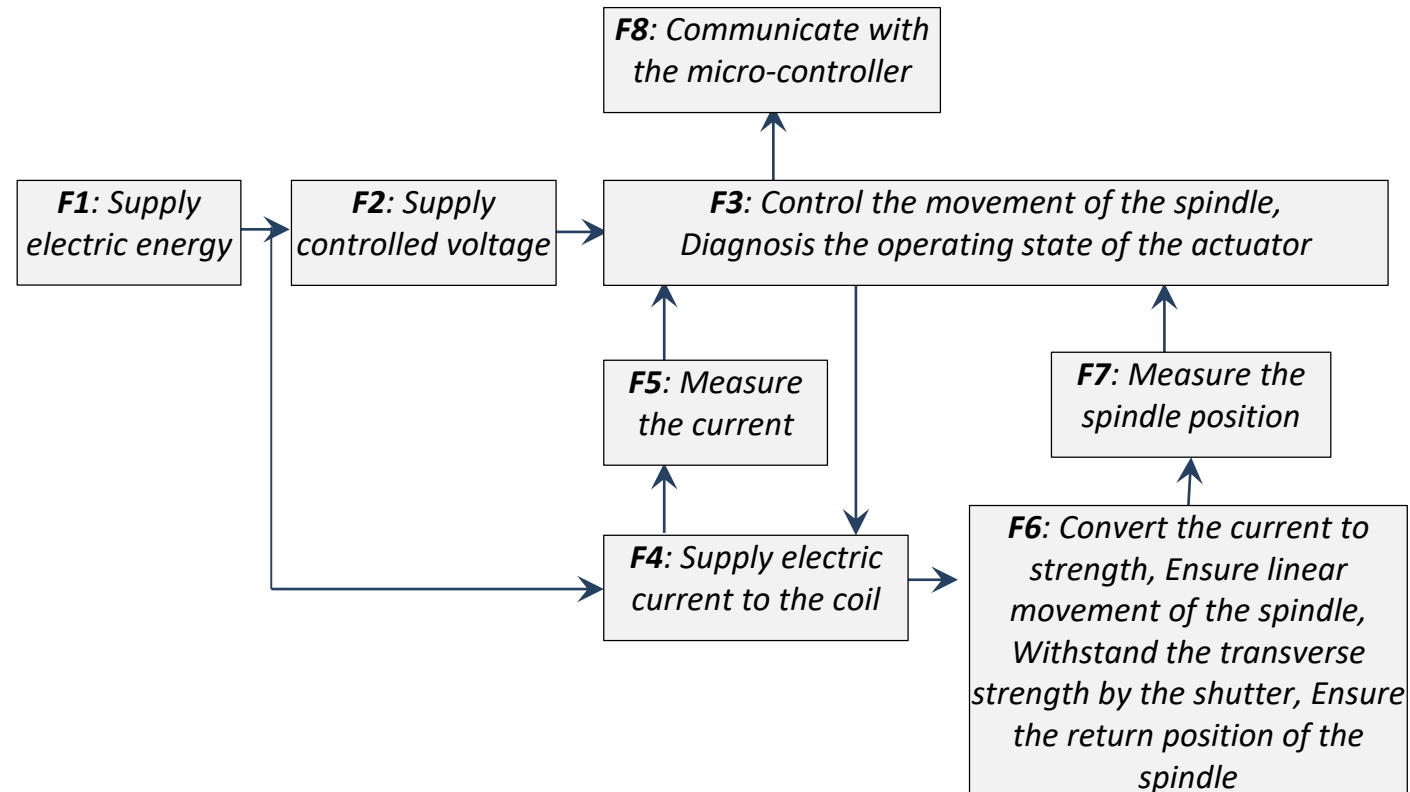
- Functional architecture,
- Choice criterion of the proposed technical solutions
- Description of the internal system & the relationships between internal functions

- 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**

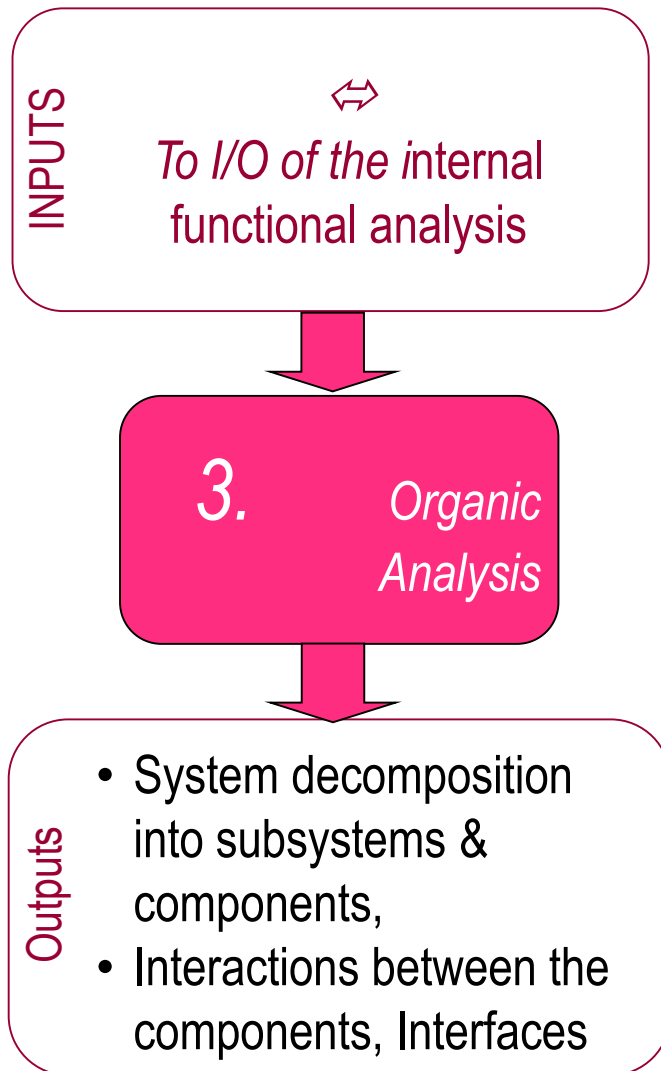
➔ To make available some elements to compare objectives between different solutions

Functional Block Diagram (FBD)

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

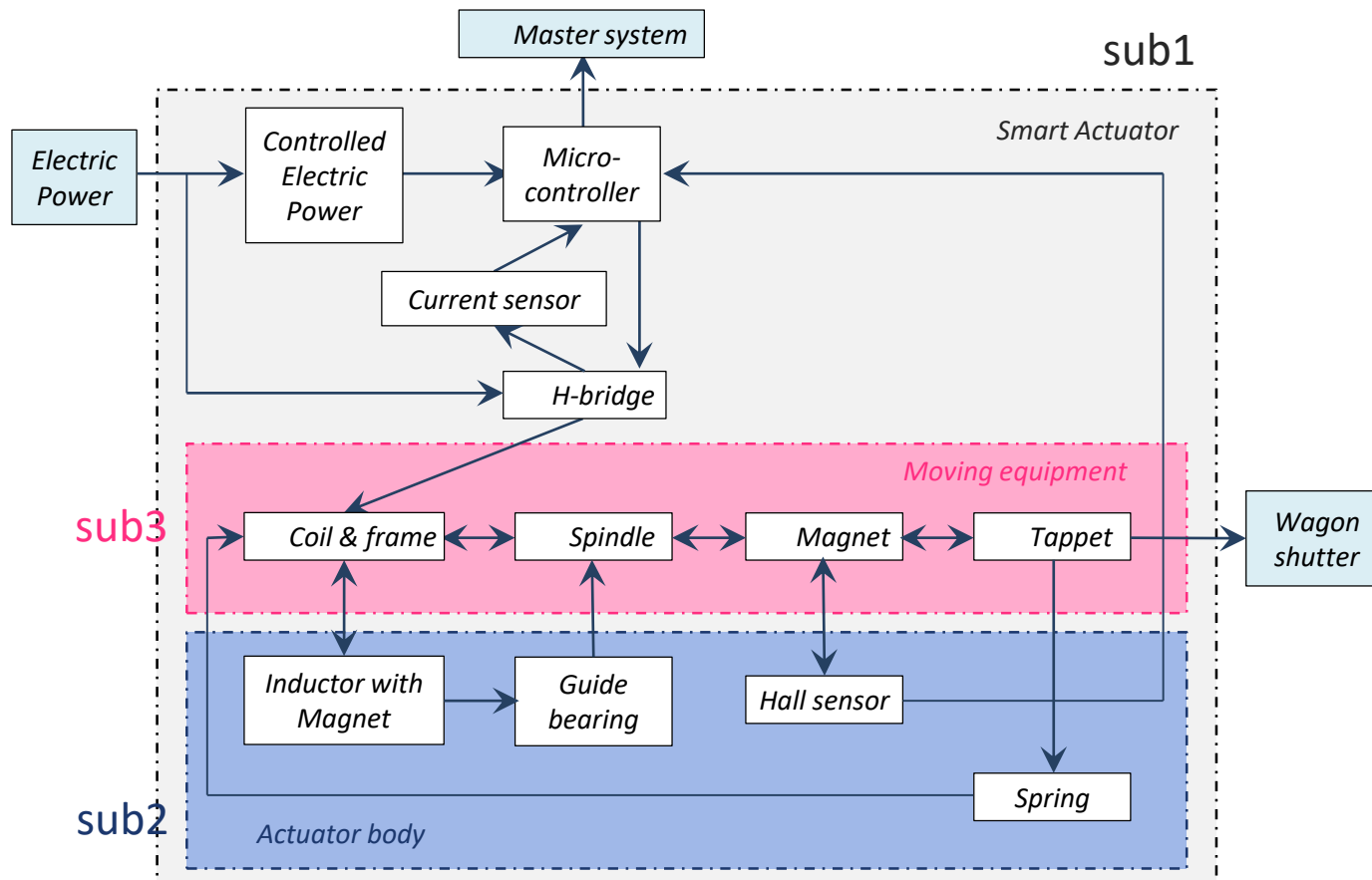


3. Organic Analysis



- 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

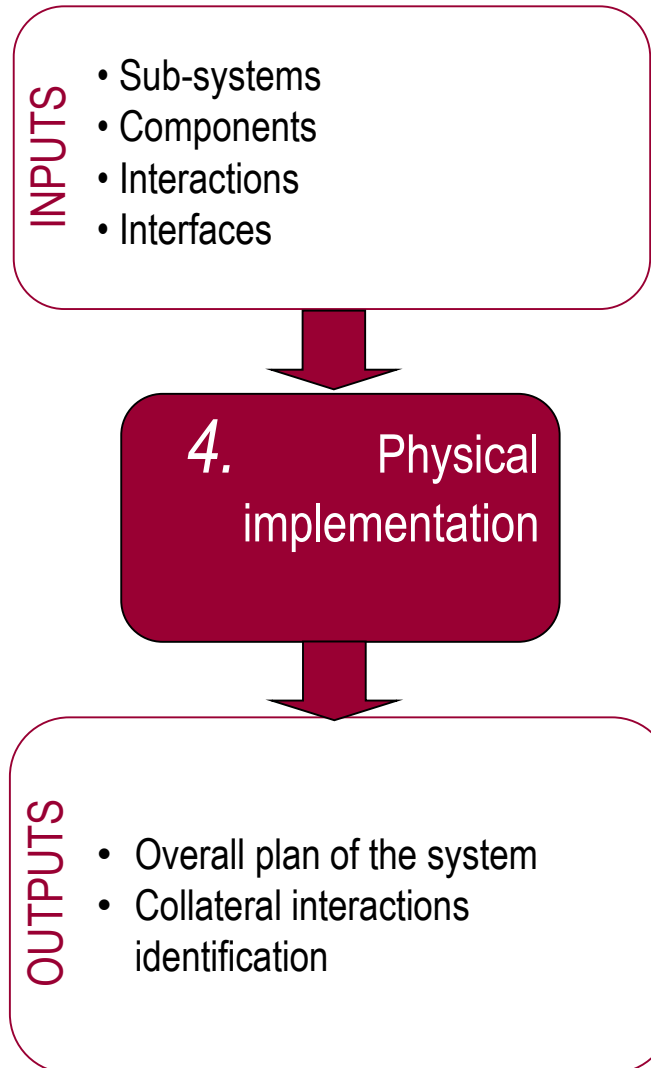
Organic system architecture



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



Supplementary step proposed compared to a conventional design approach

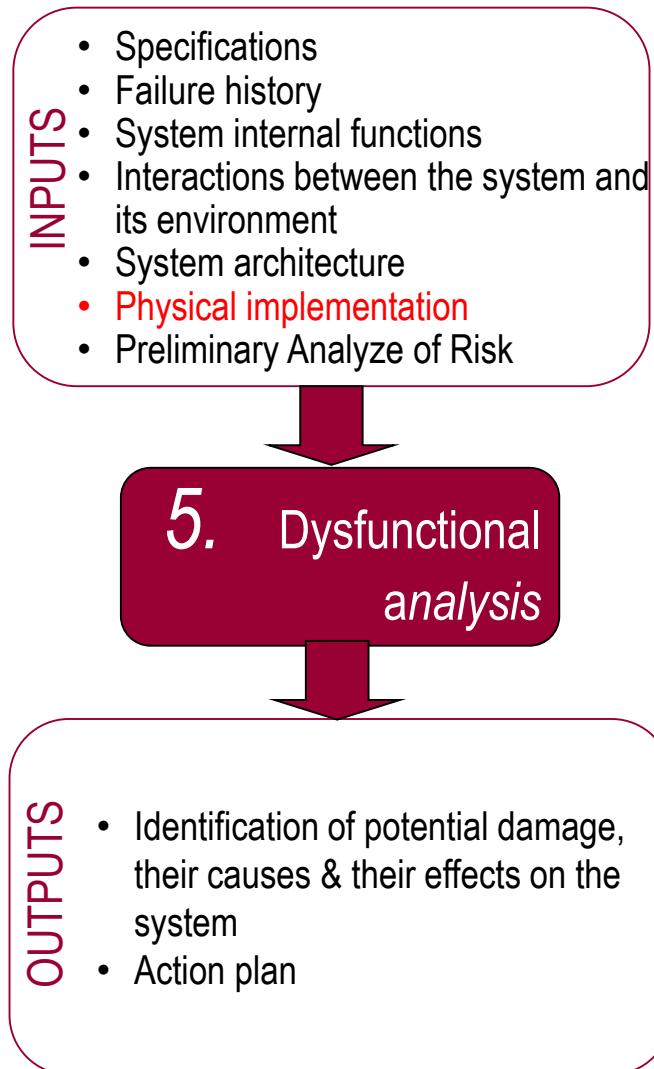


Innovative approach

- 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



- 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.

FMEA (Failure Mode Effect Analysis)

- FMEA is a widely used method for analyzing the reliability of engineering systems

- **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.

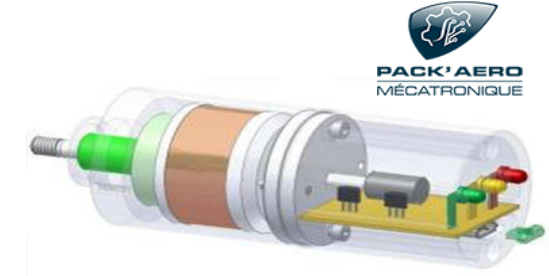
FMEA (Failure Mode Effect Analysis)

Enriched method

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

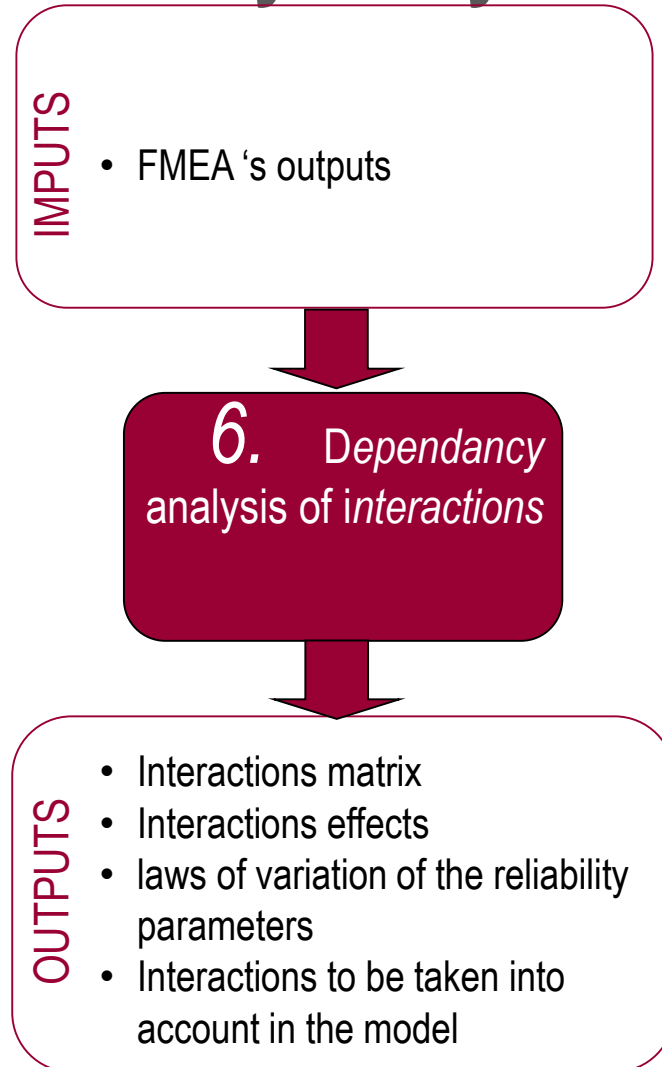
- its nature (first or second or by command)
- its event speed (sudden or progressive)
- its amplitude (partial or complete)

Innovative
approach



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 <u>cuivre</u> wire [8].- Swelling of the frame- Breakdown of the <u>material</u>- Breakdown of the <u>wire</u> [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 (<u>Inductor</u> → <u>Coil</u>)	First, sudden, complete
				Damage of H Bridge	No opening of the shutter	Fonctional (H-Bridge → <u>Coil</u>)	First, sudden, complete
				<u>Decentering</u> of the <u>rod</u>	No opening of the shutter	Fonctional (<u>Rod</u> → <u>coil frame</u>)	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.

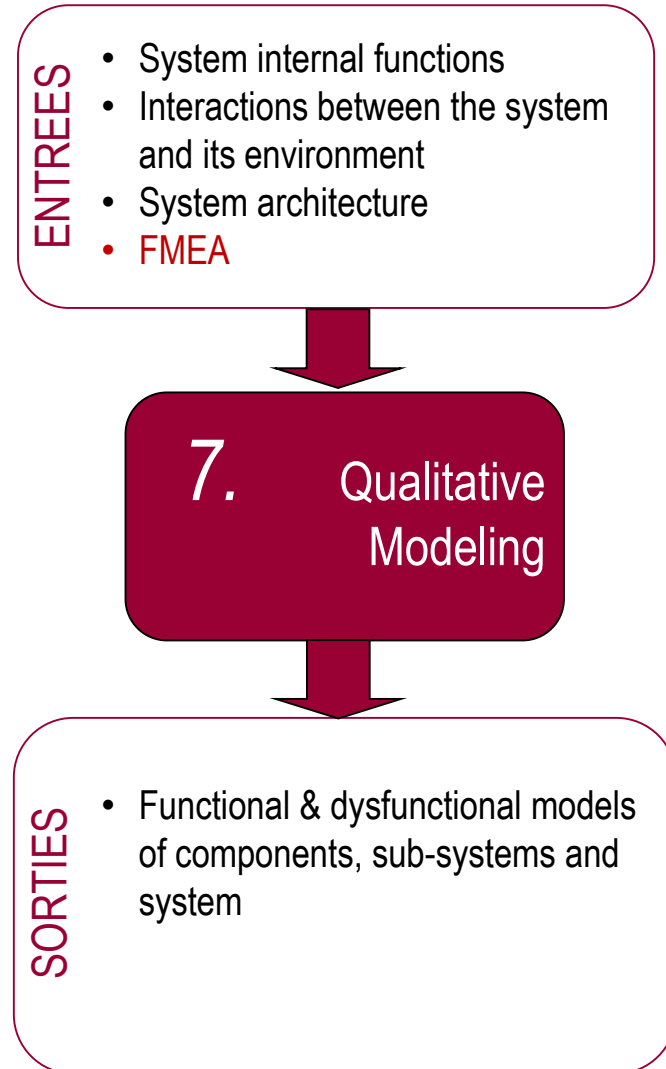
Interactions matrix

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

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

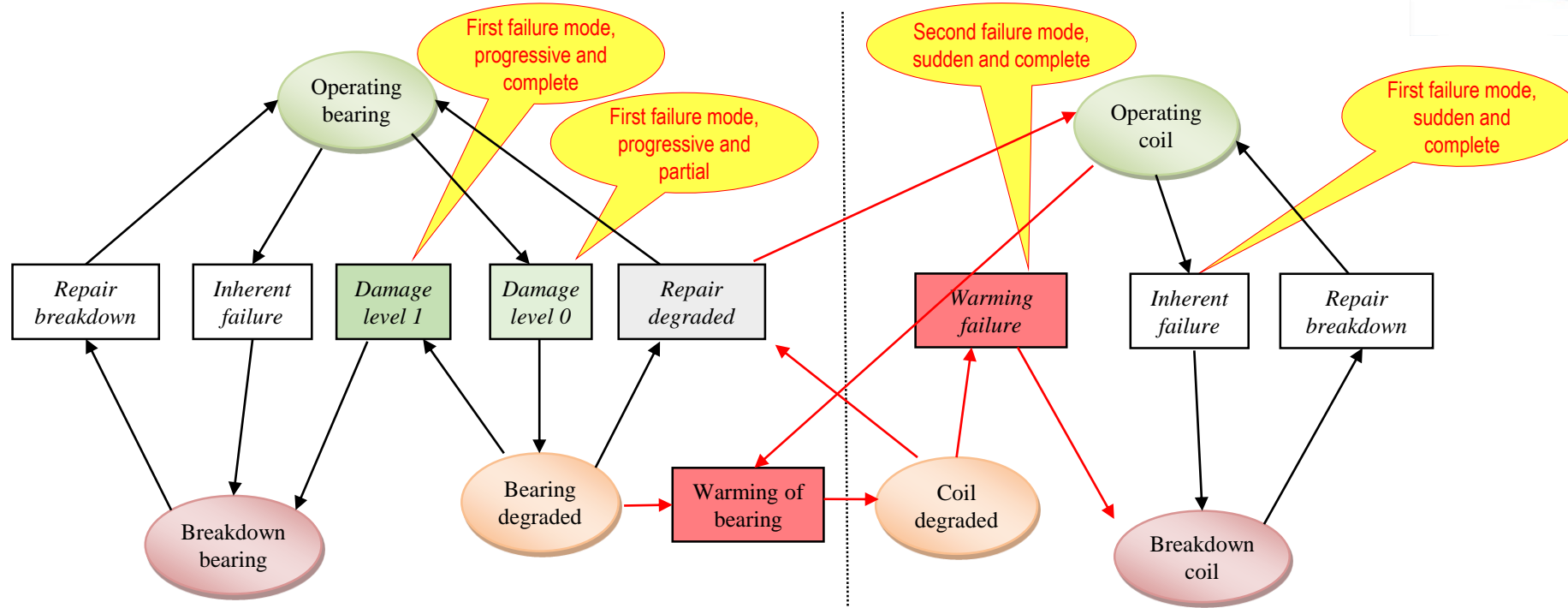


Models the functional and dysfunctional behavior of the system and its components, taking into account the interactions

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

7. Qualitative modeling

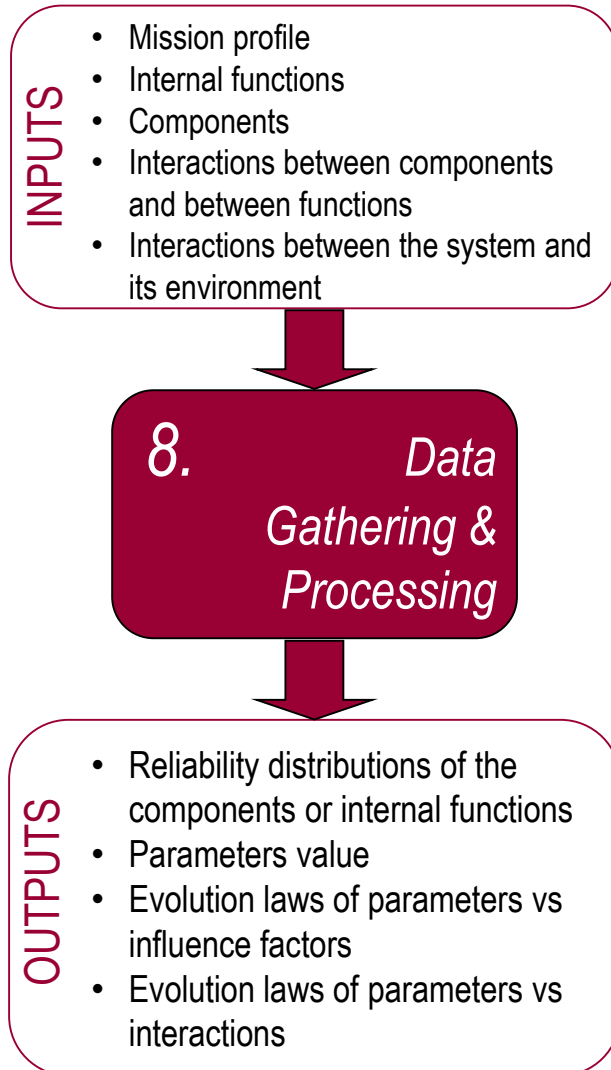
- Modeling of both components: guide bearing / coil
 - Bearing wear
 - Collateral interaction linked to the physical implementation guide bearing / coil



- 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 :

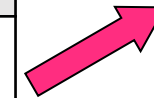
- **Gather the reliability** data available on components (database, experiment, simulation, expertise...)
- **Process the data** (statistic analysis, influence of influential factors, influence of interactions...)
- **Identify relevant distributions** of reliability and the associated parameters for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

Reliability distribution and parameters

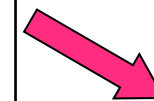
Technology	Comments	Reliability distribution and parameters
Electronics	Known distribution and parameters available in Database	Exponential : MTTF* or λ (failure rate)
Mechanics	<ul style="list-style-type: none">Distribution are known for few standard elementsTo find for most of specific components	Weibull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



FIDES 2009
(reliability database for electronic components)



Feedback or estimation
of reliability parameters
for mechanical components

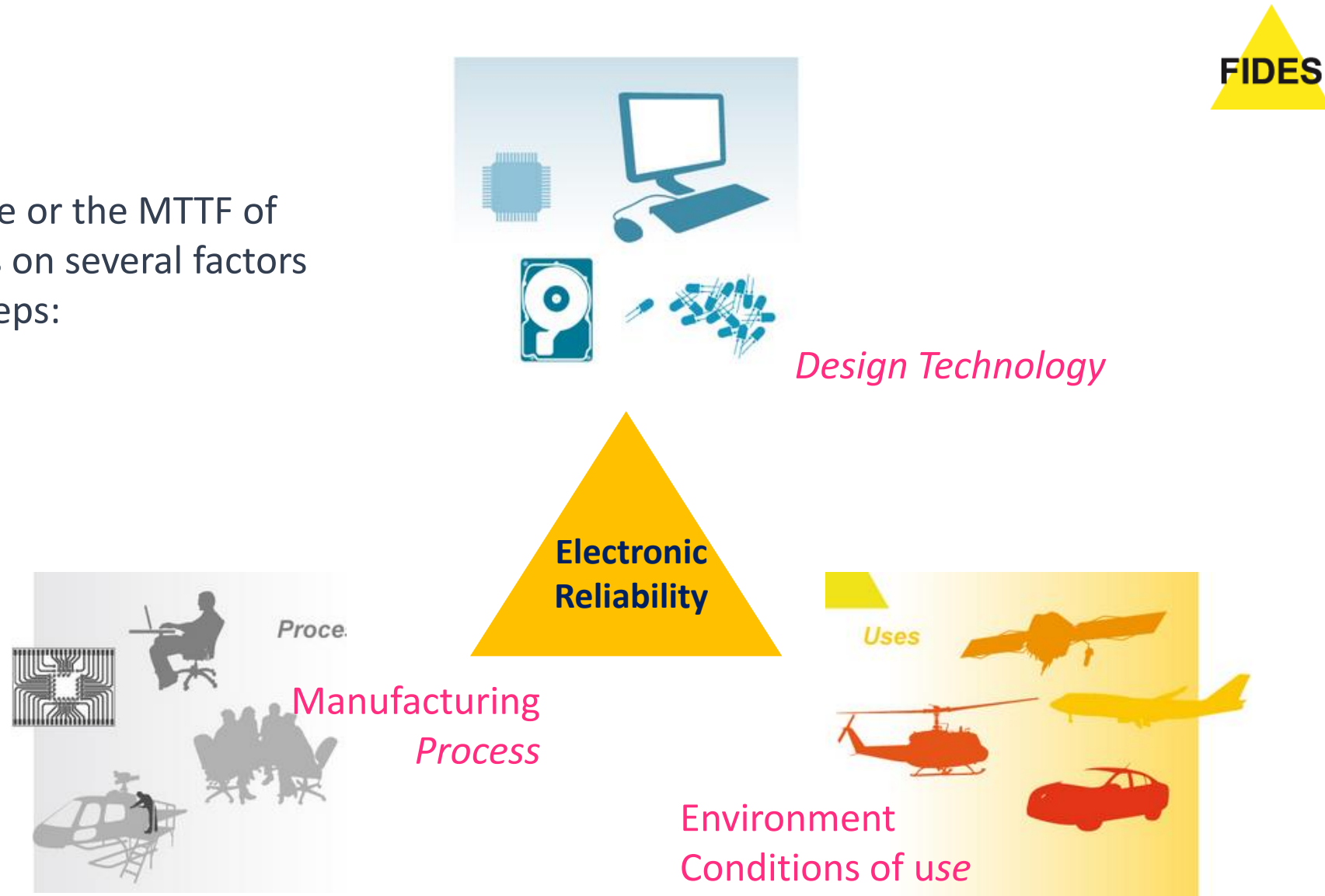


*MTTF : Mean Time To Failure

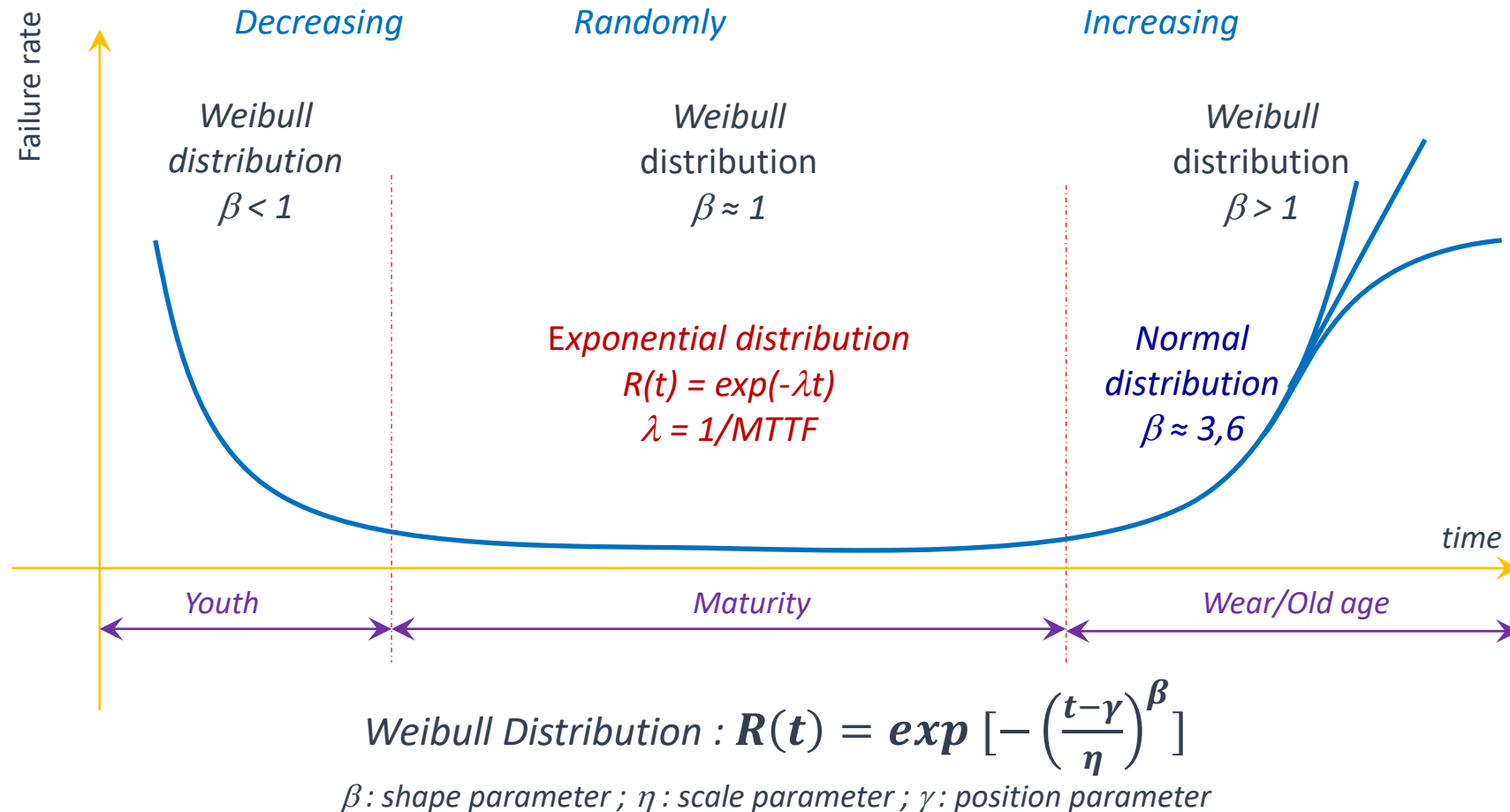
FIDES database

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



Reliability distribution and parameters



Reliability estimation

Example of data

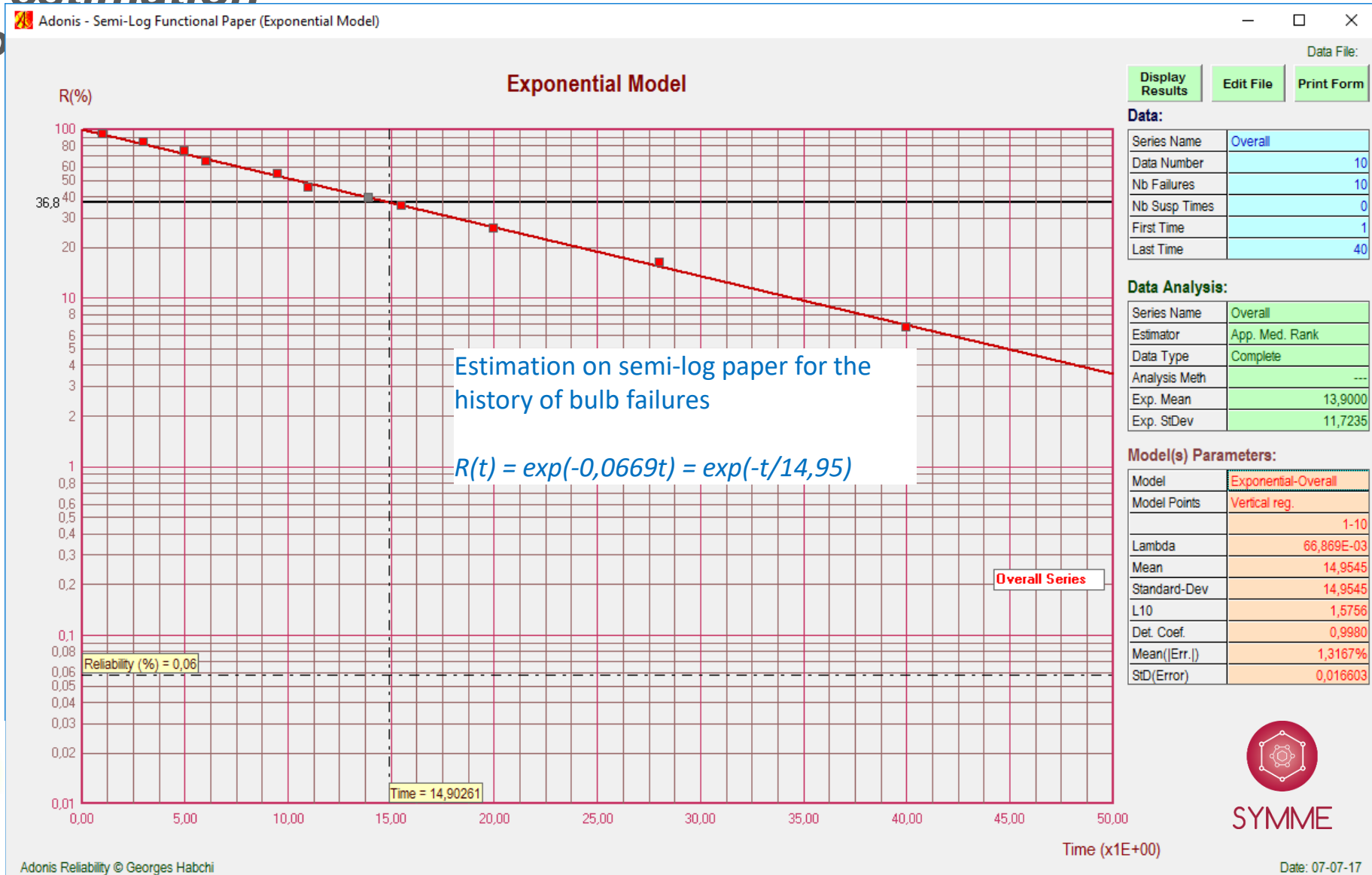
- Imagine that you have installed *10 identical light bulbs* (same brand, same power...) at the *same time* and that operate under *identical conditions*
 - At 0 month, the 10 bulbs work
 - 1 month later, 1 bulb is out of service
 - 3 months later, another bulb is out of service
 - Etc.



Time (month)	0	1	3	5	6	9,5	11	15,5	20	28	40
Reliability	1	0,9	0,8								

Reliability estimation

Use of expo



Reliability estimation (6)

Example of data

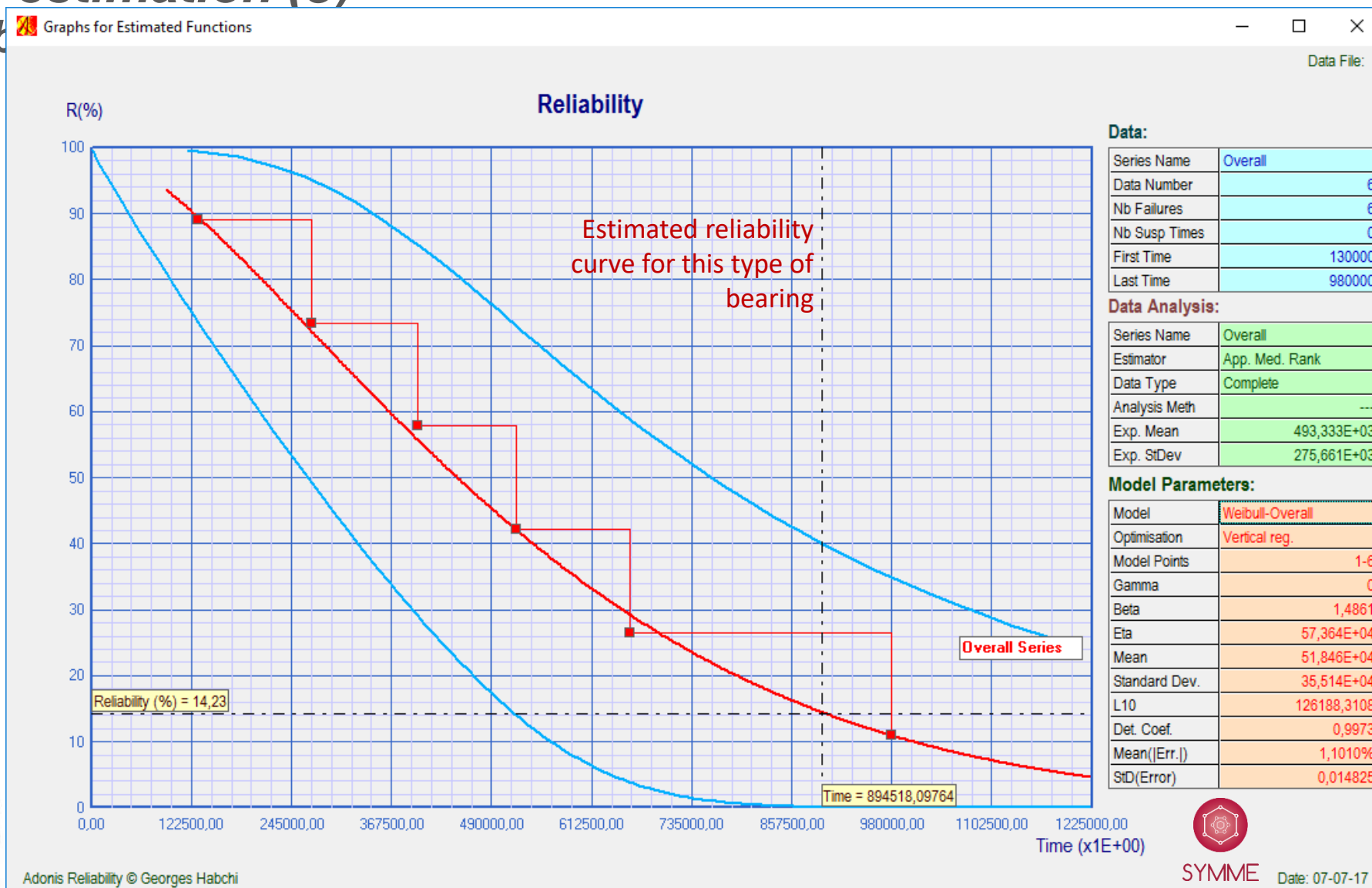
- A life test was performed on a lot of 6 loaded bearings under specific conditions and the following results were recorded



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 (8)

Use of Weibull



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

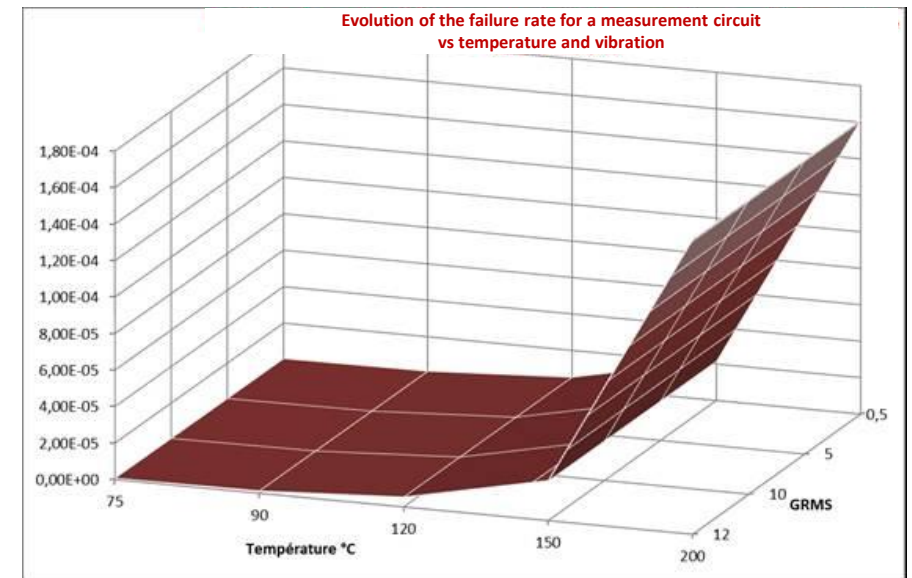
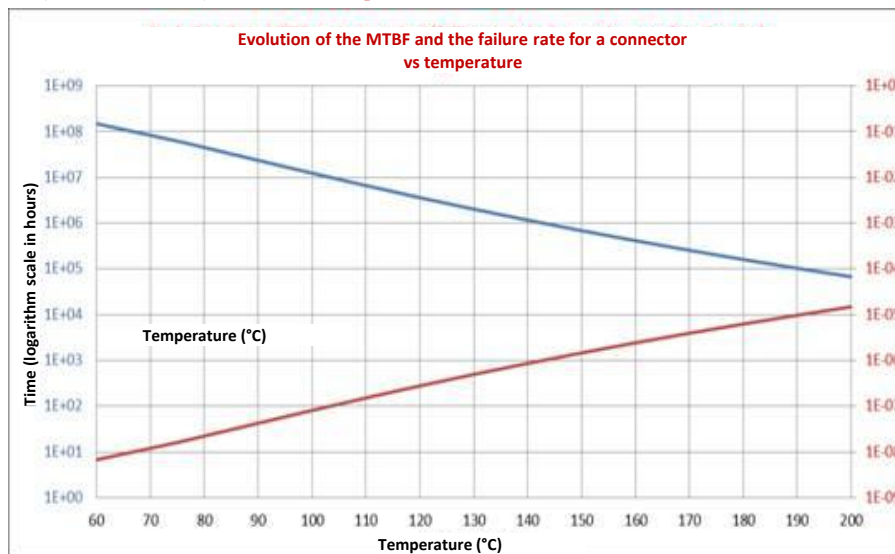
Two influent factors considered:

- *Temperature*
- *Vibration*

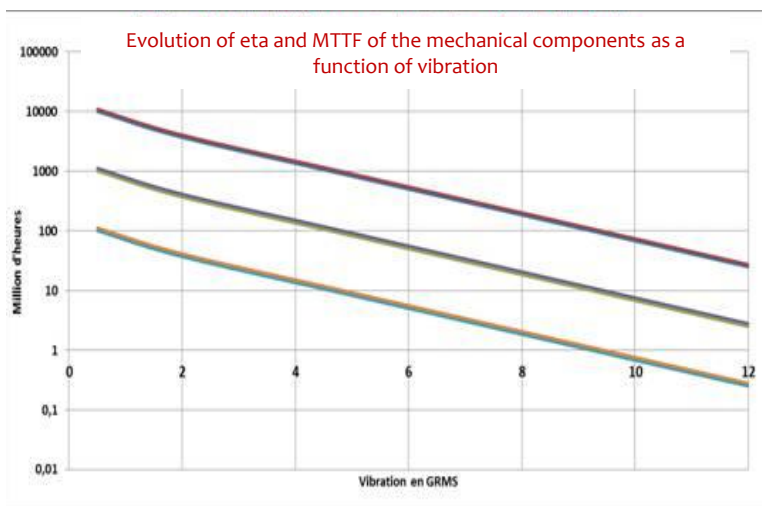
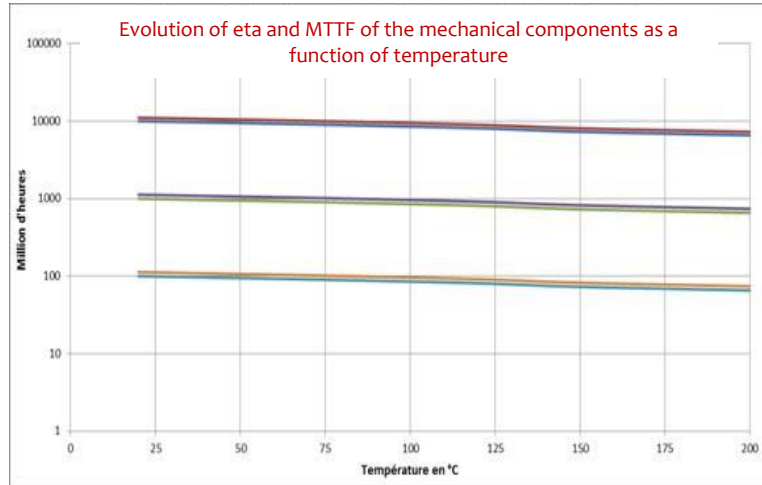
Vibration (Grms)	Temperature (°C)				
	75	90	120	150	200
0,5	15 experiments have to be done				
5					
12					



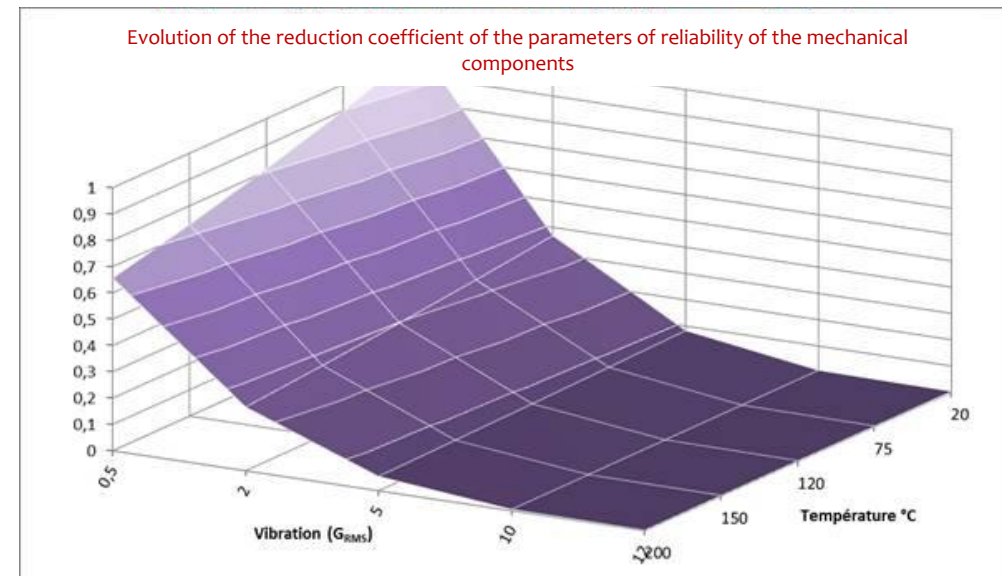
Influence of the *temperature*



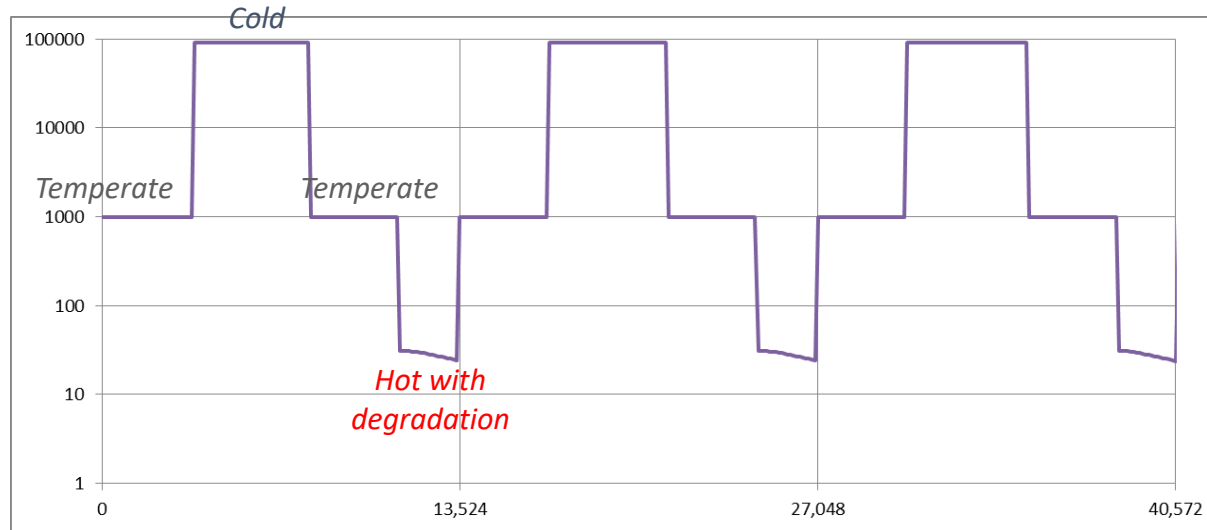
Influence of the environment on the degradation of mechanical components



- 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

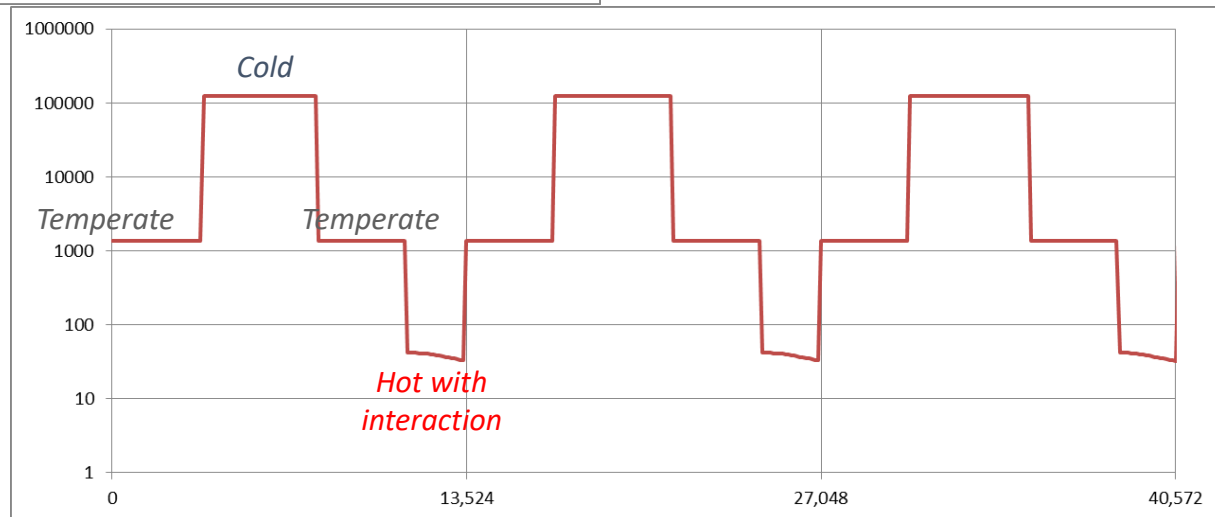


Evolution of the scale parameter η of the bearing according to:

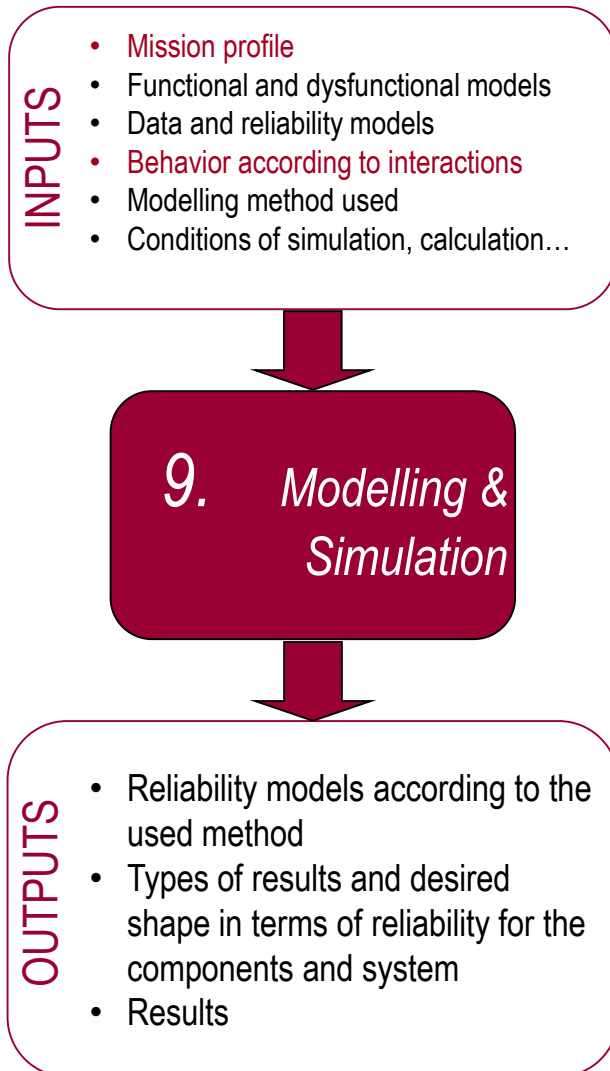
- Mission profile phases
- Degradation in the “hot” phase

Evolution of the MTTF of the coil according to:

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



9. Modelling and Simulation

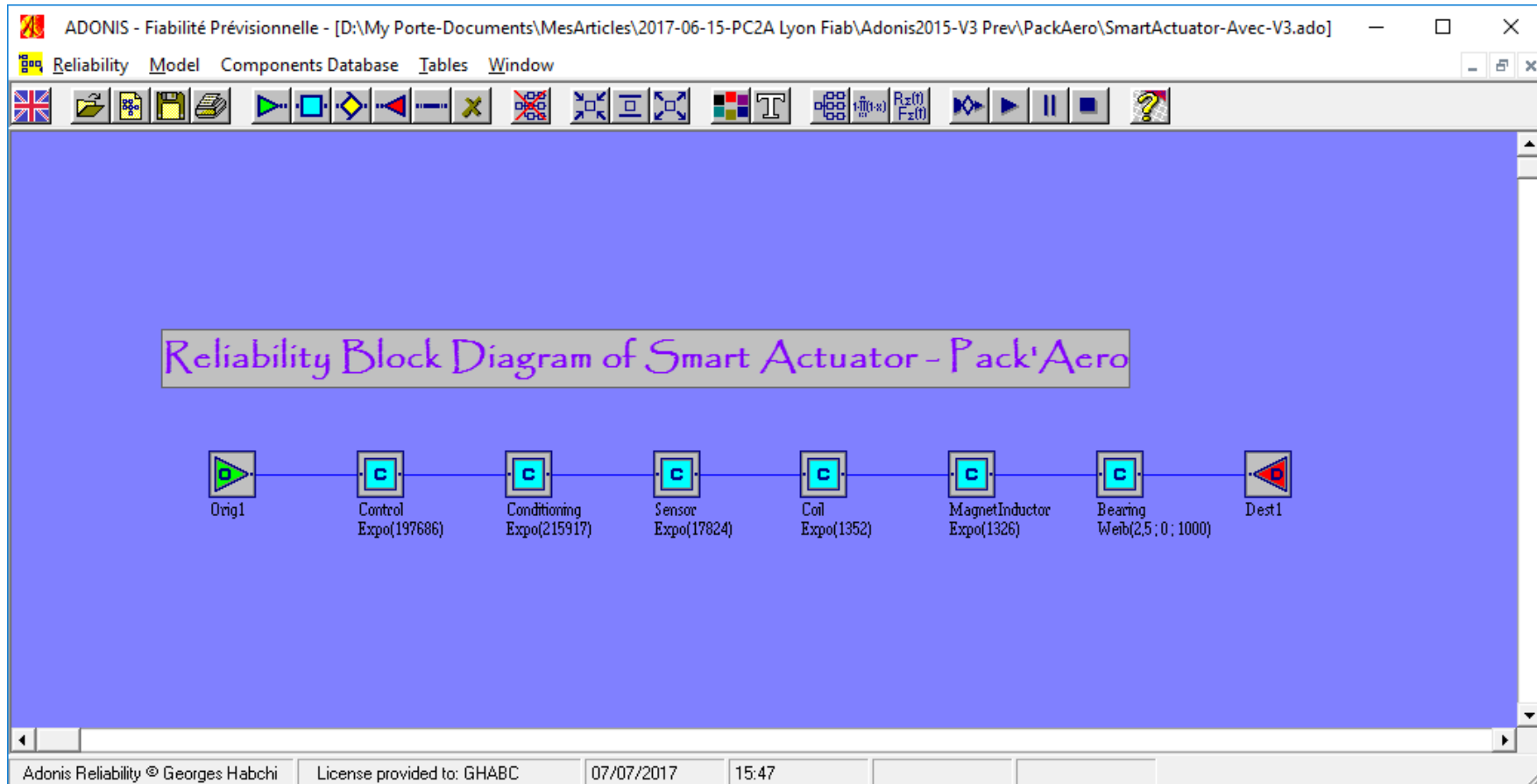


Implements the reliability models according to the chosen method, taking into account inputs and outputs and provides reliability results

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

Pack'Aero Smart Actuator RBD

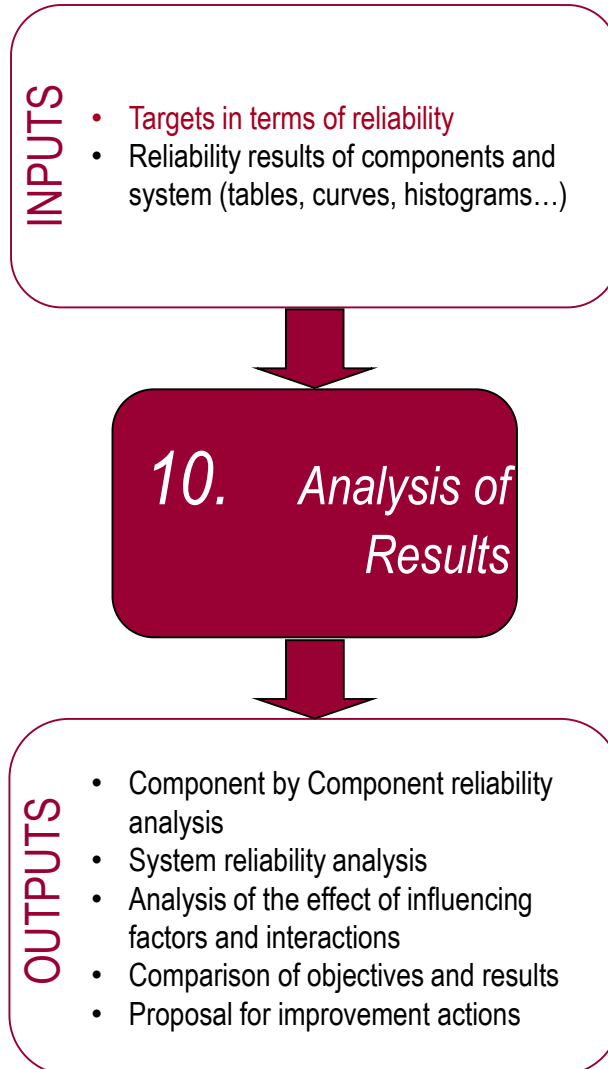


ADONIS Reliability Software

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)

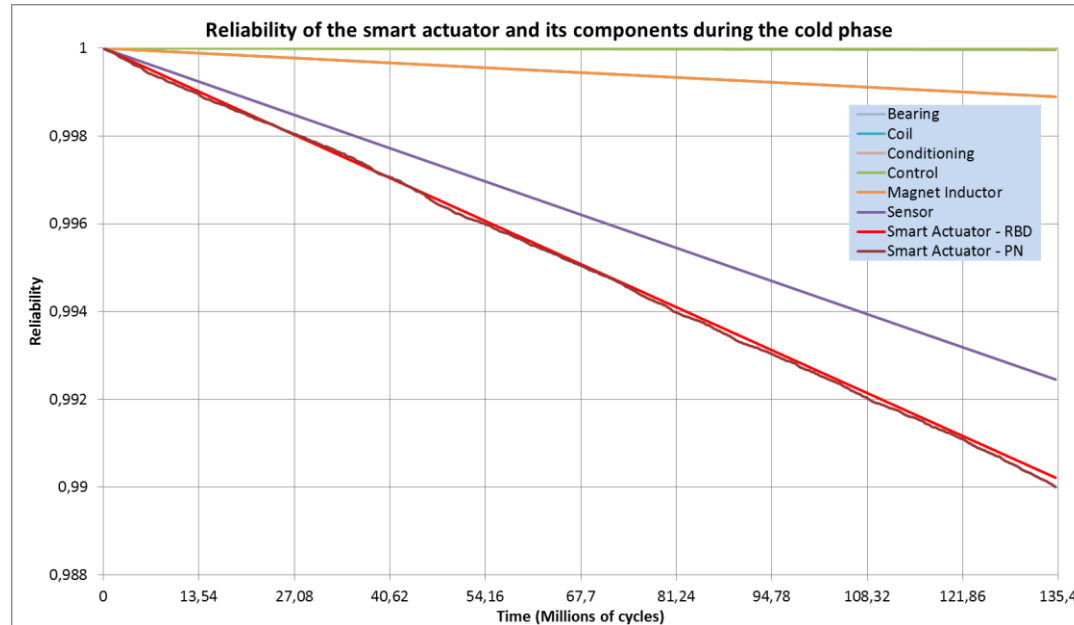
10. Analysis of Results



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

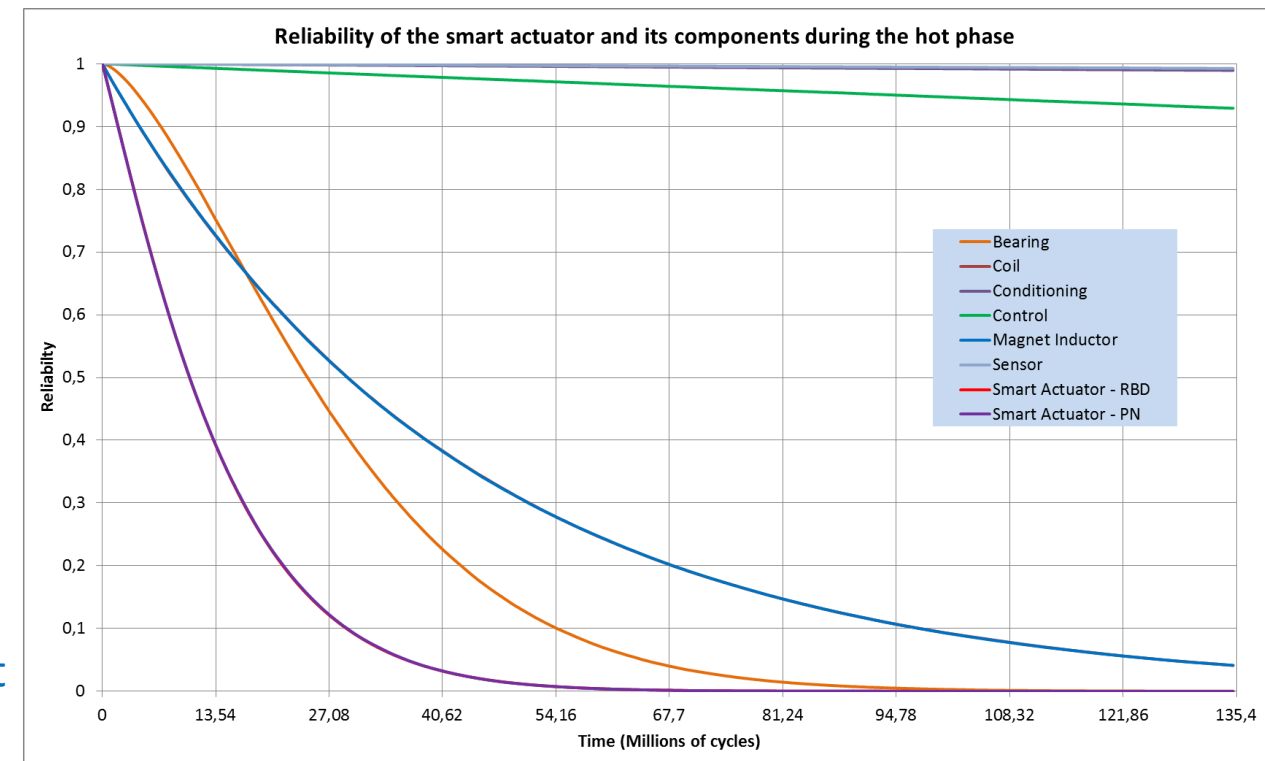
Results of reliability

Reliability of the smart actuator and components phase/phase



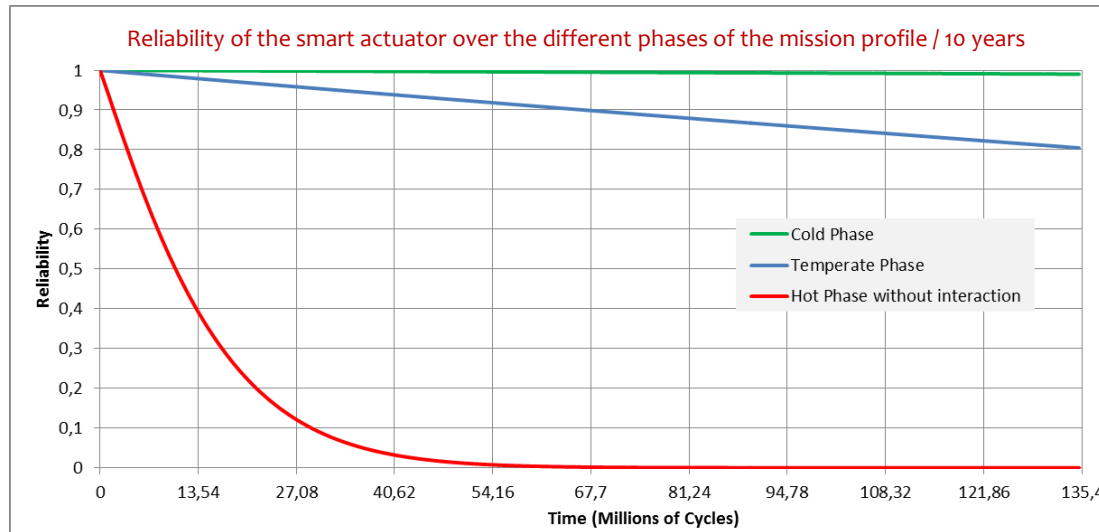
Reliability of the smart actuator and its components for the "cold" phase without bearing/coil interaction

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



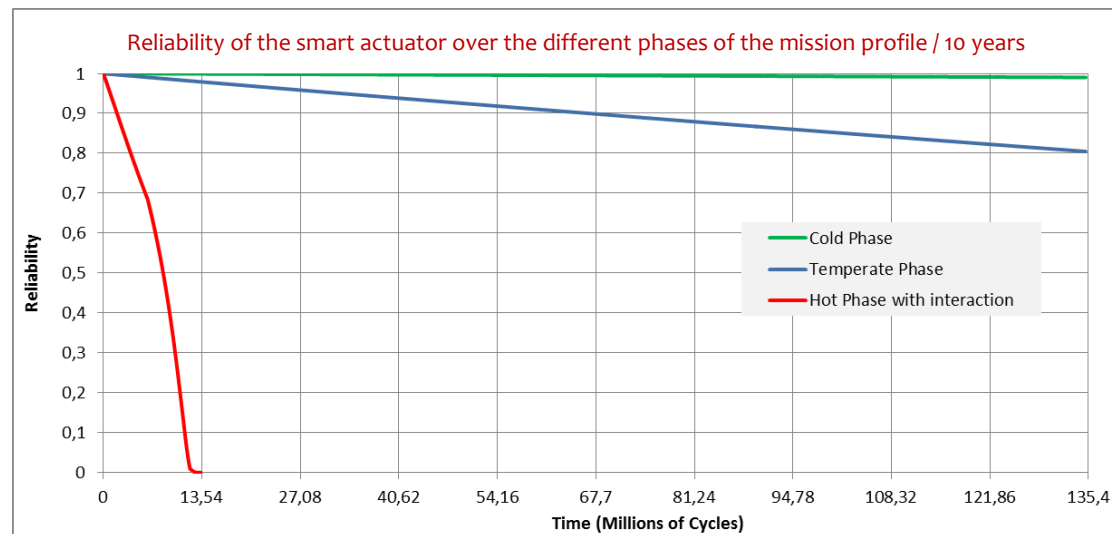
Results of reliability

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



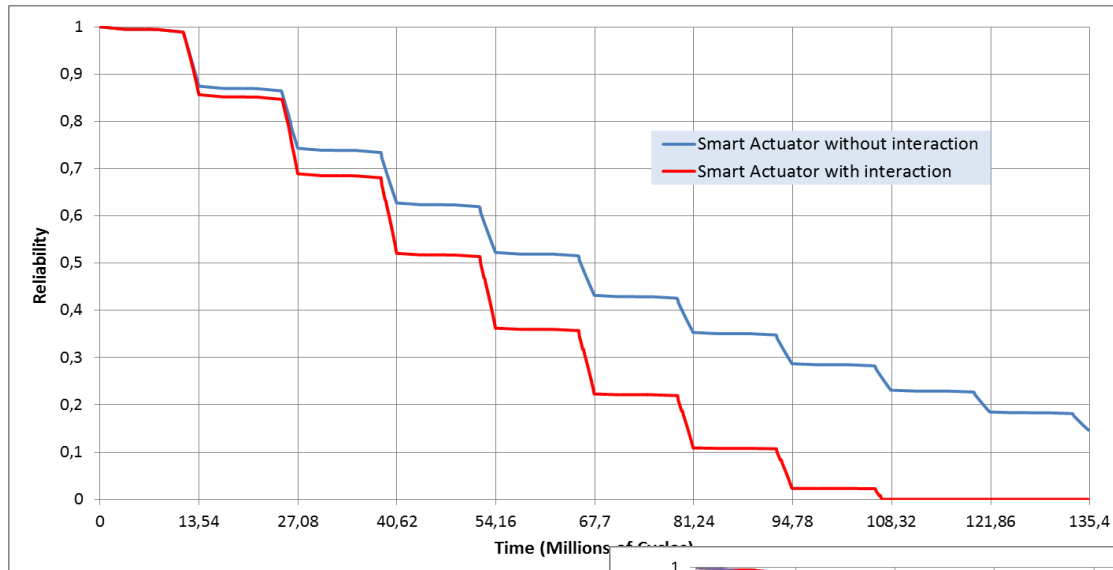
Reliability of the smart actuator phase/phase
without bearing/coil interaction

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



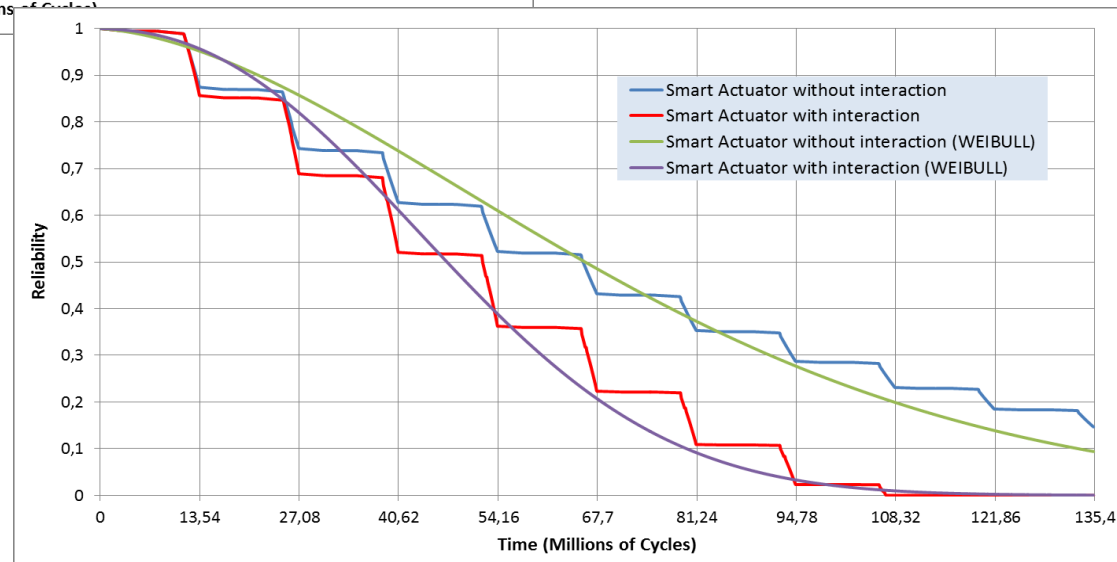
Results of reliability

Reliability of the smart actuator according to the mission profile



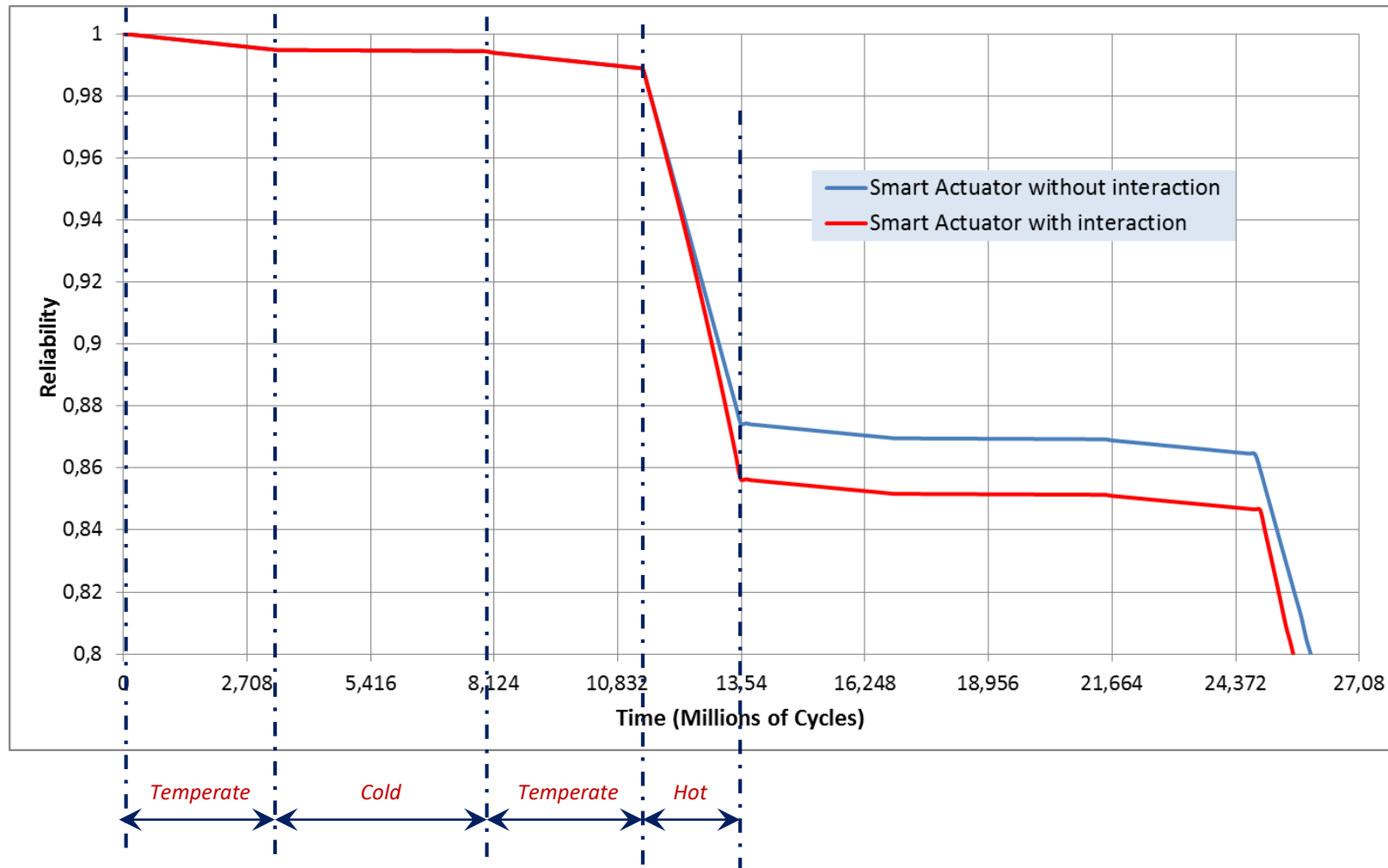
Reliability of the smart actuator **without**
and **with bearing/coil interaction**

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



Results of reliability

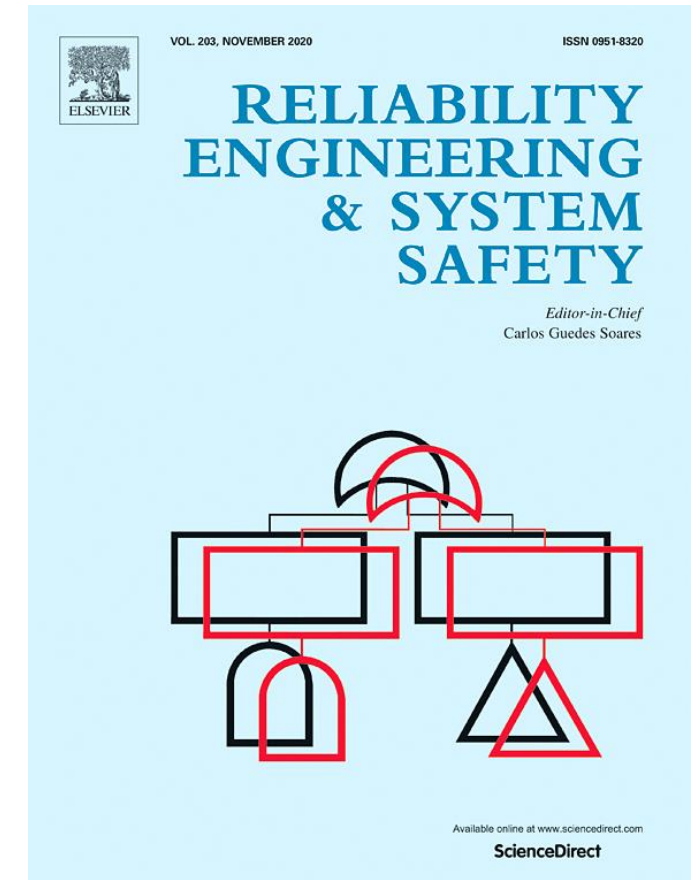
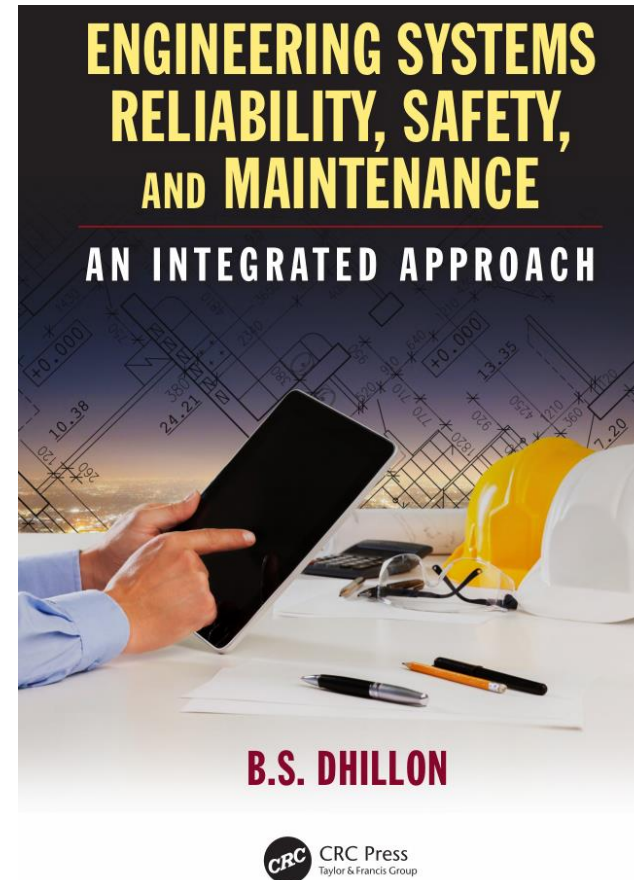
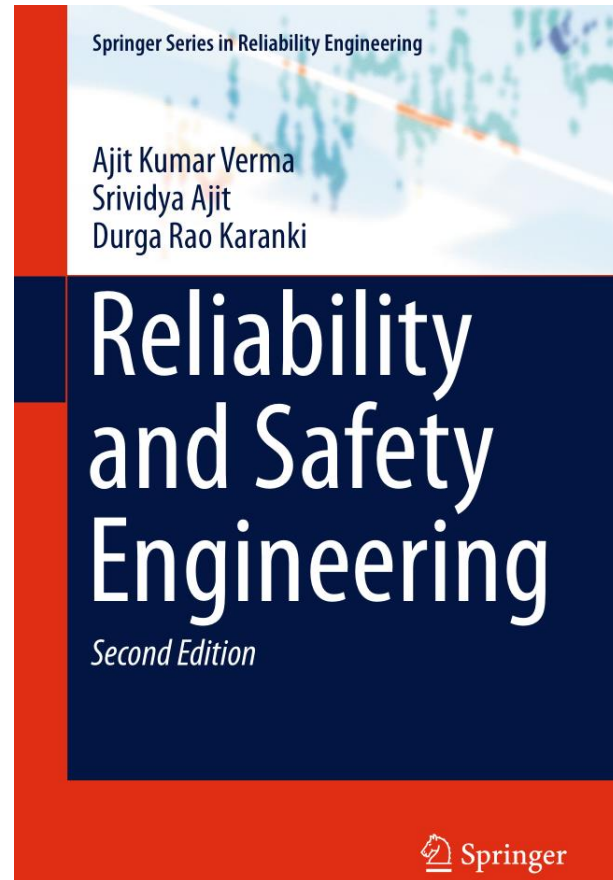
Reliability of the smart actuator according to the mission profile (one-year zoom)



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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