Incertitude et robustesse

Maîtrise des risques industriels: le point de vue de l'intégrateur de systèmes

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Outline of the presentation

1. Meaning of uncertainty in an industrial context
2. Presentation of some test-cases : mono disciplinary view, multi disciplinary view
3. Mathematical framework of the problem
4. Current initiatives around the subject : industrial community, research groups, open source initiatives, training

Engineering activities during the life cycle of a product

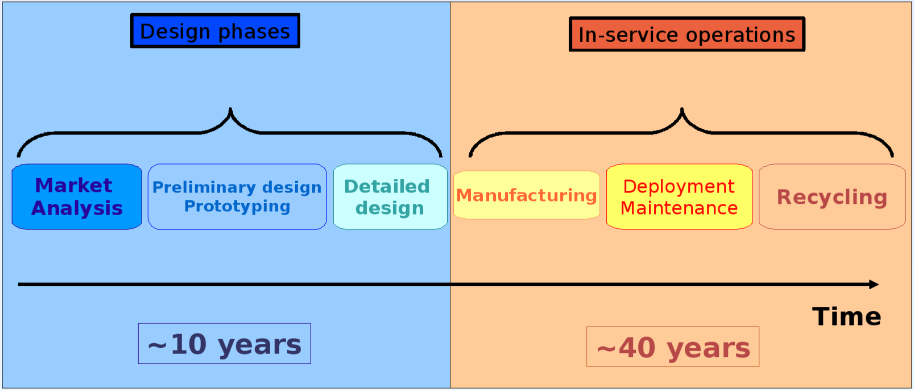
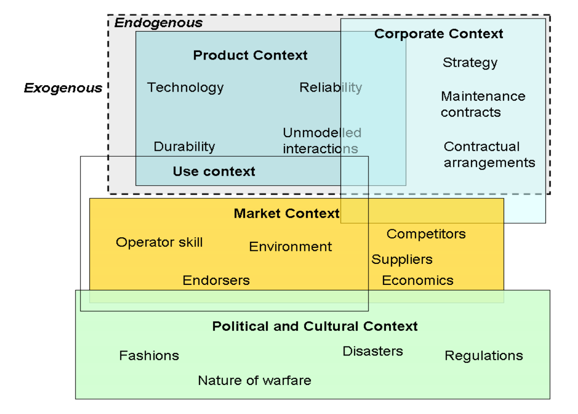


Fig.: Life-cycle of a product/service/utility

Links between uncertainties and industrial contexts



1. **Internal uncertainties** : Each product or system bears its own uncertainties with it, which arise primarily from the "inside". It can be influenced by the system designer or company to a certain extent.
2. **External uncertainties** : Uncertainties outside the system boundary can be influenced by the designers or company to a lesser extent.

Natures of uncertainty

Classical distinctions

- 'Irreducible'/'aleatory' *vs* 'reducible'/'epistemic'
- 'Variability' *vs* 'uncertainty'
- 'Epistemic uncertainty' *vs* 'error'
- 'Parametric uncertainty' *vs* 'model uncertainty'

From a practitioner point of view

- For many there is a clear distinction to be made between uncertainty which is **irreducible or reducible in the light of an increase of data/knowledge**.
- However, it is generally necessary in practice further to distinguish uncertainties that are theoretically reducible from those that are industrially irreducible because of operational or economic constraints, data scarcity or modelling limitations.
- For practitioners, the **reducibility** issue may therefore be more of a context-dependant feature or even of a modelling choice.

New opportunities to improve procedures and practices around uncertainty management

1. Recent conceptual reformulation : **shift from "failure-driven risk approach" to "option-exploring approach"** in uncertainty management.
2. Recognition that **the performance of an engineered system has to be taken into account in its larger commercial and political environment** :
   - To bullet-proof design against technical and human failure
   - To enable the system to evolve to new circumstances
3. **New advances in information technology** (development of models, acquisition of computer, etc) make it possible to conceive of a much more coherent uncertainty management approach.

Popular concepts

Robust design

1. It encompasses a set of design methods for improving the consistency of system function across a wide range of conditions.
2. The basic practice is to introduce noise factors in experiments so that systems can be made less sensitive to variations in customer-use conditions and internal degradations.

Real option analysis

1. Analogy between the analysis of a stock market by *Option Analysis* and a the analysis of technical solutions during a design cycle.
2. The goal is to compute the flexibility of a design, similarly to the 'volatility' of a market.

Time scale and uncertainty management strategies

Short-term

These decisions concern immediate issues. Being limited to the available data and pre-existing models, the objective is to treat the existing information to aid the decision-maker.

Mid-term

Unlike short-term decisions, these involve situations in which a support is conceivable, such as the development of refined models or collection of additional data to improve the understanding of the global phenomenon.

Long-term

These concern long-term issues, including the influence of societal, political and market evolutions.

Scope of the rest of the presentation

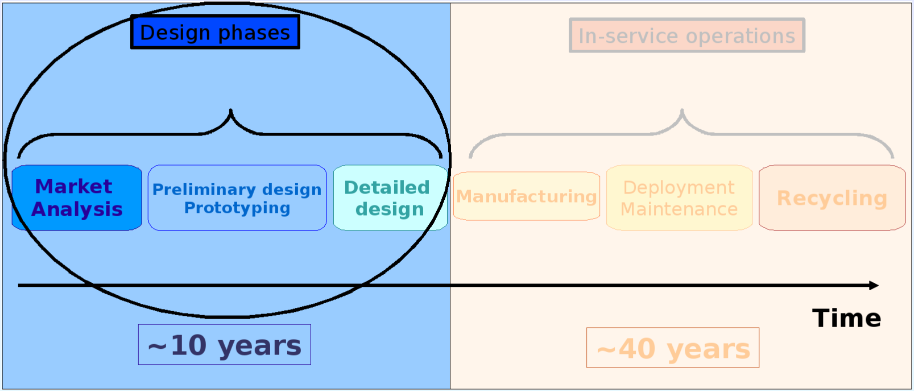
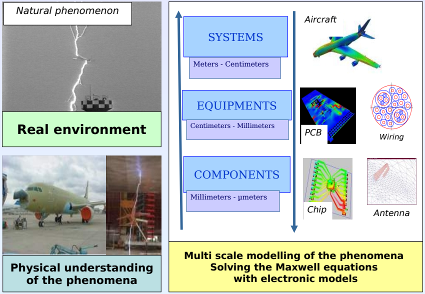


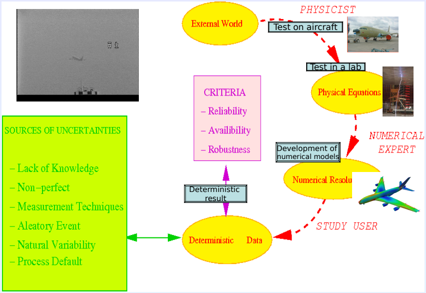
Fig.: Design phases

Mathematical Formalization

$$t \in \mathbb{T} = [0, T]$$

Electromagnetic Compatibility in design phases





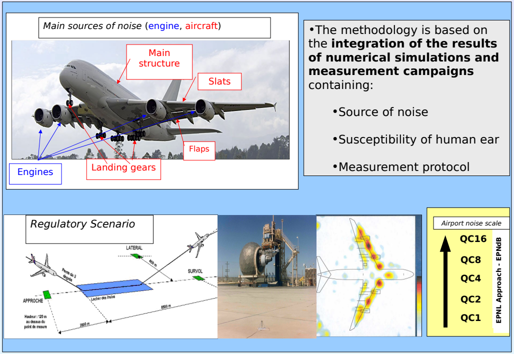
Sources of uncertainty during design

- The variability is due to some electrical parameters (composite materials, electrical junction, installation parameters).
- The lack of knowledge of the detailed behaviour of some electronic equipments (PCB, chips, ...).

Robust analysis

- To ensure the functional requirements by mastering of the current paths,
- To optimize the electromagnetic protection strategy.

Guarantee of an acoustic performance towards environmental standards



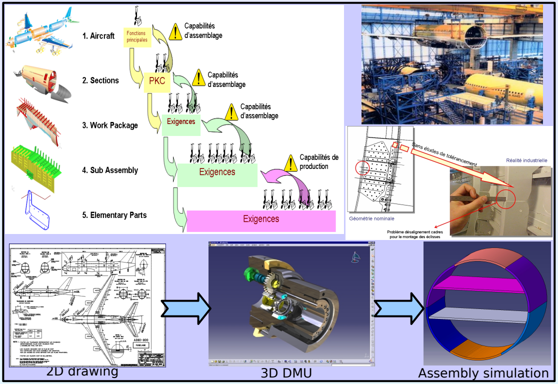
Sources of uncertainty during design

- The lack of knowledge / variability of the main characteristics of the aircraft (engine, aero brakes, ...)

Robust analysis

- To anticipate the fulfillment of the regulatory/commercial standards of the aircaft
- To optimize the use of active control as soon as possible in the design phases

Statistical tolerancing for manufacturing puposes



Sources of uncertainty during manufacturing

- Variability of the manufacturing process in the assembly line.

Robust analysis

- To define tolerancing intervals taking into account the variability of the process
- To manage the manufacturing capabilities (6-σ quality management)

An architect view

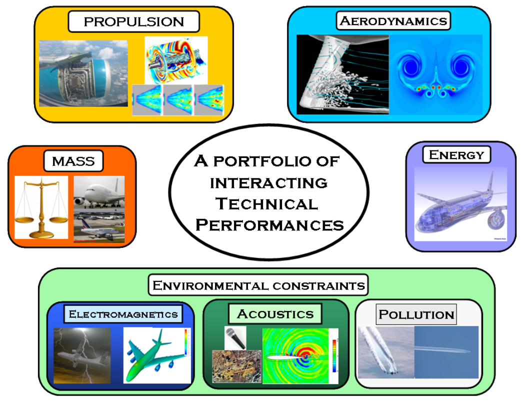


Fig.: Portfolio of technical performances

Performances

Aerodynamic : Drag,

Mass : Maximum Weight,

Acoustics : Perceived Noise Level,

Energy : Maximum Electric Power,

Propulsion : Specific Fuel Consumption...

$$\Downarrow$$

$$\mathbf{y} = (y_1, \ldots, y_Q)$$

Mathematical formalization

$$\begin{array}{rccc} \mathbf{y} : & \mathbb{T} & \longrightarrow & \mathbb{R}^Q \\ & t & \longmapsto & \mathbf{y}(t) \end{array}$$

Disciplinary perspectives

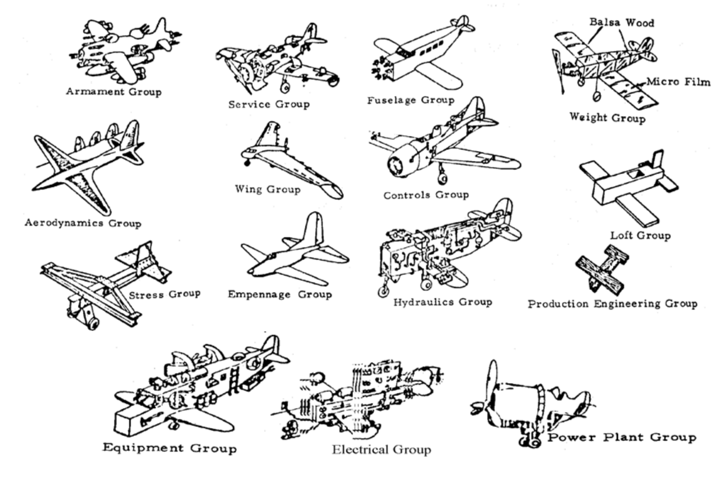


Fig.: Disciplinary perspectives

Modelling activities during the design phases

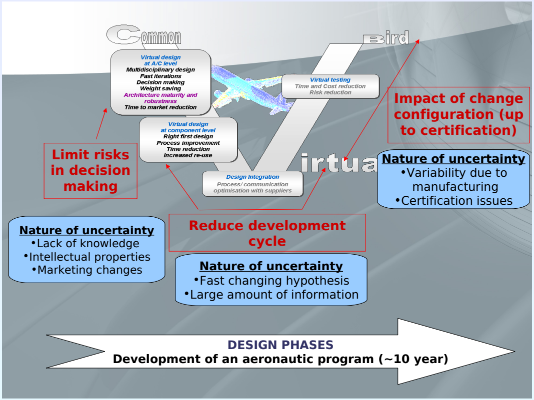


Fig.: Multiple design objectives and uncertainties during the design cycle

The "amount" of information (linked to uncertainty) and the objectives of the design evolve during the design cycle.

Mathematical formalization

1. $\mathbb{T} = \cup_{i=1}^{P} [\tau_i, \tau_{i+1}]$
2. Filtration : $(\mathcal{F}_i)_{i \in [1,P]}$

The role of the technical architects

What is the Graal ?

- The team of **technical architects** should **monitor the vector of macroscopic performances y all along the design cycle** and reach the target domain $\mathcal{T}$ of acceptable performances.
- This monitoring should **take into account the interactions between the different disciplines and the evolutions of the level of uncertainty/information** of each performance all along the design cycle.

Mathematical formalization

1. $\mathcal{T} \subset \mathbb{R}^Q$: Target domain in which the stochastic process $\mathbf{Y}$ is to be expected at time T (end of the design cycle).
2. A stochastic process $\mathbf{Y}_t$ can be defined on $(\Omega, \mathcal{F}, (\mathcal{F}_i)_{i\in[1,P]}, \mathbb{P})$ with values in $(\mathbb{R}^Q, \mathcal{B}(\mathbb{R}^Q))$

Graphical summary in 1D

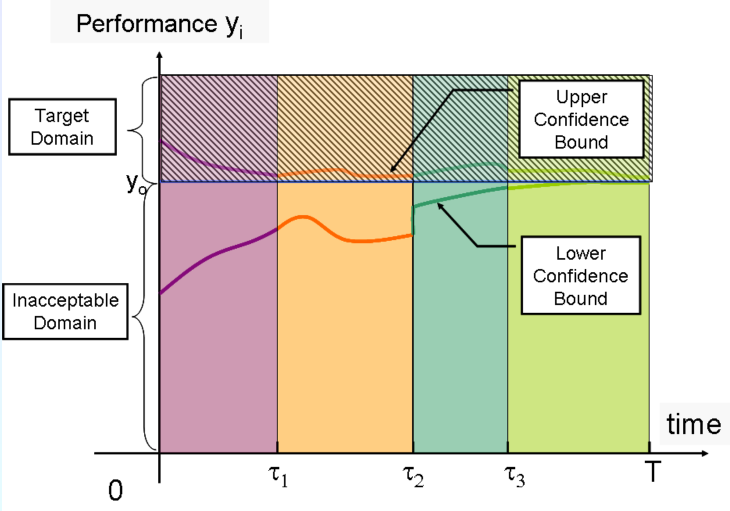


Fig.: Single performance along the design cycle

Graphical summary in 1D

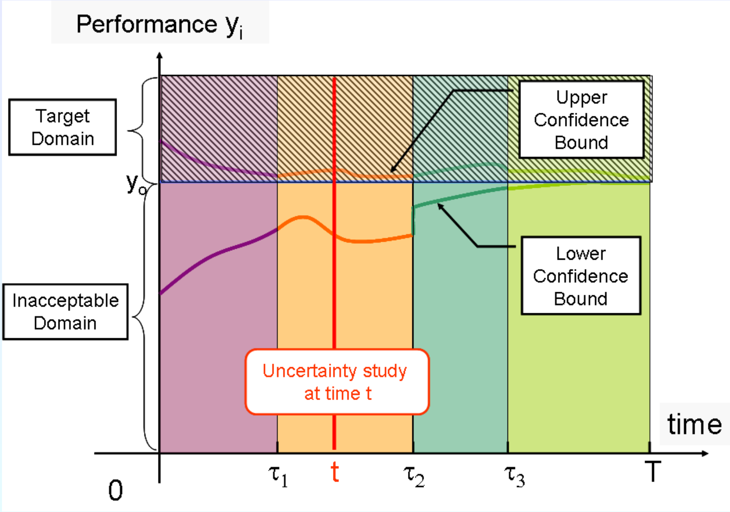


Fig.: Single performance at time t

Graphical summary in 1D

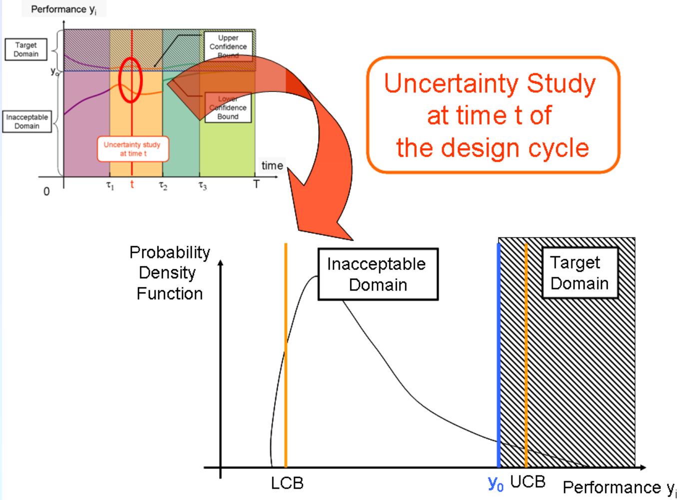


Fig.: Single performance along the design cycle

What do we compute in our uncertainty studies today ?

The model uncertainty is poorly taken into account !

Probabilistic modelling of uncertainty on input variables

- The index t is forgotten, thus, $\mathbf{y}_t \to \mathbf{y}$.
- The variable of decision (of performance) $\mathbf{y}$ is often known thanks to a numerical model h.
- This numerical model is the implementation of the numerical model of a theoretical solution. $h \longleftrightarrow \tilde{h}$
- $h \in \mathcal{F}(\mathbb{R}^P, \mathbb{R}^Q)$, $Q = 1$ very often.
- The input variables of the model h are splitted into deterministic variables $\mathbf{d}$ and uncertain variables $\mathbf{x}$.

$$\mathbf{y} = h(\mathbf{x}, \mathbf{d})$$

A General methodology....

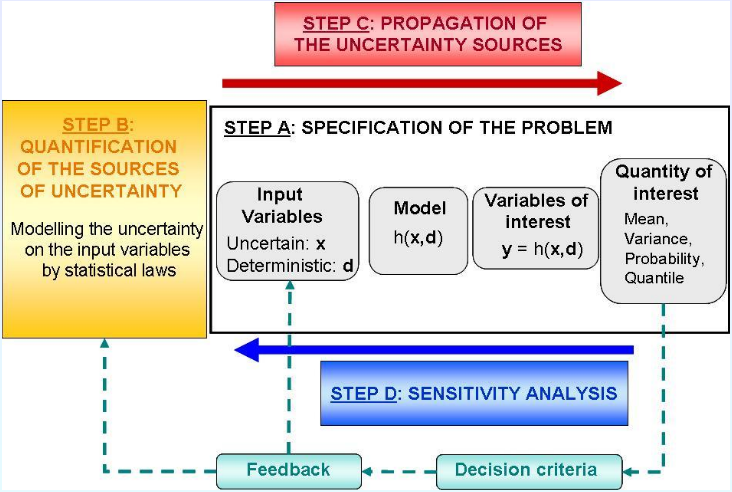


Fig.: Generic methodology for an uncertainty study

Back to the modelling problems

Step A : To specify the problem

- **To choose a model** The variable of interest **y** may be computed by several models. The practitioner has to choose among this panoply

$$h \in \{h_1, \ldots, h_P\}, \text{with } h_i \in \mathcal{F}(\mathbb{R}^{n_i}, \mathbb{R}) \forall i \in [1, P]$$

Back to the modelling problems

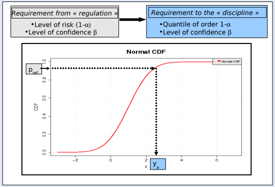
Step A : To specify the problem

- **To characterize the properties of the model**
  - **Dimension** : h is a real function belonging to $\mathcal{F}(\mathbb{R}^P, \mathbb{R}^Q)$. Even if the dimension of $\mathbf{x}$ can be large, most of the engineering problems are focused only on problems where $P \leq 50$ and $Q \leq 10$.
  - **Computational budget** : A single computation of h can be very expensive. The computational budget will represent the number of runs N affordable to solve the problem.
  - **Black box/white box** : h is either a black box (*the inner operations of the model are not accessible*), a grey box (*part of the inner operations is accessible*) or a white box (*all the operations of the model are accessible*).
  - **Mathematical properties** : the basic mathematical properties (regularity, monotony, linearity or non linearity towards certain parameters) may be unknown to the practitioner.
  - **Domain of validity** : h should be delivered with its domain of validity $\mathcal{V}^{[\epsilon]} \subseteq \mathbb{R}^P$.

Back to the modelling problems

Step A : To specify the problem

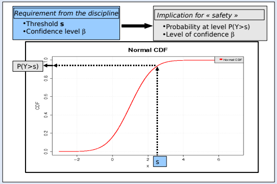
- **To define the criterion** : Expertise in reliability and system approach
  - **Quantile**



- Classical version : Knowing $p_{ref} \in]0,1[$, compute y_p such $y_p = \min_{\mathbb{P}[Y>y_s]<p_{ref}} y_s$.

This a computation of quantile or a boundary on a quantile.

  - **Probability**



- Classical version : Knowing $s \in \mathbb{R}$, compute $\mathbb{P}[Y > s]$.

This a computation of a probability or a boundary on a probability.

Back to the modelling problems –> to develop surrogate models

Motivation

Let $h \in \mathcal{F}(\mathbb{R}^P, \mathbb{R}^Q)$ be the numerical model. A surrogate model is a function $\overline{h} \in F(\mathbb{R}^P, \mathbb{R}^Q)$ with the following properties :

1. $\overline{h}$ is close to h in the domain of validity of h
2. The cost of $\overline{h}$ is much cheaper than the one of h (CPU or memory)

The motivation is thus to reduce the computational costs and to preserve the pertinence.

- To replace the model
- To collaborate with the model

Back to the modelling problems

Step B : To quantifify the uncertainties

- **Simple probabilistic representation**
  Some of the input variables are uncertain for different contextual reasons (lack of knowledge, variability due to a manufacturing process, will to explore different configurations...). This uncertainty is modelled in a probabilistic framework by a random vector $\mathbf{X} = (X_1, \cdots, X_P)$ characterized by its cumulative distribution function $F_X(\mathbf{x}, \theta)$, where θ is a vector of real parameters. Thus, $\mathbf{Y} = (Y_1, \cdots, Y_Q)$ is a random vector characterized by the unknown cumulative distribution function $F_Y(\mathbf{y})$.
- Parametric/non parametric models - dependency models

Back to the modelling problems

Step B : To quantifify the uncertainties

- **Complex probabilistic representation**

  In several practical cases, the definition of the cumulative distribution function $F_X(\mathbf{x}, \theta)$ can not be unique and it seems interesting to consider a family of acceptable cumulative distribution function $\mathcal{A}_X$, defined by :

$$\mathcal{A}_X := \{F_X(\mathbf{x}, \theta_k), k = 1, \cdots, N_A\}$$

  where :

  - $F_X(., \theta_k) : \mathbf{x} \in \mathbb{R}^P \mapsto F_X(\mathbf{x}, \theta_k)$ is a cdf on $\mathcal{V}^{[\epsilon]}$,
  - $\theta_k \in \mathbb{R}^{N_k}$ is a real vector of size N_k.

Back to the modelling problems

Step C : Situation today : to propagate the uncertainties

- **Deterministic method** : Quadratic methods, perturbation methods
- **Sampling methods** : Monte Carlo, Variance Reduction techniques, FORM/SORM, polynomial chaos
- **Collaborative methods** : controlled stratified sampling

Back to the modelling problems

Step D : To rank the uncertainties

- **Today's indexes** : Importance factors, Sobol indexes, sensivity analysis
- **To be invented** :

Diversity of method for the different use-cases

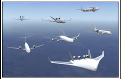
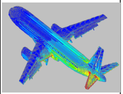
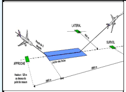
Application	Nb de variables d'intérêt	Modèle stochastique (X)	Caractéristiques du modèle de calcul (G)	Grandeur d'intérêt (c(Z))	Budget calcul (Nb runs)	Méthodes utilisées
	Qqs dizaines	Lois paramétriques évaluées par jugement d'expert	Des lois simples non linéaires	Tendance centrale + Sensibilité	Qqs milliers	Optimisation stochastique Sobol
	1 – 5	Lois paramétriques/non paramétriques	Résolution d'EDP (Maxwell)	Proba faibles + Sensibilité	Qqs dizaines	MC avec réduction de variance FORM/SORM
	1 - 5	Lois paramétriques évaluées par jugement d'expert et/ou test de lois	Extrapolations – Résolution d'EDP (acoustique)	Proba d'un évènement + Sensibilité	Qqs centaines	Cumul quadratique MC
	Plusieurs milliers	Lois paramétriques recalées à des mesures	Modèle cinématique linéaire	Taux de rebus Intervalle de tolérancement	Qqs milliers	MC Fct caractéristiques

Fig.:

Summary

- First part of the talk : uncertainty management is a real demand !
- Second part of the talk : test-cases and current status !

- What is available at the beginning of the study ?
  –> *Information/model/criteria*
- What kind of goal is attached to this study ?
  –> *Understand, Acredit, Select, Comply*
- What kind of uncertainty is arising ?
  –> *Internal/external*
- Is it possible to reduce the uncertainties in the frame of the project ?
  –> *Reducible/irreducible*

SCIENTIFIC challenges

Architect view

- What kind of processes to describe the evolution of $\mathbf{Y}_t$ between the different phases ?
- Is this stochastic process helpful to enrich the mono disciplinary view ?

Mono disciplinary view

- How to choose *a priori* between the choice of the model h, the criterion of decision to be computed
- To develop theory and algorithm to solve PDE with stochastic parameters (boundary conditions and coefficients of the EDPs)

Other CHALLENGES

CULTURAL challenges

Engineers ARE NOT USED to express the uncertainty in their domain. By the way, only a few of them are trained on the subject !

- Problem to build the probabilistic criteria
- Quantification of the sources of uncertainty

TECHNOLOGICAL challenges

The simulation tools are not adapted to evolve towards this revolution !

- Automatization of the computational workflow
- Is the computational budget compatible with the probabilistic criterion ?

CERTIFICATION challenges

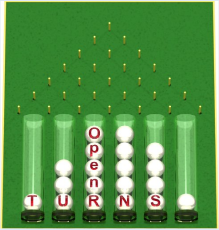
The uncertainty management process has to be compatible with certification issues (legal responsability, safety issues, ...)

Open source software iniative - Open TURNS –> OPUS

OpenTURNS = Open soure Treatment of Uncertainty, Risks aNd Statistics

Software developed since 2005 in partnership with EDF R&D and PhiMECA :

- C++ librairy to directly integrate computational chains ;
- A pyhton module for a scripting usage ;
- Available under an Open Source LGPL !



OpenTURNS

A tool integrating the previous methodology

The Open TURNS documentation covers :

- Installation ;
- Architecture, interfacing ;
- User Manual Guide ;
- Use Case Guide ;
- Theoretical Guide.

www.openturns.org !

Goals

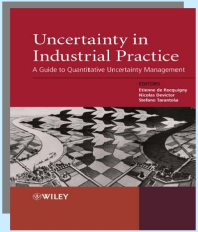
These projects enable to develop elementary bricks (methodology, numerical tools, demonstrations, ...) that will be incorporated into other applications (proprietary softwares, platform (CSDL)).

Framework of the projects

OPUS (supported by ANR) : EDF, Supélec, EADS IW, Dassault Aviation, Softia, Ecole Centrale Paris, Université Paris VI, Université Joseph Fourier, INRIA - Development of a generic platform (library, platform, forum) and upstream research

EHPOC (supported y System@tic) : EADS IW, IFP, Dassault Aviation, Bertin Technologies (CNES), Ecole Centrale Paris, INRIA - Demonstration on industrial use-cases.

Industrial groups



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EsREDA network

EsREDA is a European Association established in 1992 to promote research, application and training in Reliability, Availability, Maintainability and Safety (RAMS). The association provides a forum of information, data and current research in Safety and Reliability and a focus for specialist expertise. **www.esreda.eu**

ImdR

Institut de maîtrise des Risques : **www.imdr.eu** –> training at LNE

Research groups

GDR MASCOT NUM

The GDR CNRS MASCOT NUM is research group on Stochastic Analysis Methods for COdes and NUMerical treatments. Its main objective is to coordinate research efforts in this scientific area, often called by design, modelling and analysis of computer experiments. Its activities involve many techniques of applied mathematics. More specifically, it concerns statistics, probability, computer science, numerical analysis, operational research, mathematical physics, ...

www.gdr-mascotnum.fr

Scientific activity

- Design of experiments and computer codes
- Response surface and metamodels
- Uncertainty analysis
- Industrial problems

Complexity and uncertainty

*"**Complexity** lies within the entanglement that does not allow to tackle things separately, it severs what binds groups, and produces a crippled knowledge. The problem of complexity further appears since we are part of a world, which is ruled not only by determination, stability, repetitions, or cycles, but also by outbursts and renewal. Throughout complexity, there are **uncertainties**, either empirical or theoretical, but, most of the time, both."*

Edgar Morin, Philosopher.