Prognostics and Health Management (PHM)

Integrated Approach for the PHM of Complex Systems – Application to Aircraft Engines

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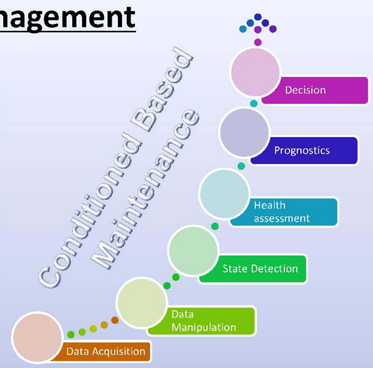
General Background

➔Prognostic and Health Management

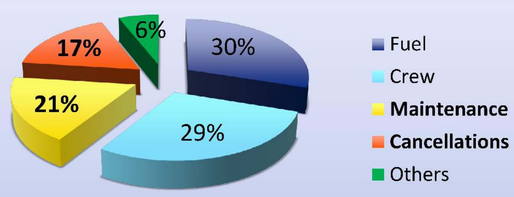
What? Detection, Diagnostics and Prognostics of a system health status by the monitoring of relevant variables named Health Indicators

Why? To perform a continuous assessment of the system and increase its availability

How? By using PHM to implement advanced maintenance strategies such as Conditioned Based Maintenance (CBM)



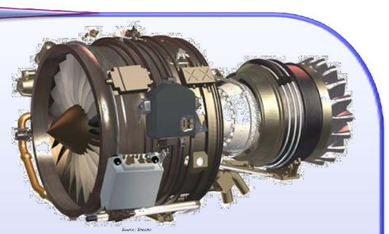
Main Purpose : Reduction of maintenance-related costs

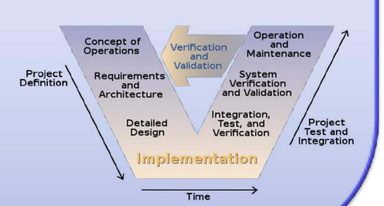


Tool: Prognostic and Health Management

➔Main Issues:

1. PHM System Development Framework
2. PHM System Design
3. PHM System Validation
4. Health Indicators Construction
5. Health Indicators Validation
6. Mathematical Methods and Tools



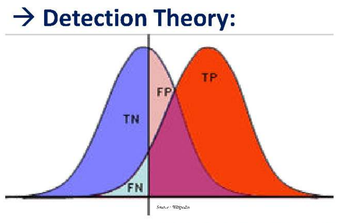


Integrated PHM

1/ Extraction Part – Upstream Stage

- **When?** Before the system implementation
- **What?** - Health Indicators Definition and Validation
  - Extraction Algorithms Coding
- **How?** By using Numerical KPI for validation

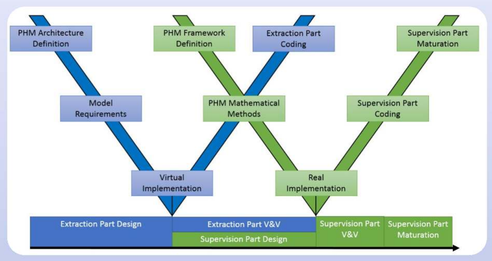
→ **Detection Theory:**



Name	Definition
TN: True Negative	The system is healthy and there is no detection → Good Result
FN: False Negative	The system is faulty and there is no detection → Bad Result: no detection
TP: True Positive	The system is faulty and there is detection → Good Result
FP: False Positive	The system is Healthy and there is detection → Bad Result: false alarm

→ **NO DATA FOR THE VALIDATION**

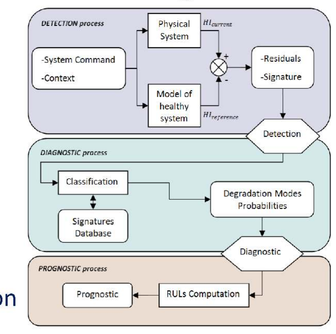
New Proposal: Integrated PHM
To optimize PHM system capabilities at each stage of the development process



Central Concept: W-model

2/ Supervision Part – Downstream Stage

- **When?** After the system entry into service
- **What?**
  - PHM system Definition and Validation
  - Supervision Framework Coding
  - PHM Maturation
- **How?**
  - By using advanced mathematical tools for detection and identification and Operational KPI for validation



→ **LACK OF DEGRADED DATA FOR VALIDATION**

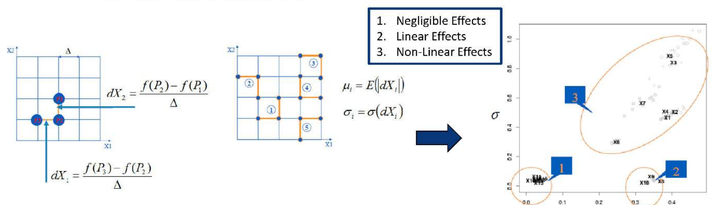
Modeling

Difficulty 1 : managing multiple parameters

→ Sensitivity Analysis for parameters prioritization

A. Morris Method

→ One at the time method



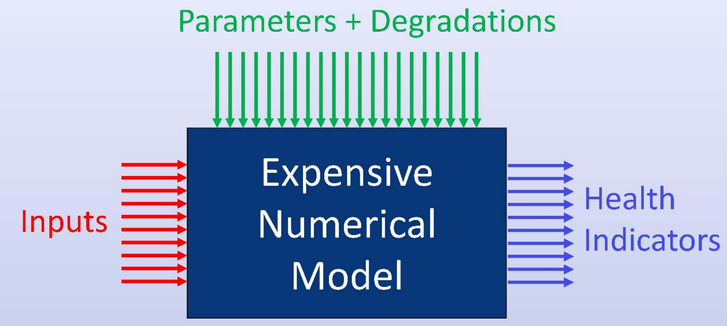
B. Sobol Indices

→ Based on Variance Decomposition

→ More precision but more simulations needed

$$S_i = \frac{\mathrm{Var}\left[\mathbb{E}\left(Y|X_i\right)\right]}{\mathrm{Var}(Y)} = \frac{V_i(Y)}{\mathrm{Var}(Y)}, \quad S_{ij} = \frac{V_{ij}(Y)}{\mathrm{Var}(Y)}, \quad S_{ijk} = \frac{V_{ijk}(Y)}{\mathrm{Var}(Y)}$$

Solution: Numerical Modeling
To create the data needed for the validation of the PHM Framework



Purpose: To simulate Health Indicators distributions with variations of Parameters and Degradations

Difficulty 2 : managing uncertainties

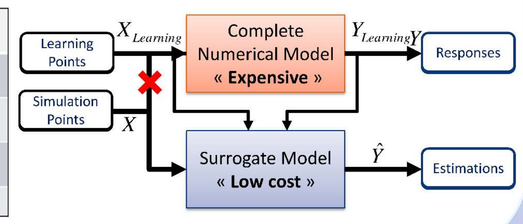
→ Uncertainties **Quantification** by expertise and experience feedback

→Uncertainties **Propagation** to introduces parameters variability into the model

A. Monte-Carlo Algorithm → too many simulations

B. Less expensive Method : **Surrogate Modeling**

1	Distribution of influential inputs
2	Choice of Surrogate Modeling
3	Learning base construction
4	Surrogate Model construction
5	Validation



Applications

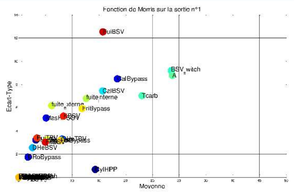
Surrogate Modeling

Sensitivity analysis: Morris Method

Surrogate Modeling: Latin Hypercube + Kriging

A. Sensitivity Analysis

- Morris Method
  → 220 simulations
- Originally 43 parameters
- Reduction to 20



B. Kriging

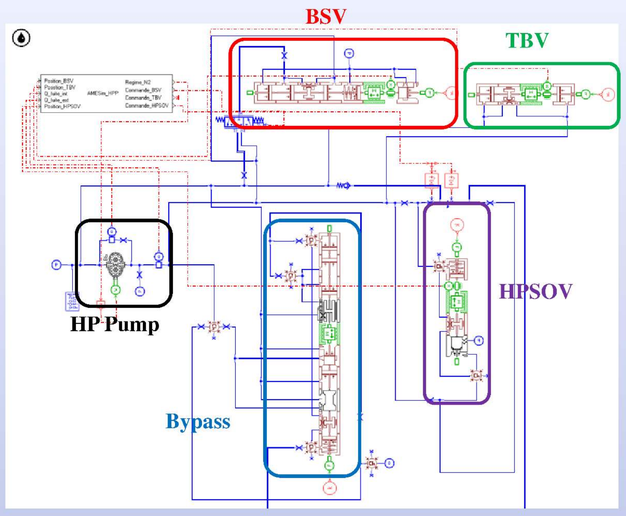
- Kriging Model : $Y(x) = f^T(x) \cdot b + Z(x)$
- $f^T(x) \cdot b$ regression model
- Z Gaussian process :
  > of mean zero
  > of covariance $\sigma^2 R(\theta, w, x)$
  > with R correlation function:

$$R(\theta, w, x) = \prod_{j=1}^{n} R_j(\theta, w_j - x_j)$$

Exponential correlation: $R_j(\theta, w_j - x_j) = \exp\left(-\theta_j \cdot |w_j - x_j|\right)$

Advantages of Kriging	
1	Best Unbiased Linear Predictor
2	Estimation of his own prediction error
3	Exact Interpolator on learning points

High Pressure Fuel Pump PHM



Software: Co-simulation AMESim/Matlab-Simulink

Numerical Key Performance Indicators

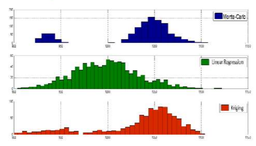
Health Indicator : Engine Rotation speed at BSV, TBV and HPSOV Opening → wBSV, wTBV and wHPSOV

Degradations : HP Pump Internal Leakage

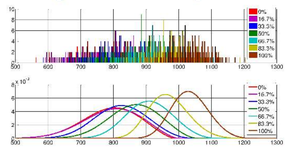
A. Health Indicators distributions

→ **Surrogate model** + Monte-Carlo simulations

Healthy state for wTBV

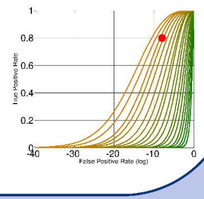


Growing size of internal leakage for wBSV



B. Numerical KPI:

- Based on semi-logarithmic ROC curves
- Common Criteria : TP > **0,8** & FP < **1e-8**
- Compliance Point (**CPt**) : (FP;TP)
- **NKPI** : Compliant Detectability $CDet =$
  $\begin{cases} 1 \; if \; the \; curve \; is \; above \; the \; CP \\ 0 \; if \; the \; curve \; is \; under \; the \; CP \end{cases}$



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