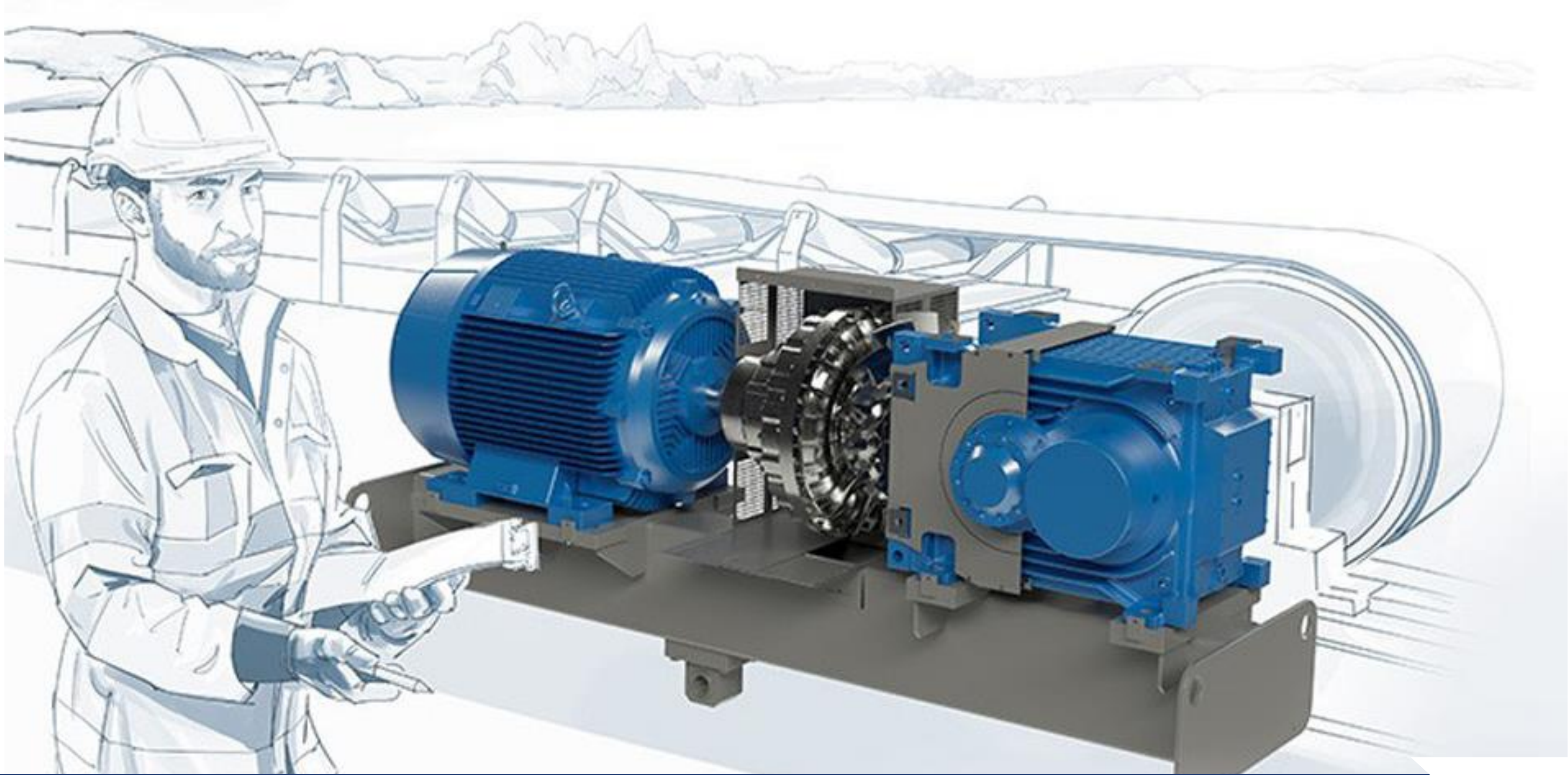


2024

MCTR 701_1
Master Advanced Mechatronics

Lecturers : Luc Marechal, Christine Barthod, Georges Habchi

UNIVERSITÉ SAVOIE MONT BLANC
POLYTECH ANNECY-CHAMBÉRY
SYMME

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:

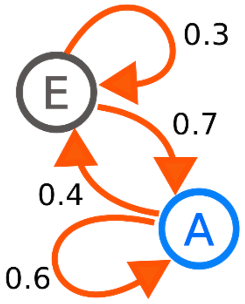
- the intrinsic characteristics of mechatronic systems
- the different components and functions of the system
- the relations between these components and functions
- the mission profile

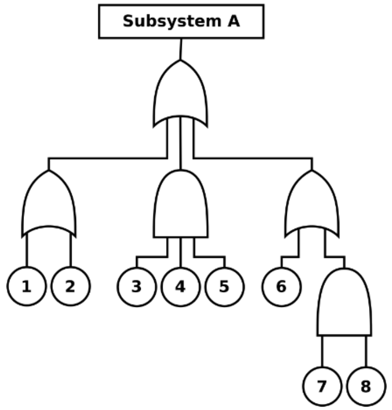
Innovative approach

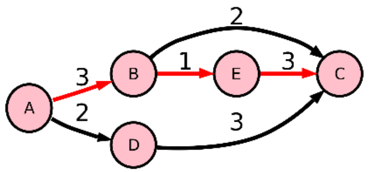
SYMME

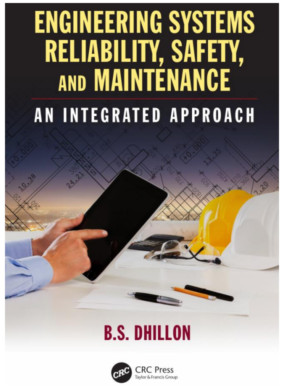
Methods for performing Reliability, Safety, and Maintenance Analysis

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









Engineering Systems Reliability, Safety, and Maintenance
An Integrated Approach, B.S. Dhillon

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

Reliability Engineering and System Safety

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

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

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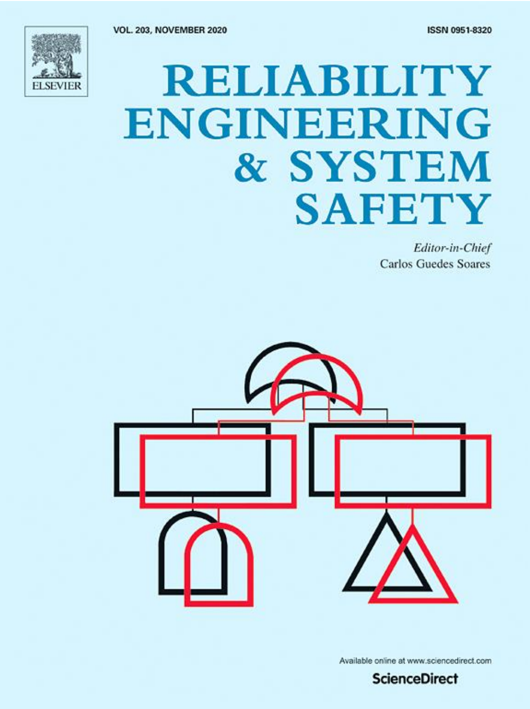
ABSTRACT

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.



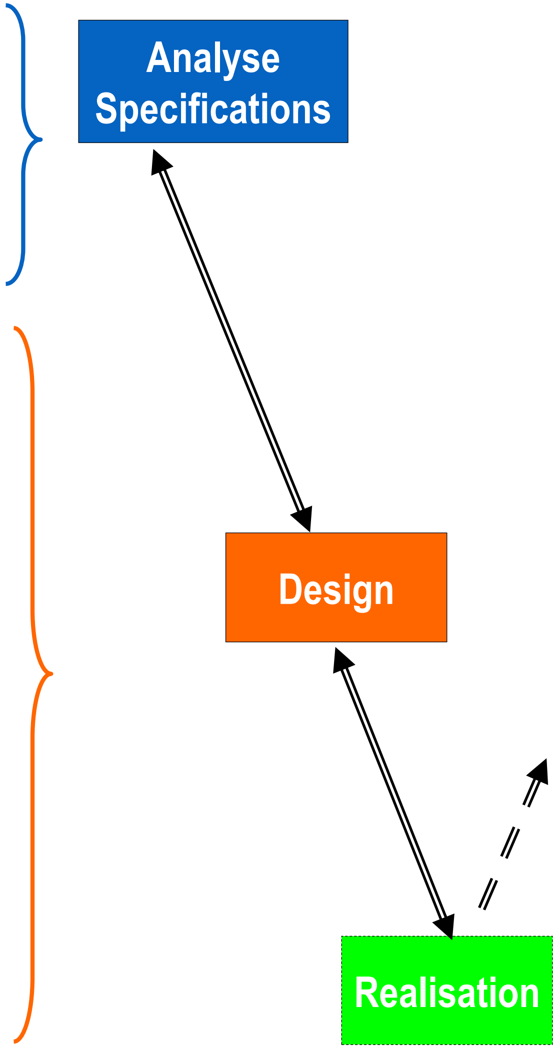
Proposed approach: 10 steps

Qualitative 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)

Quantitative analysis

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

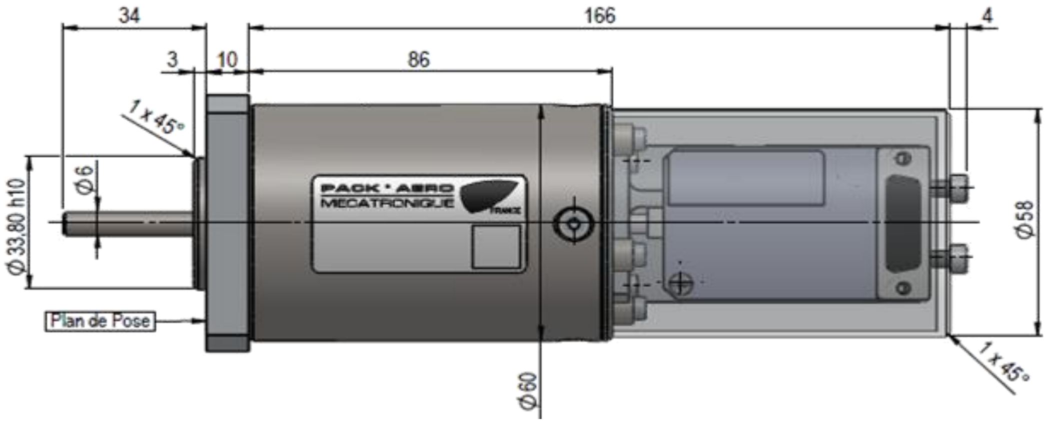


Preliminary steps to the implementation of the approach

- 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

PACK'AERO MÉCATRONIQUE

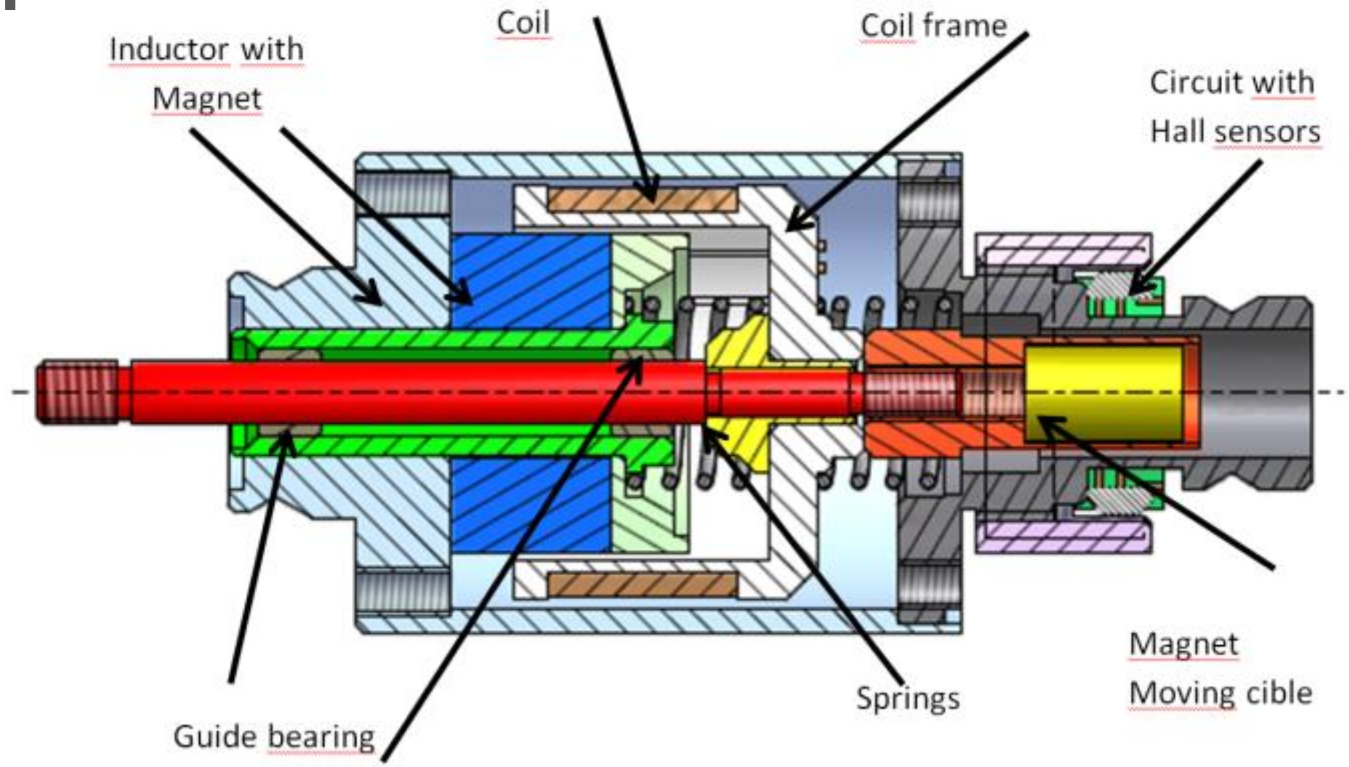
- **Specifications**

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

PACK'AERO MÉCATRONIQUE



Physical implementation
of the circuit board

1. External functional analysis

INPUTS

- System requirements specification
- Objectives
- Mission profile

1. External *Functional* Analysis

OUTPUTS

- Main functions and constraints
- Interactions between the system and its environment

Describes:

- The expected funtion for **each phasis of the profile**
- The reactive functions to take into account the environment
- The **contraints** 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

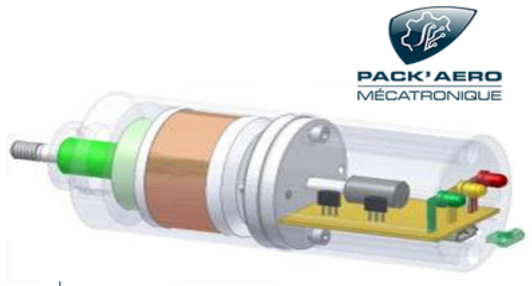
The intended use and environment of a system must be accurately stated in order to realistically measure Reliability.

Mission profiles is an effective tool for that purpose

Mission profile

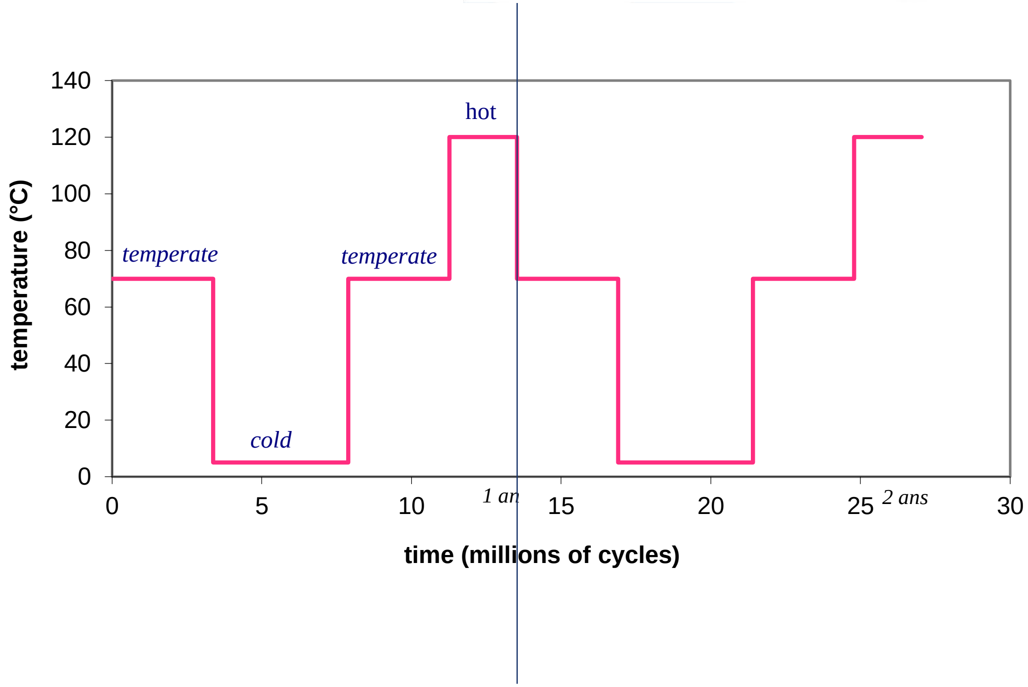
- The mission profile will be taken into account in the estimation of the predictive reliability.

Example of a mission profile for the actuator

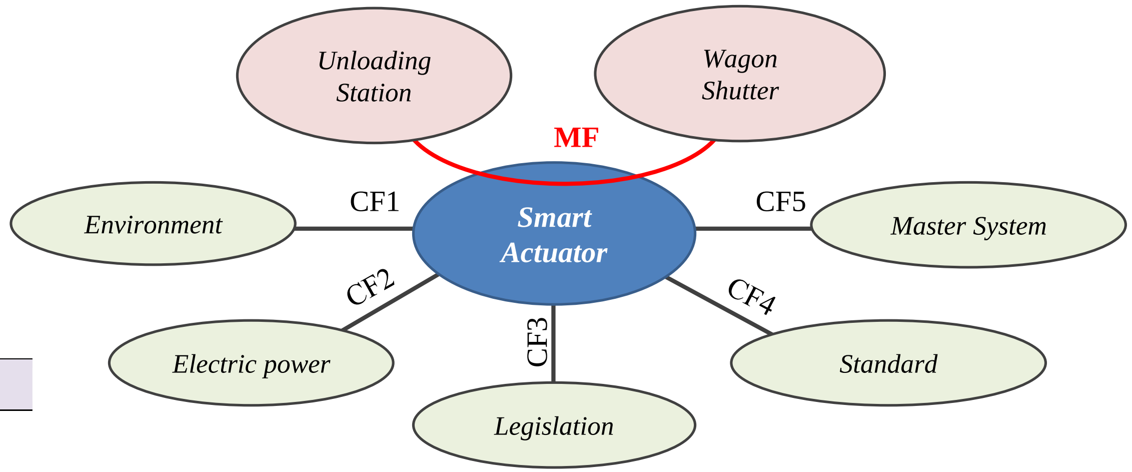


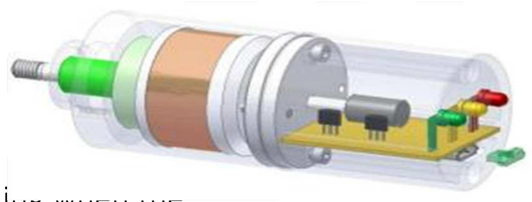
- An influent factor : temperature

- 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* *Temperature and duration of the cold phase* *Temperature and duration of the temperate phase*	*120°C for 2/12 of cycles* *5°C for 4/12 of cycles* *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

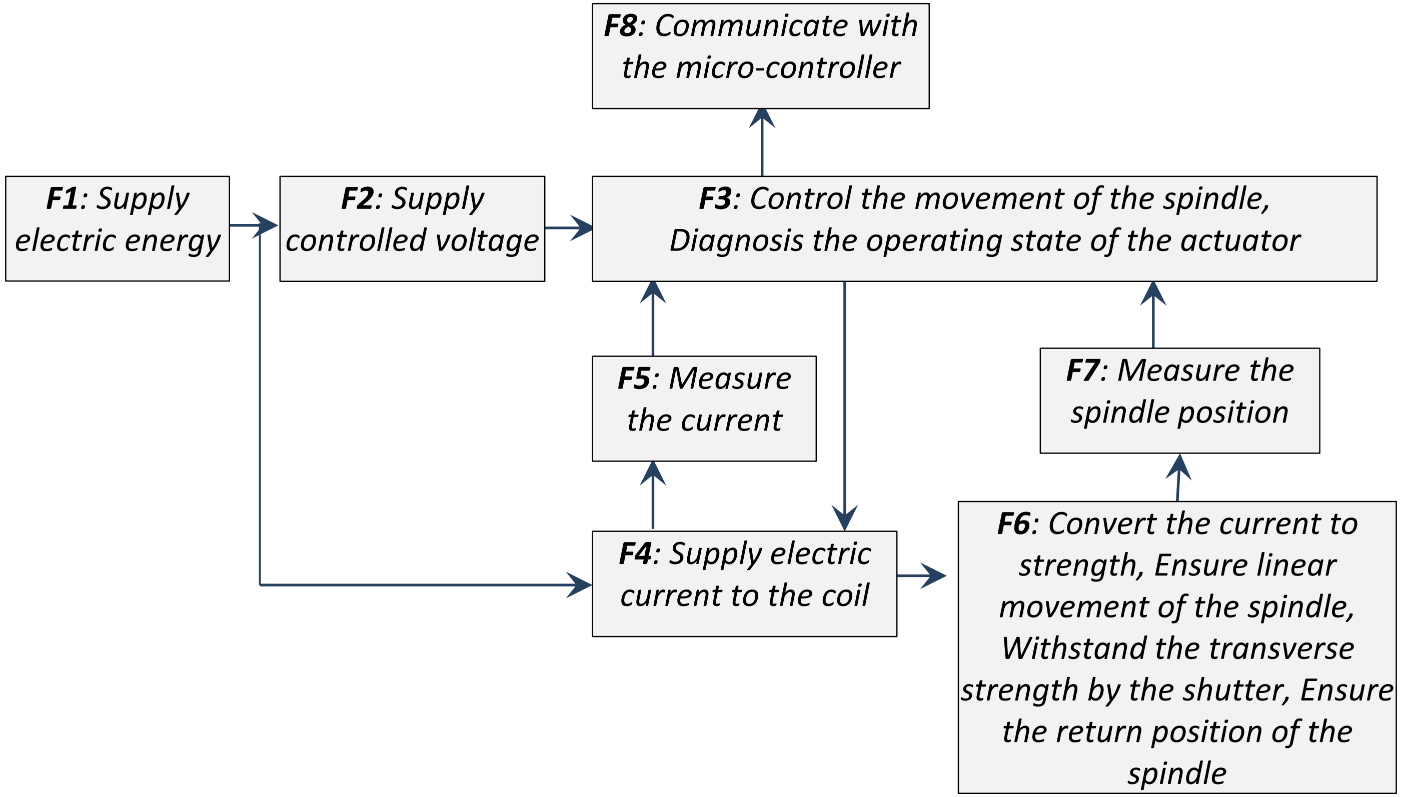
- establishes relationships between the external functional analysis and **possible solutions** to meet the need.
- allows the definition of the functions identified into **internal technical functions**

➔ 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.

PACK'AERO MÉCATRONIQUE



3. Organic Analysis

INPUTS

⇔
To I/O of the internal functional analysis

↓

3. *Organic Analysis*

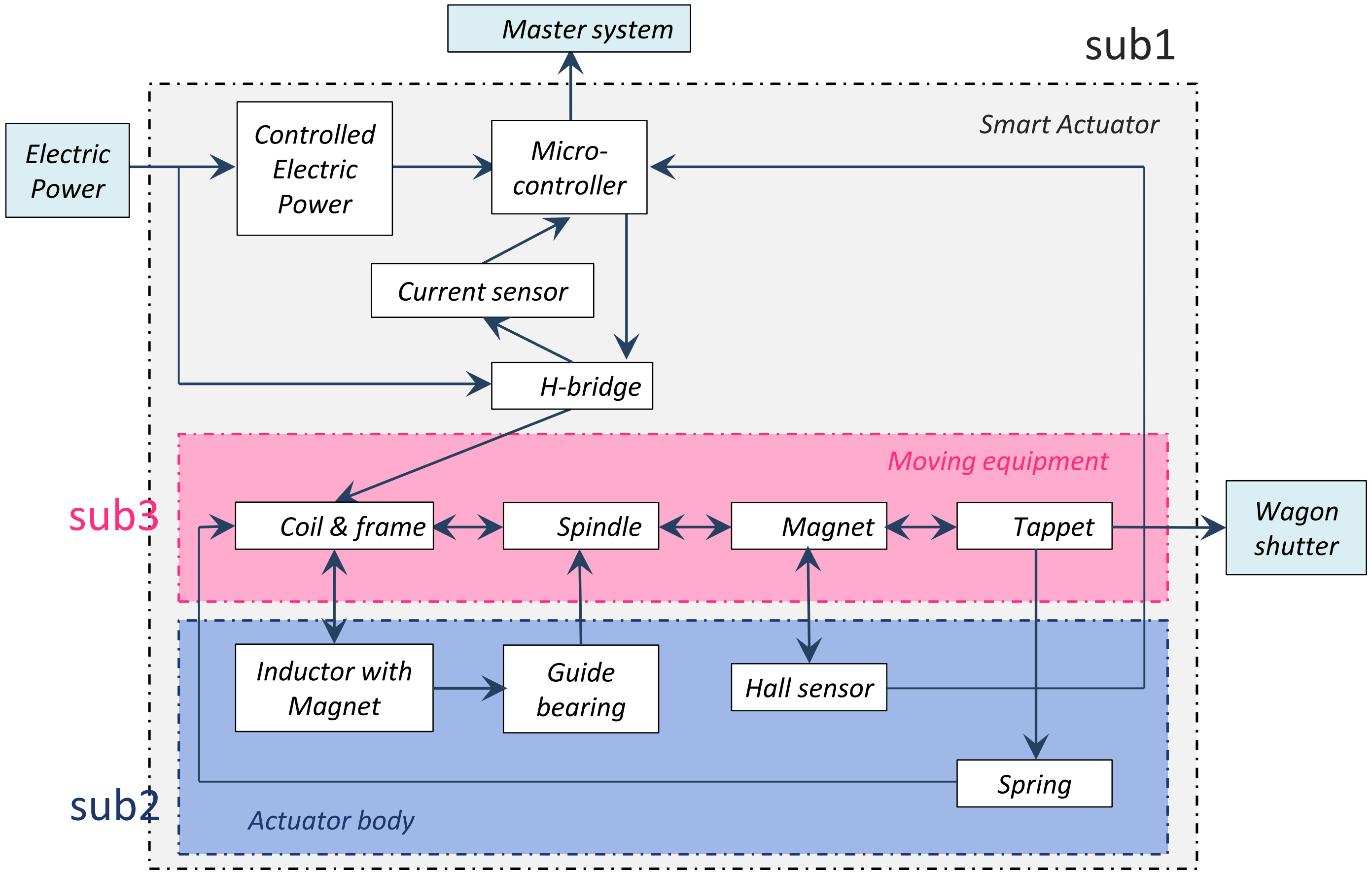
↓

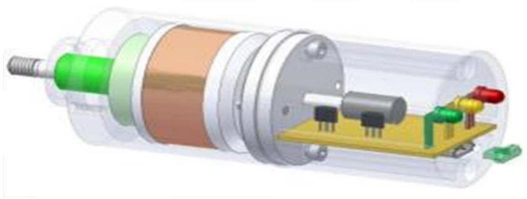
Outputs

- System decomposition into subsystems & components,
- Interactions between the components, Interfaces

- 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. Dysfonctional Analysis

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

↓

5. Dysfunctional *analysis*

↓

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

- 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	- 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

IMPUTS

- FMEA 's outputs

6. Dependancy analysis of *interactions*

OUTPUTS

- Interactions matrix
- Interactions effects
- laws of variation of the reliability parameters
- Interactions to be taken into account in the model

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

ENTREES

- System internal functions
- Interactions between the system and its environment
- System architecture
- FMEA

7. Qualitative Modeling

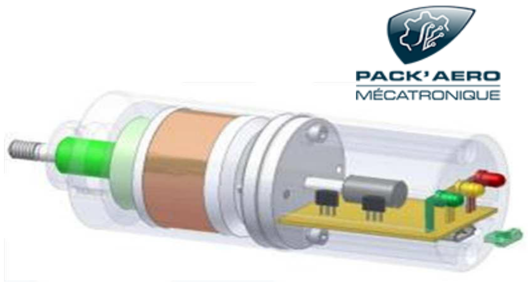
SORTIES

- Functional & dysfunctional models of components, sub-systems and system

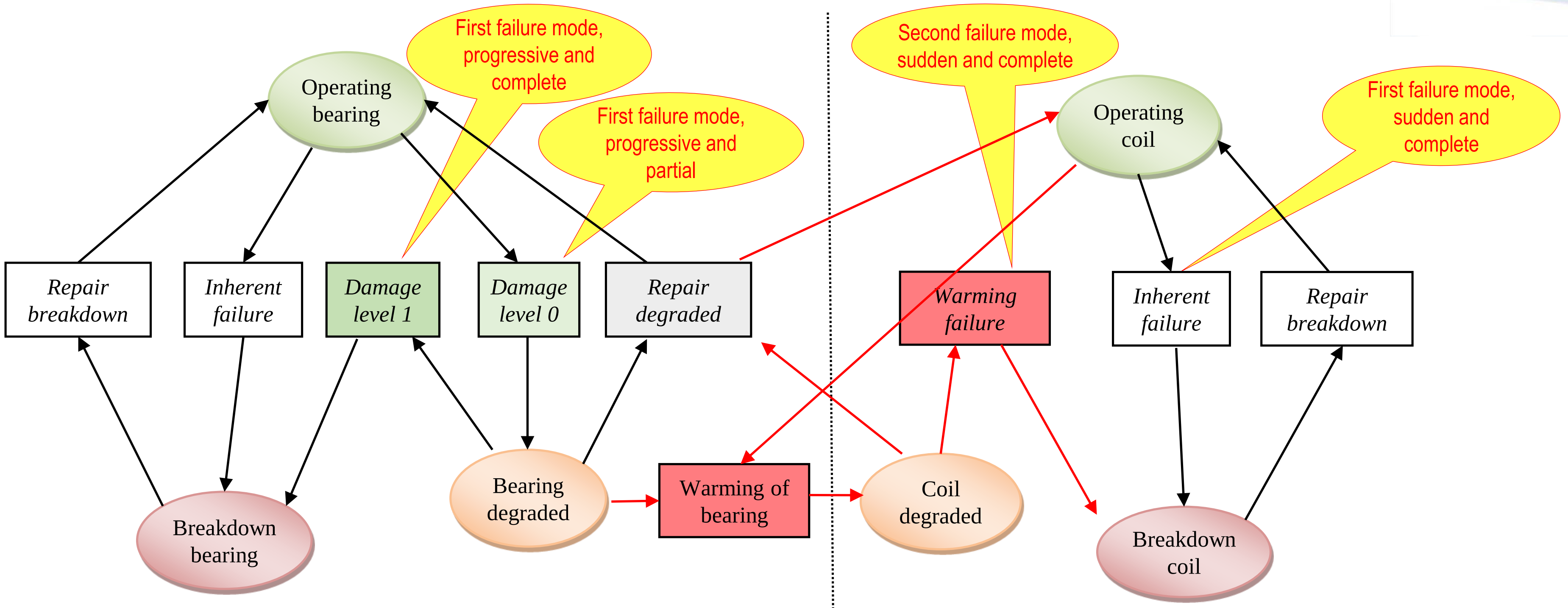
Models the functional and dysfunctional behavior of the system and its components, taking into account the interactions

- **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 componants: 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

INPUTS

- Mission profile
- Internal functions
- Components
- Interactions between components and between functions
- Interactions between the system and its environment

8. Data Gathering & Processing

OUTPUTS

- Reliability distributions of the components or internal functions
- Parameters value
- Evolution laws of parameters vs influence factors
- Evolution laws of parameters vs interactions

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	• Distribution are known for few standard elements • To find for most of specific components	Weibull : ▪ 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*

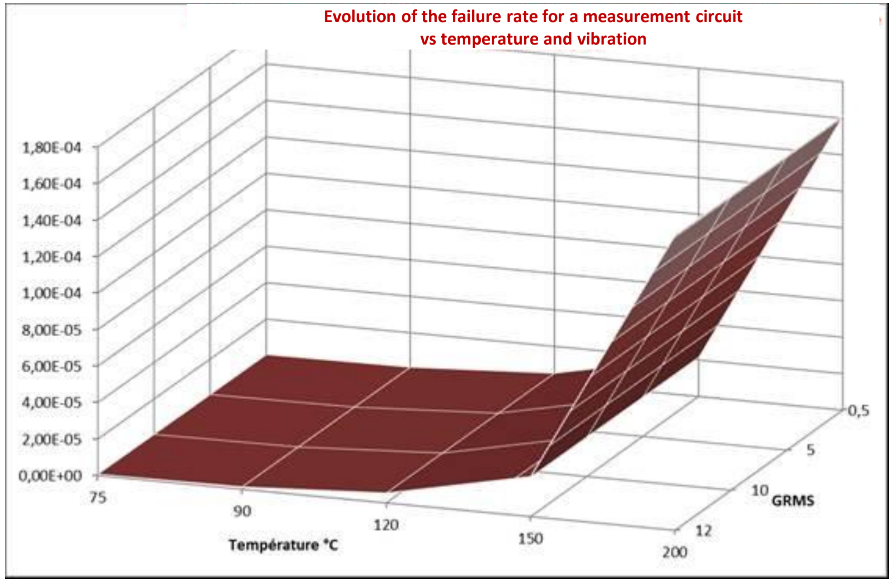
Taking into account the influent factors of the mission profile on FIDES

Two **influent factors** considered:

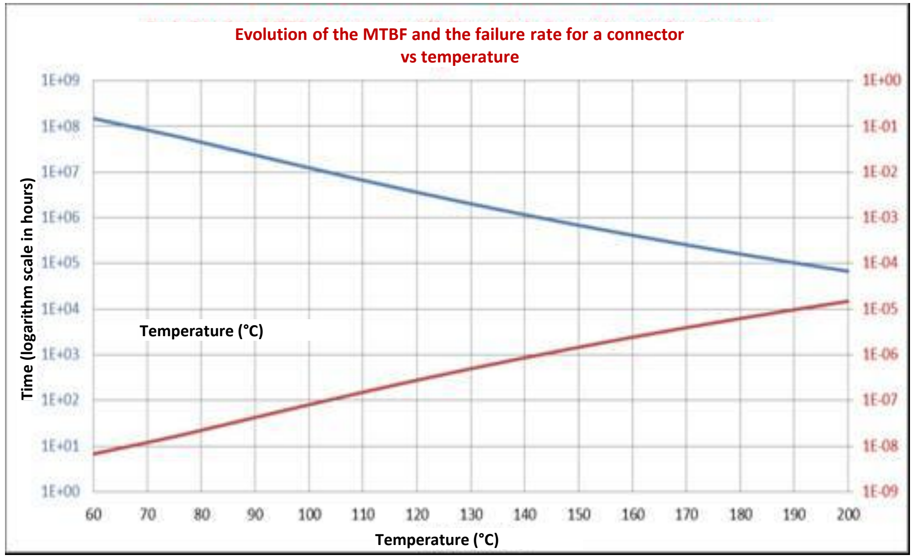
- *Temperature*
- *Vibration*

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

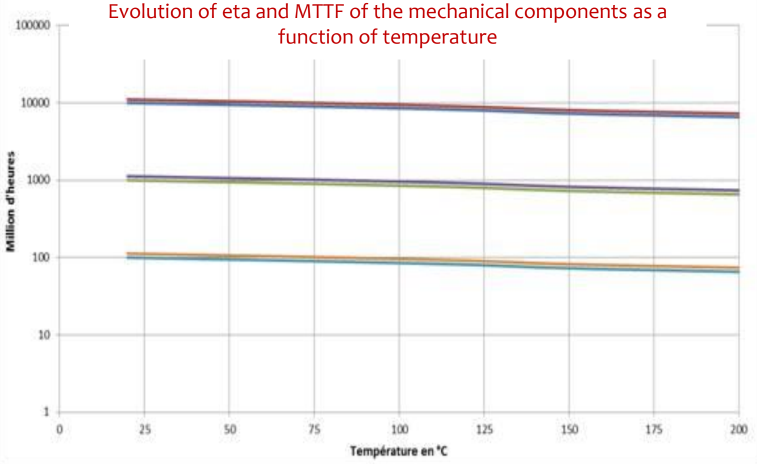
NTN SNR



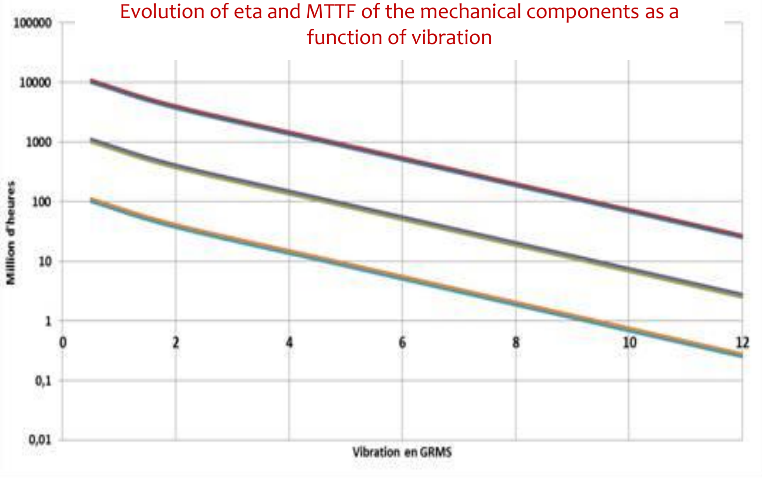
Influence of the ***temperature***



Influence of the environment on the degradation of mechanical components

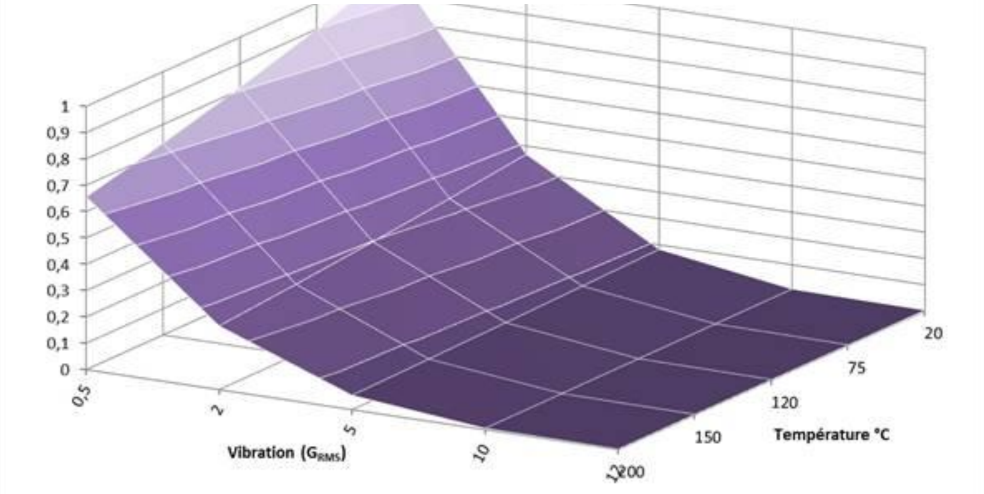


Evolution of eta and MTTF of the mechanical components as a function of temperature



Evolution of eta and MTTF of the mechanical components as a function of vibration

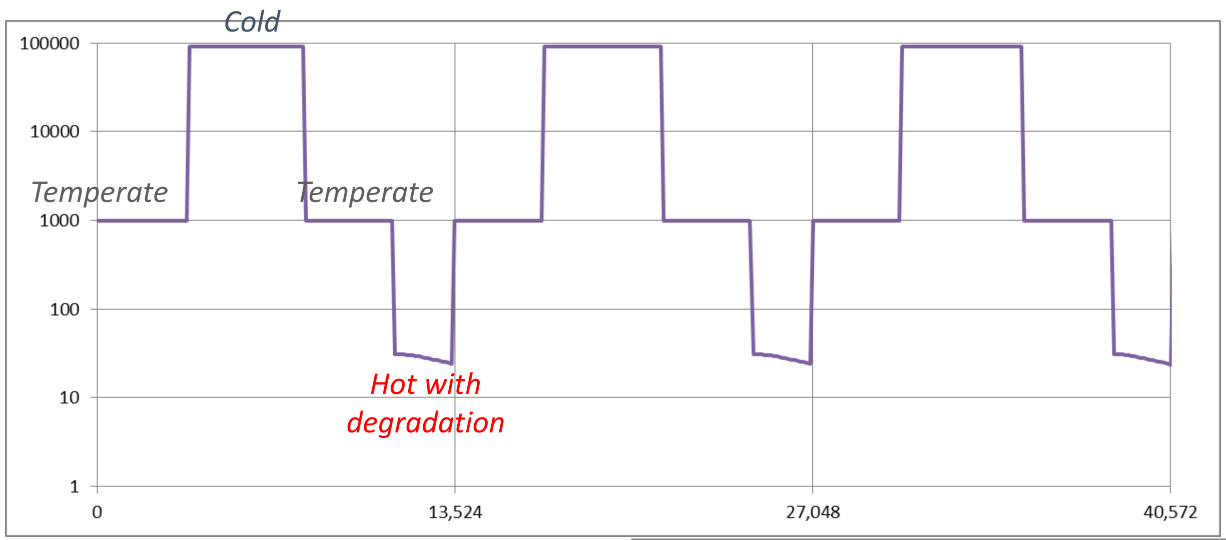
- Law and values of the parameters chosen according to the experience of the manufacturer in the field of reliability (tests, feedback)
- Proposed evolution of parameters as a function of temperature and vibration



Evolution of the reduction coefficient of the parameters of reliability of the mechanical components

NTN SNR

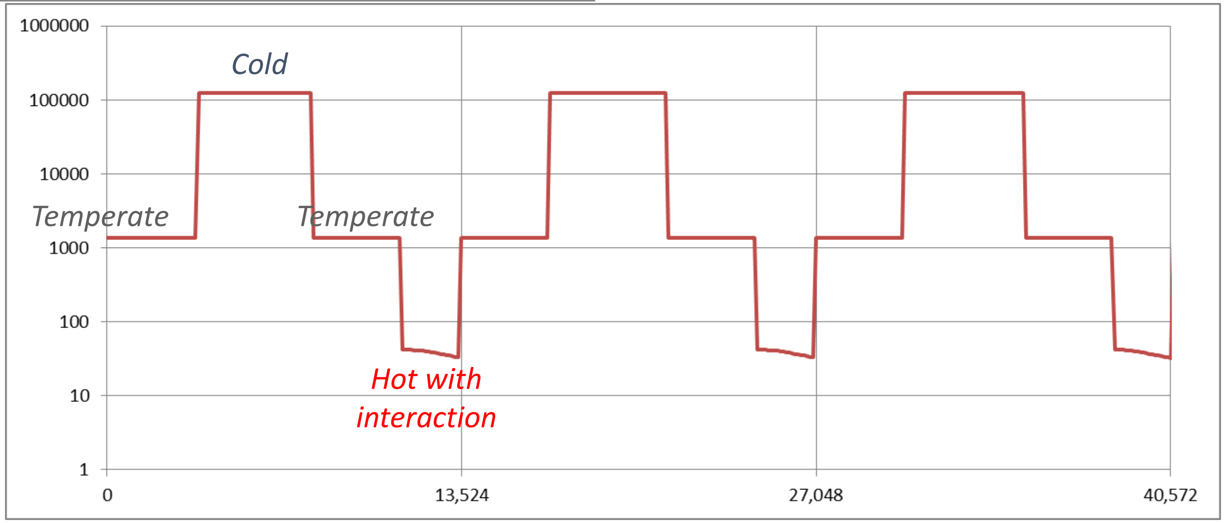
Influence of the mission profile on the parameters of reliability in the presence of interaction



PACK'AERO MÉCATRONIQUE

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

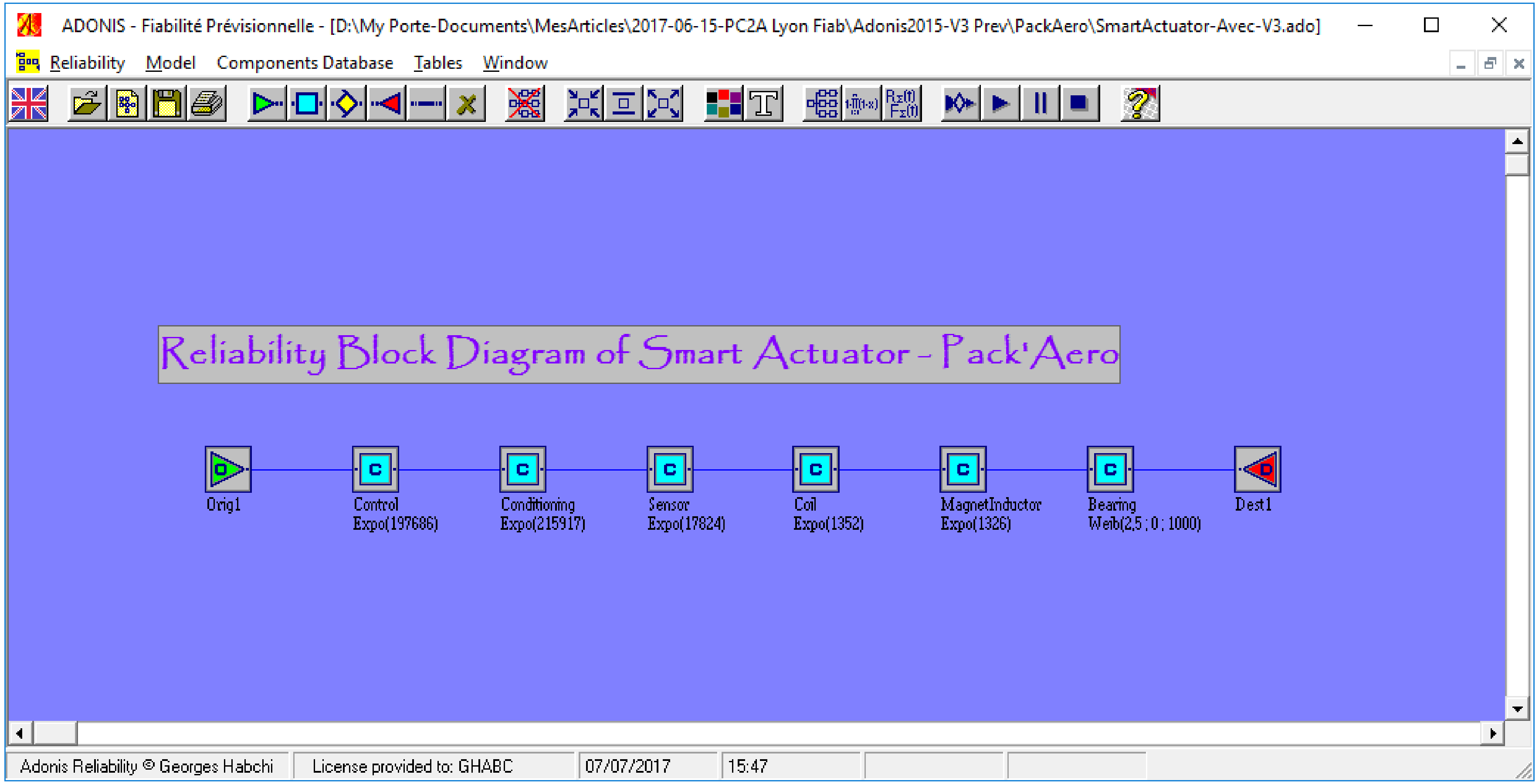
Implements the reliability models according to the chosen method, taking into account inputs and outputs and provides reliability results

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

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

INPUTS

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

10. Analysis of Results

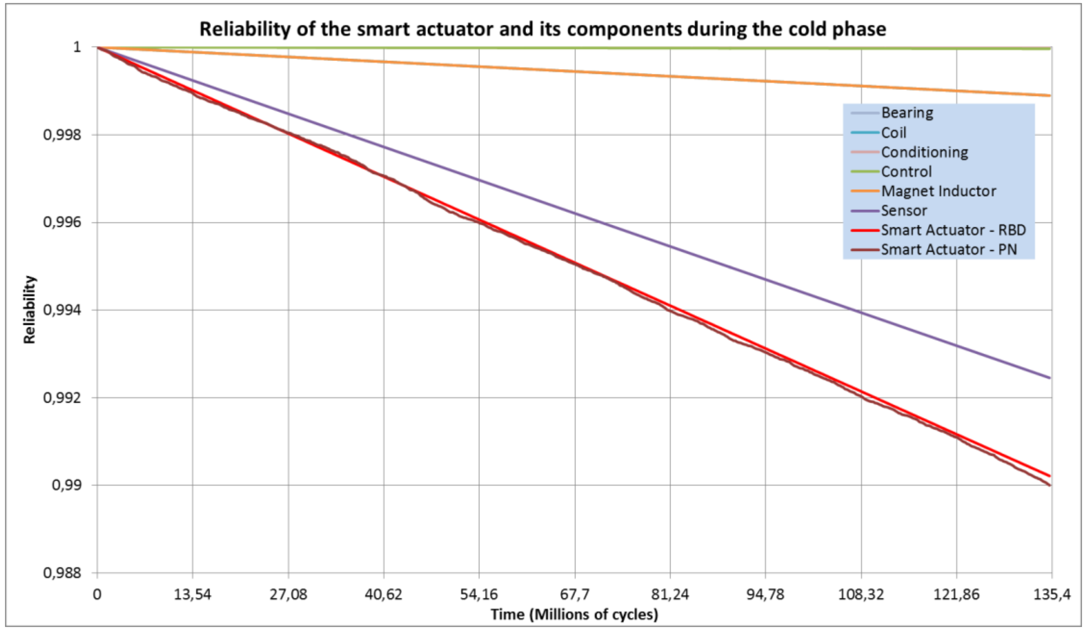
OUTPUTS

- 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

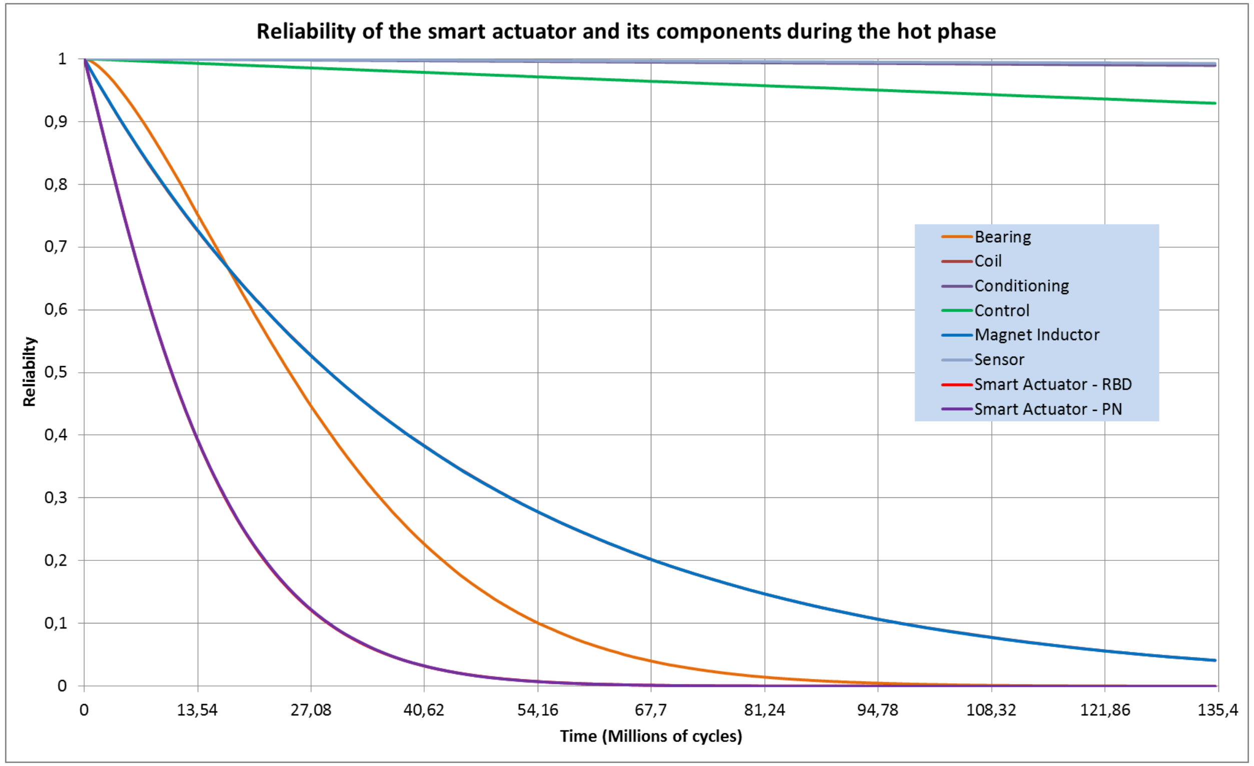
1. Evaluates the components and system reliability against targets
2. Evaluates the effect of influencing factors and interactions
3. Targets Critical Components
4. Proposes conclusions and improvement actions

Results of reliability

Reliability of the smart actuator and components phase/phase



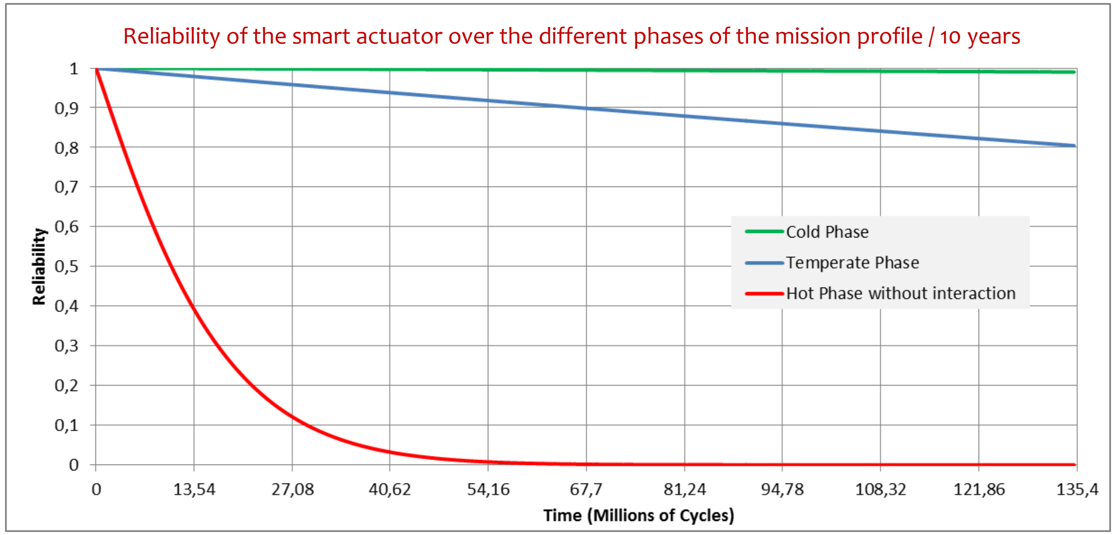
Reliability of the smart actuator and its components for the "**cold**" phase without bearing/coil interaction



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

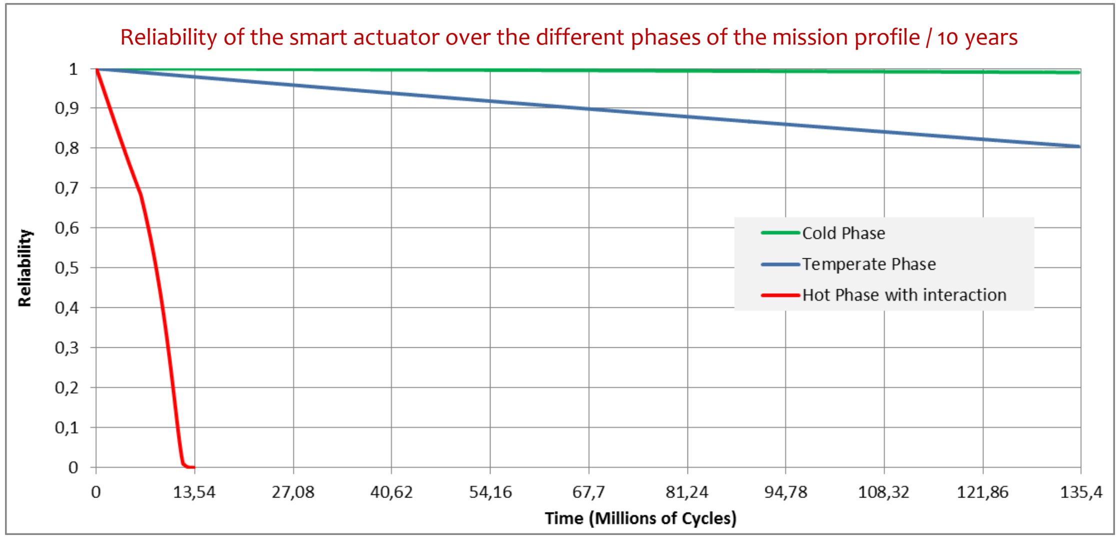
Results of reliability

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



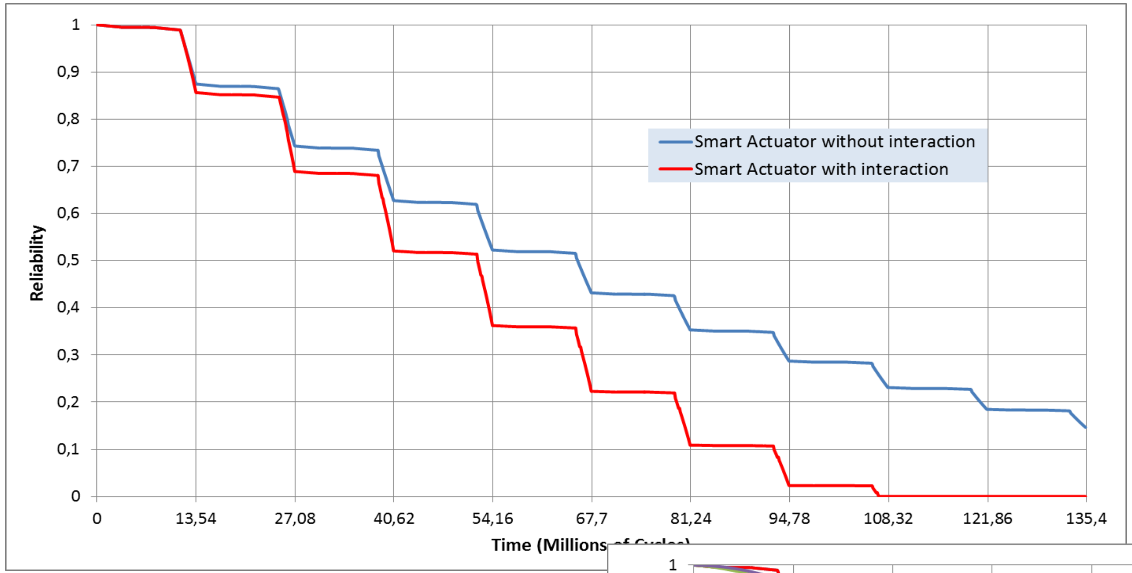
Reliability of the smart actuator phase/phase
without bearing/coil interaction

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



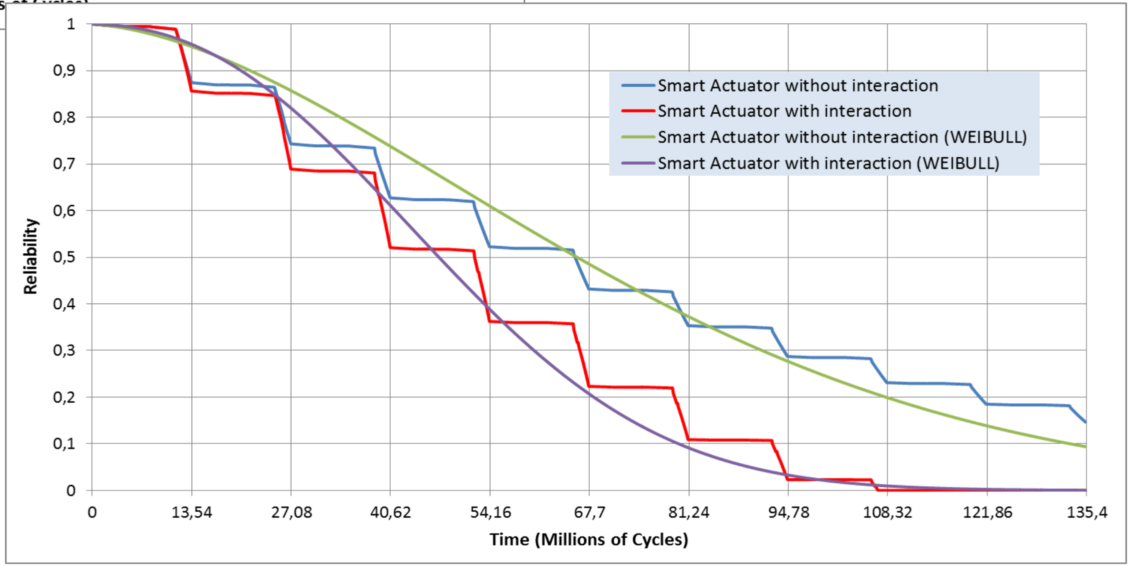
Results of reliability

Reliability of the smart actuator according to the mission profile



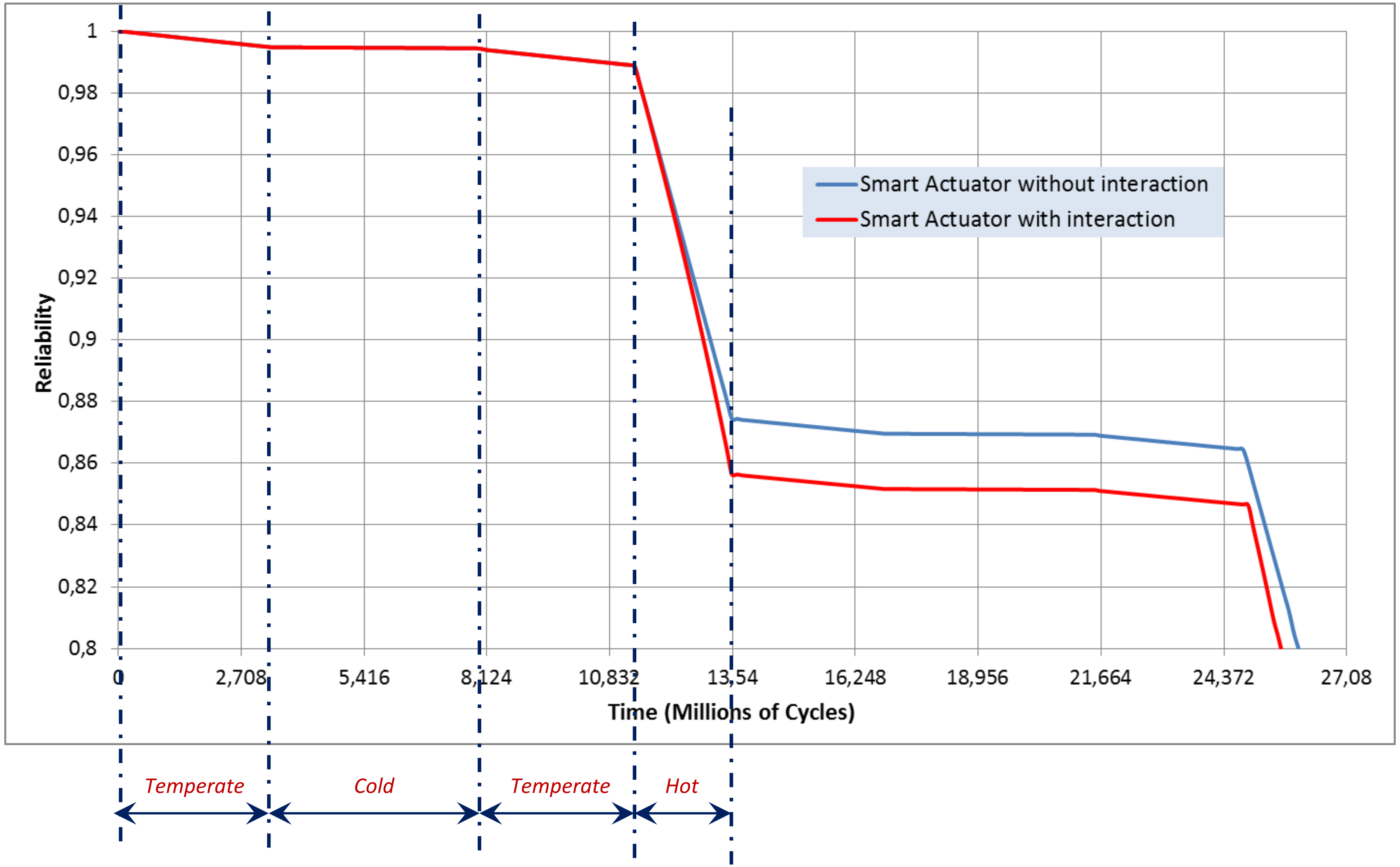
Reliability of the smart actuator **without** and **with bearing/coil interaction**

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



Results of reliability

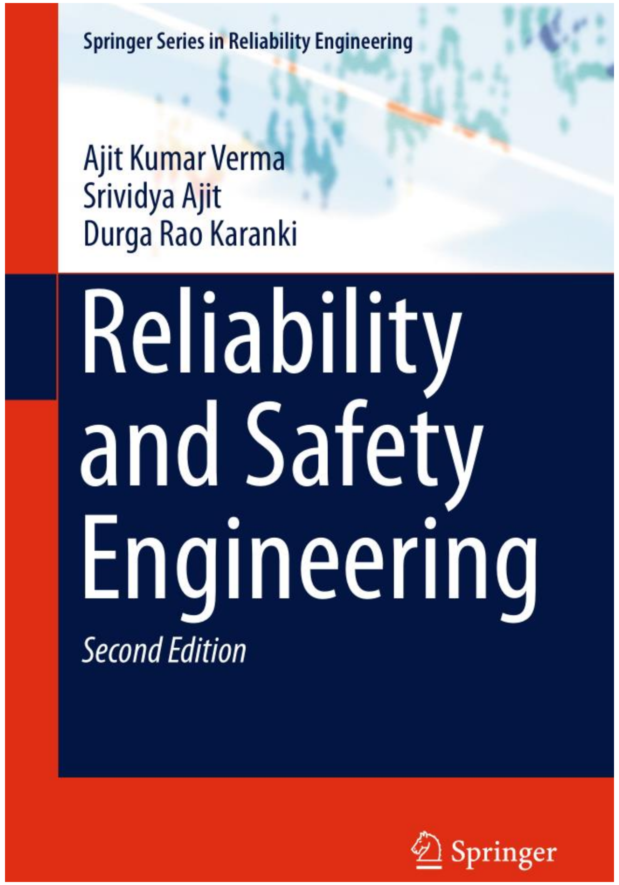
Reliability of the smart actuator according to the mission profile (one-year zoom)

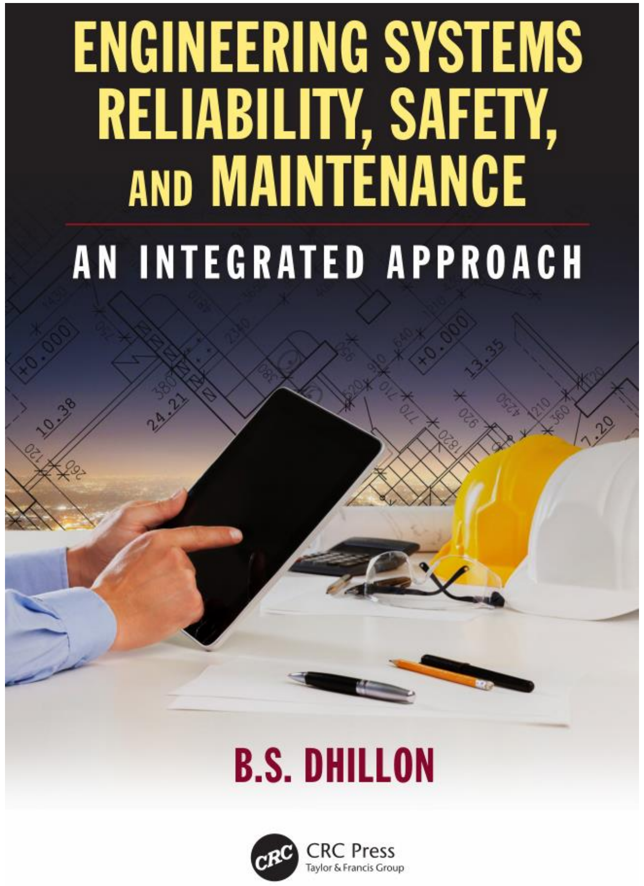


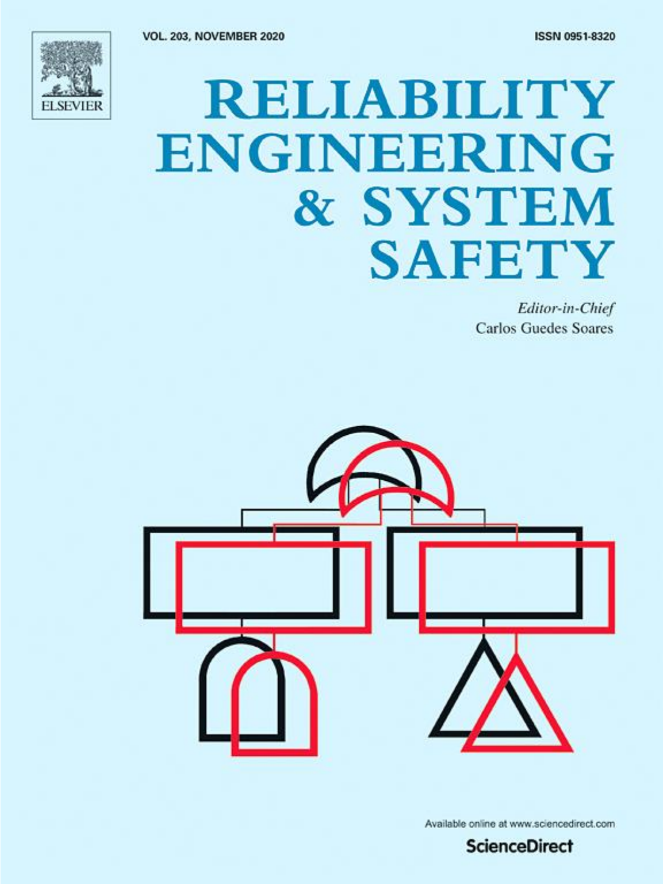
Conclusions

- 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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