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Surrogate Modeling for Composite Aircraft Structure Optimization

S. GRIHON[a], S. ALESTRA[b], E. BURNAEV[c], P. PRIKHODKO[c]

[a]ESAZO, Airbus Operations SAS

[b]Applied Mathematics Group, Airbus Group

[c]Data Analysis Lab, DATADVANCE

Contents

- ✈ Aircraft Structural Components Optimization
- ✈ Surrogate Modeling and Optimization: Motivation
- ✈ Applications of Surrogate Modeling for Structure Optimization

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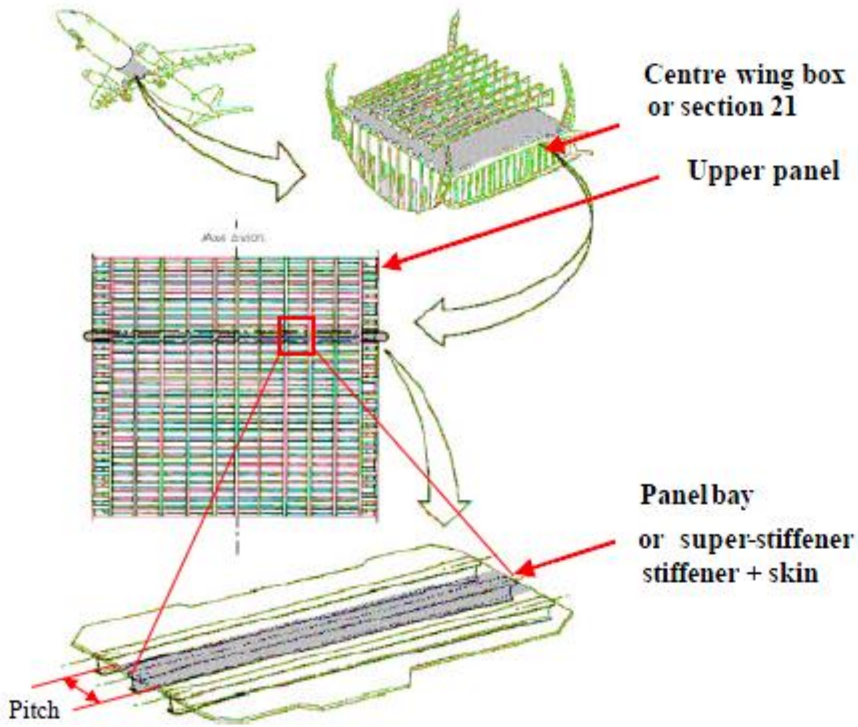
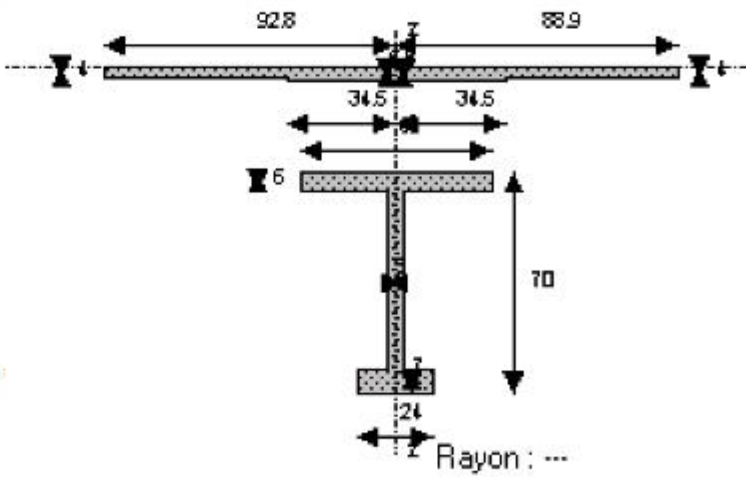
- **Aircraft Structural Components Optimization**
- Surrogate Modeling and Optimization: Motivation
- Applications of Surrogate Modeling for Structure Optimization

Introduction: Pre-sizing problem

Aeronautical structures are mainly made of stiffened panels enforced with stiffeners

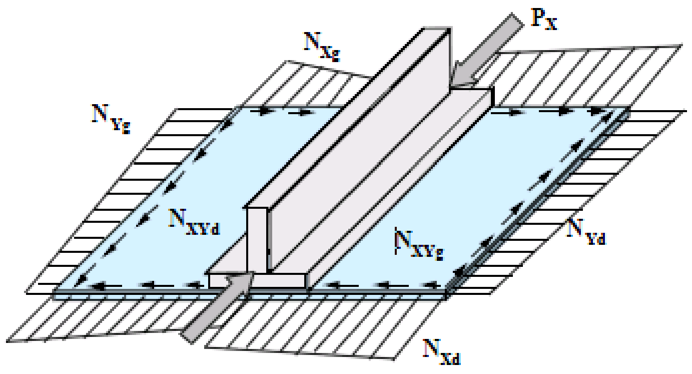
Define Super Stiffeners as the theoretical union of a stringer and two half panels





Introduction: Pre-sizing problem

✈Super Stiffeners are subject to highly non-linear phenomena such as buckling, collapse and damage tolerance



✈To determine the optimal size of these super stiffeners, static mechanical criteria must be computed using dedicated software that is based on non-linear calculation

Introduction: Optimization

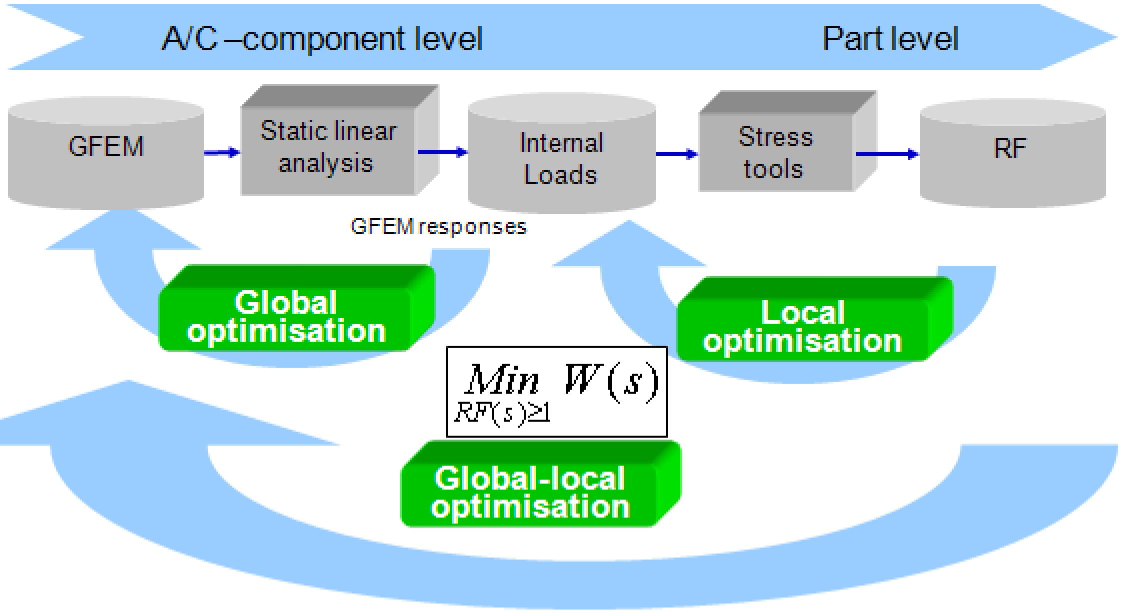
The analysis and the dimension estimation of the whole structure is currently computed by running a two-level study:

- global level: Finite Element (FE) analysis run on the whole FE model provides internal loads, applied to each S-Stiffener

- local level: these loads are used to compute static mechanical criteria

3 optimisation schemes:

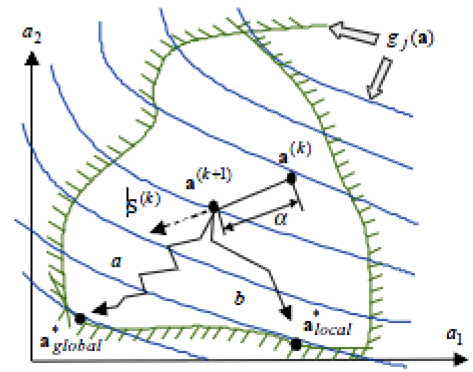
✓Driven by **the analysis process**



Introduction: Optimization

✈ Most of static mechanics criteria are formulated using Reserve Factors (RF): a structure is validated provided all its RFs are greater than one.

✈ Optimization problem is to minimize weight under constraints on geometry and RFs



$$\textit{Minimize}_{s_i}\ W(s), \qquad i = 1..I,$$

$$\textit{Subject to:}\quad RF_j^{\,strength}(s) \geq 1.0, \qquad j = 1..J$$

$$RF_k^{\,geometry}(s) \geq 1.0, \qquad k = 1..K$$

$$\min s_i \leq s_i \leq \max s_i, \qquad i = 1..I$$

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Motivation: computational burden

✈The dimension estimation step in an aircraft development program is a repetitive, time-consuming process:

- Huge dimensionality of the problem (**O(10^3) variables** and **O(10^5) constraints**)
- Optimization methods require gradients of the constraint functions, which can only be obtained by finite differences
- Values of mechanical strength constraints are computed using dedicated software
- **Each of numerous calls to this software takes up to 1 sec**

The need for finite difference calculations in each of numerous local optimizations greatly increases the time between two update steps of optimization

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Solution: Use of Surrogate Models (Response Surface Models)

✈ Expected benefits of surrogate models use:

- <u>time saving in pre-sizing processes</u>

- <u>response smoothing</u>

RFs are sometimes are not themselves continuous (as often for semi-empirical approaches)

BUT

Surrogate Models (SMs) may provide a continuous and differentiable approximation

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BUT

Surrogate Models (SMs) may provide a continuous and differentiable approximation

=> calculation of gradients directly instead of using costly finite differences

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Examples of Surrogate Modeling Applications

- ✈ Problem 1: Surrogate Optimization of Wing Covers

- ✈ Problem 2: Surrogate Modeling of Thin Composite Plates

Examples of Surrogate Modeling Applications

- **Problem 1: Surrogate Optimization of Wing Covers**

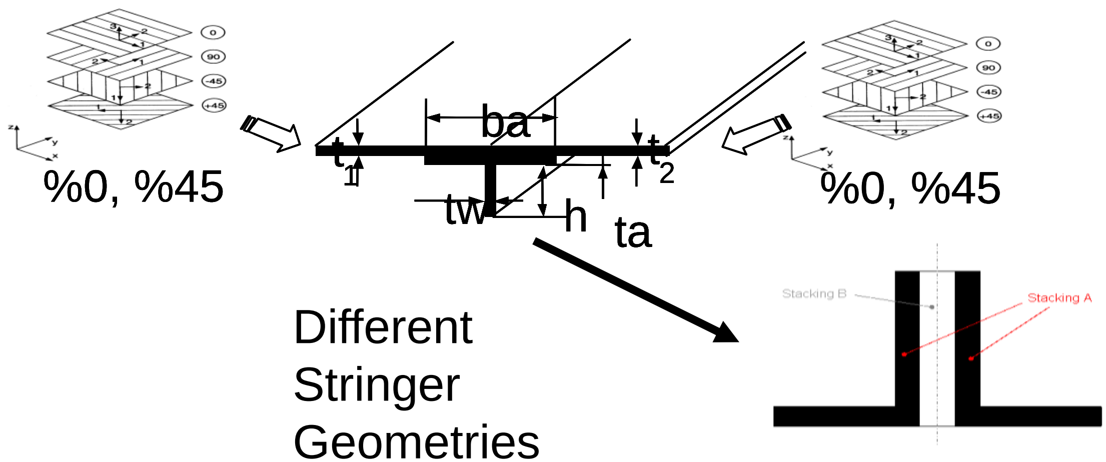
- Problem 2: Surrogate Modeling of Thin Composite Plates

Design Variables and Criteria

A350XWB

✈Design variables

Skin angle thicknesses / stringer section parameters



Different
Stringer
Geometries

✈Design criteria (calculated by Airbus in-house software)

- stability: Rayleigh Ritz approach & Karman theory for post-buckling
- damage tolerance
- reparability: bearing, by-pass

✈All composite design variables and criteria are considered

Surrogate Models (Response Surface Models)

Original model

$$\frac{\partial h}{\partial t} + \nabla_s \cdot (h \bar{\mathbf{u}}_F) = \frac{S}{\rho_F}$$

$$\frac{\partial (h \bar{\mathbf{u}}_F)}{\partial t} + \nabla_s \cdot (h \bar{\mathbf{u}}_F \bar{\mathbf{u}}_F + \mathbf{C}) = \frac{1}{\rho_F}(\boldsymbol{\tau}_{fs} - \boldsymbol{\tau}_w) + h\mathbf{g} - \frac{h}{\rho_F}\nabla_s p_F + \frac{\mathbf{S}}{\rho_F}$$

Y = F(X) – simulates behaviour relationship between X and Y

DoE ➔ Data Base

$(X_i, Y_i = F(X_i))$, i = 1,…,N – training data set

IDX	[1]	[2]	[3]
[0]	1	1	2.48585e-014
[1]	1	3	1.15955e-013
[2]	1	5	4.99297e-013
[3]	1	7	1.98466e-012
[4]	1	9	7.2823e-012
[5]	1	11	2.46665e-011
[6]	1	13	7.71264e-011
[7]	1	15	2.22616e-010
[8]	1	17	5.93149e-010
[9]	1	19	1.45891e-009
[10]	1	21	3.31246e-009
[11]	1	23	6.9427e-009
[12]	1	25	1.34327e-008
[13]	1	27	2.39913e-008
[14]	1	29	3.9555e-008
[15]	1	31	6.02011e-008

Construct such **Y = F_{approx}(X)** that

$F_{approx}(X) \approx F(X)$

In the considered case:

- X is composed of
  - Skin thickness,
  - Percentages of standard draping angles 0%, 45%, 90%,
  - T-stringer core and web percentages 0%, 45%, 90%,
  - etc. (> 20 parameters)
- F(X) is realized by Airbus in-house skill-tool
- Y = F(X) is composed of various Reserve Factors (>20 RFs)

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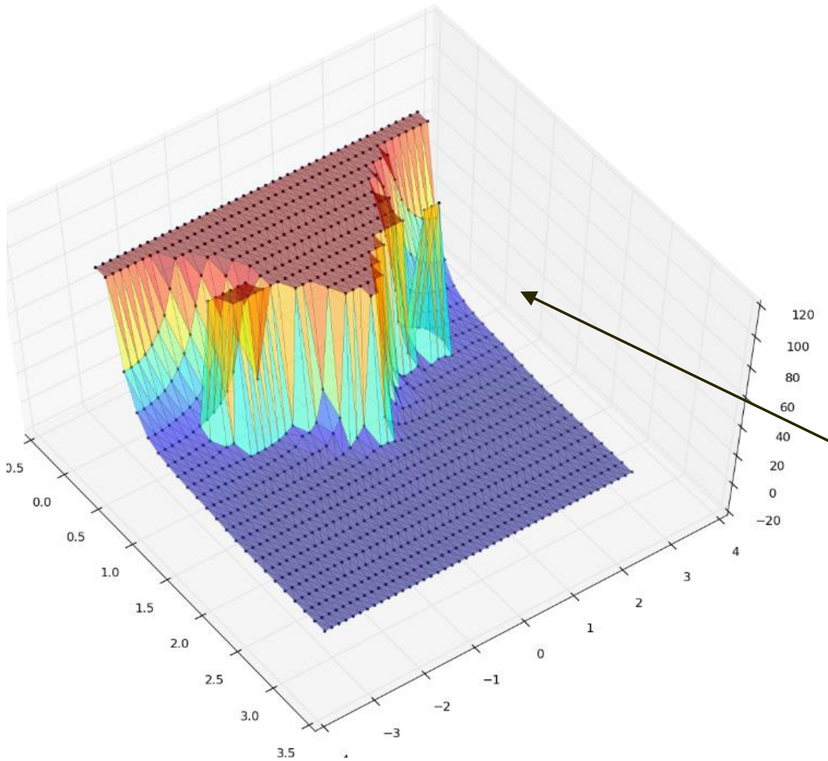
Challenges

- nonlinear multivariate functions (> 20 input parameters)
- discontinuities and large gradients
- strict requirements on model accuracy (for 95% of errors are less than 5%)



Example of two-dimensional slice of function to approximate

MACROS: a surrogate modeling and optimization software toolkit

MACROS is a software toolkit for

- intelligent data analysis and
- multi-disciplinary optimization

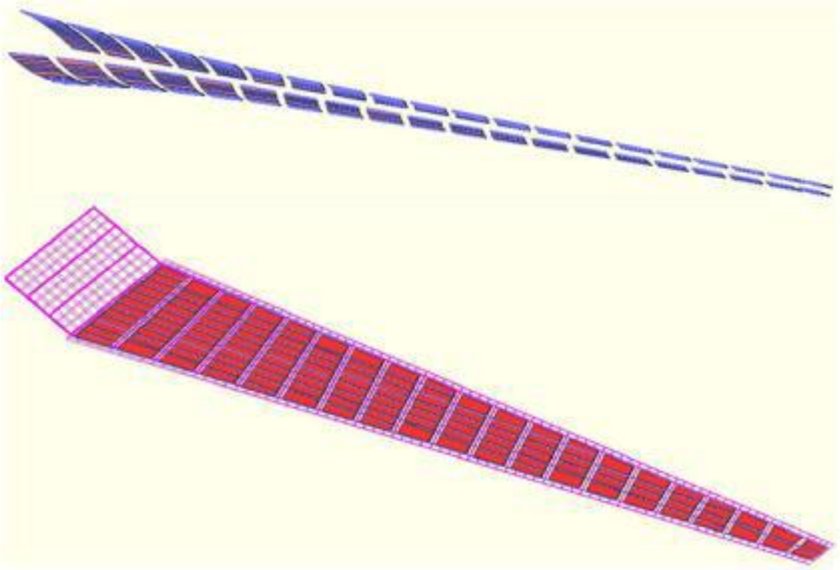
developed by **DATADVANCE** llc.

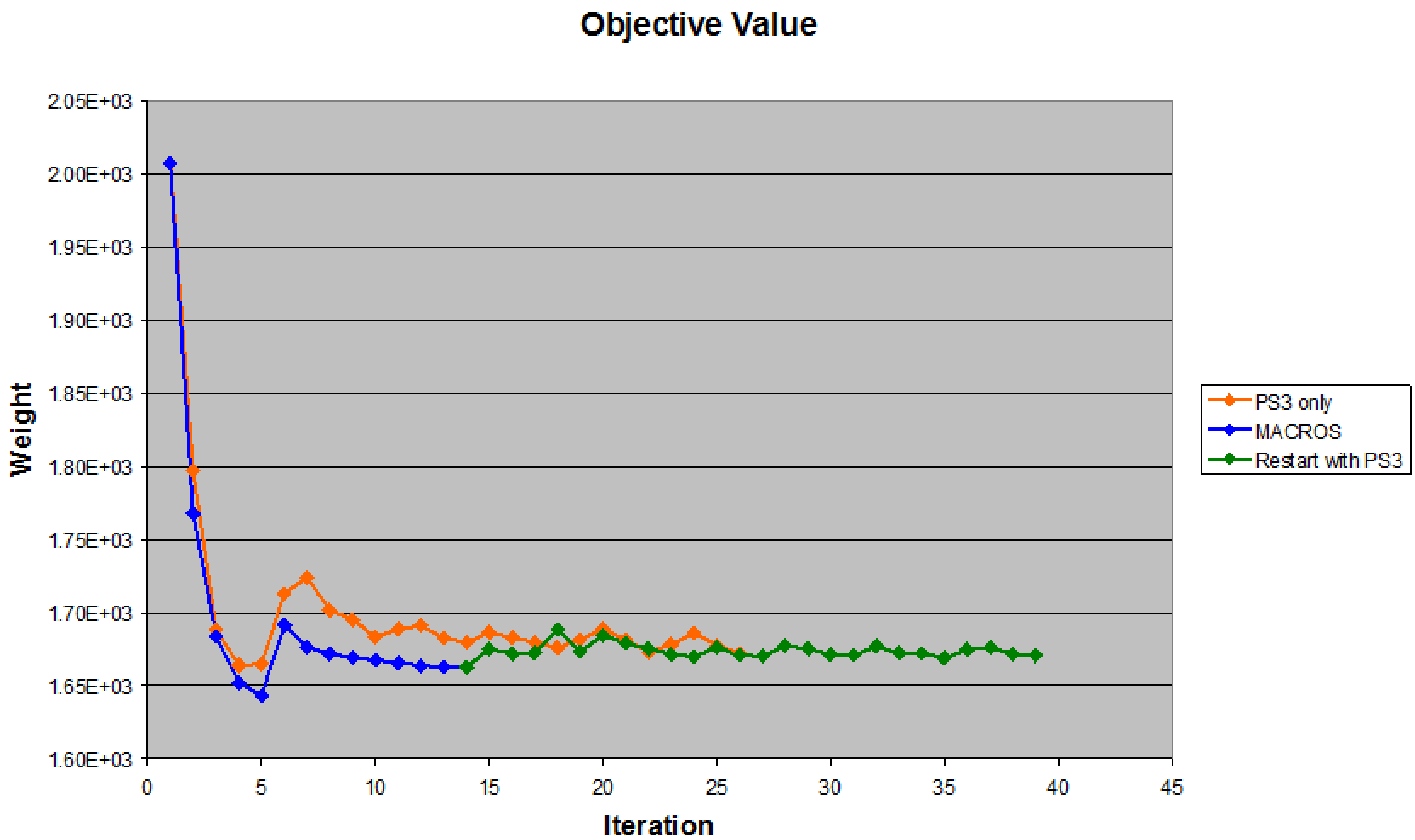
Provides proprietary and state-of-the-art data analysis and optimization techniques and consists of Generic Tools for

- Dimension reduction
- Sensitivity Analysis
- Design of Experiments
- Construction of Surrogate Models
- Variable Fidelity Data Modeling
- Optimization

Results: Wing stress model

- ✈ Optimization of the wing lower and upper covers





Smoother convergence with MACROS SM

✈ A check of Reserve Factors was performed with the optimum based on MACROS SM

Satisfactory accuracy for a pre-sizing result, according to AIRBUS experts and considering that a pre-sizing is always to be re-engineered including, for example, manufacturing constraints

	RF EIIV	Rib Bay																			
	Stringer	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21
Top Cover	1	1.01																			
	2	1.03	0.95	1.00	0.99	0.98															
	3	0.99	0.99	0.99	0.97	0.98	1.00	0.99	0.95												
	4	1.03	1.02	1.01	1.00	0.99	1.01	1.00	0.96	0.97	1.04	0.98	0.97								
	5	0.99	0.97	0.97	0.98	0.97	0.97	0.97	0.96	0.99	0.95	0.95	0.95	1.01	0.98	0.95	0.99	0.95			
	6	0.99	0.95	0.96	0.97	0.96	0.96	0.99	0.97	1.00	0.95	0.96	0.95	1.04	0.97	0.95	0.98	0.96	1.00	0.91	1.01
	7	0.99	0.96	0.96	0.96	0.95	0.95	0.97	0.97	0.98	1.05	0.95	0.96	0.93	0.95	0.92	0.98	0.67			
	8	0.99	0.97	0.95	0.95	0.94	0.95	0.96	0.97	0.99	0.98	0.93	0.96	0.90							
	9	1.01	0.94	0.98	0.96	0.94	0.98	0.96	0.92	0.93											
	10	0.99	0.99	1.01	1.01	0.94															
	11	1.02																			

Conclusions

✈ MACROS surrogate model gives high accuracy of approximation

✈ MACROS surrogate model allows obtaining smoother convergence in less iterations with a smoother distribution of thickness/stringer dimensions and a small violation of constraints which then could be easily repaired at the detailed design phase

✈ MACROS surrogate model provides expected reduction of structure optimization computational time **from several days to a few hours**.

Examples of Surrogate Modeling Applications

- ✈ Problem 1: Surrogate Optimization of Wing Covers

- ✈ **Problem 2: Surrogate Modeling of Thin Composite Plates**

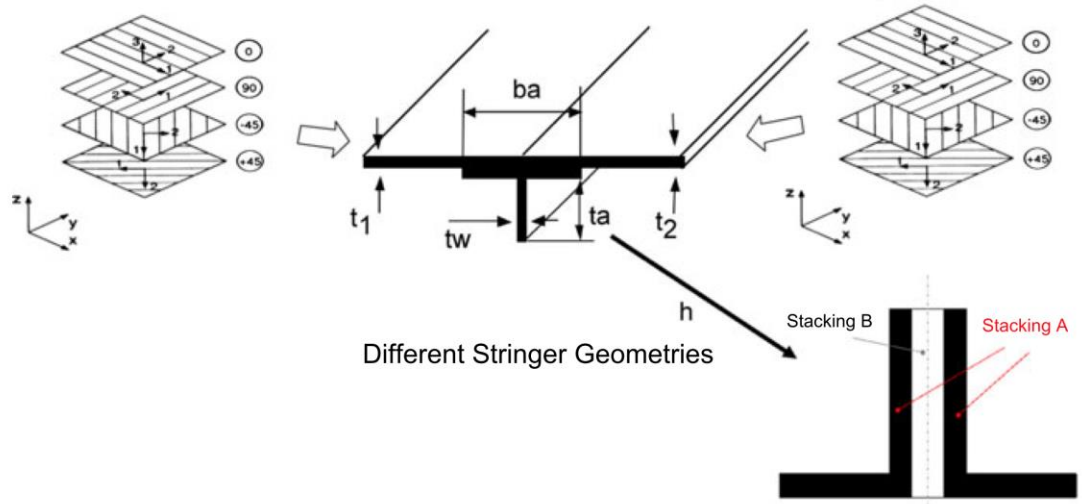
Problem statement

Objective:

Approximate Reserve Factors (RFs) of thin composite plates as a functions of loads with smooth and fast surrogate model

PRESTO Data Base:

- **~ 900** Gigabytes divided into catalogues
- Each catalogue is defined by a specific stacking sequence
- Each catalogue contains for different pairs of thickness and area values of different RFs depending on applied forces



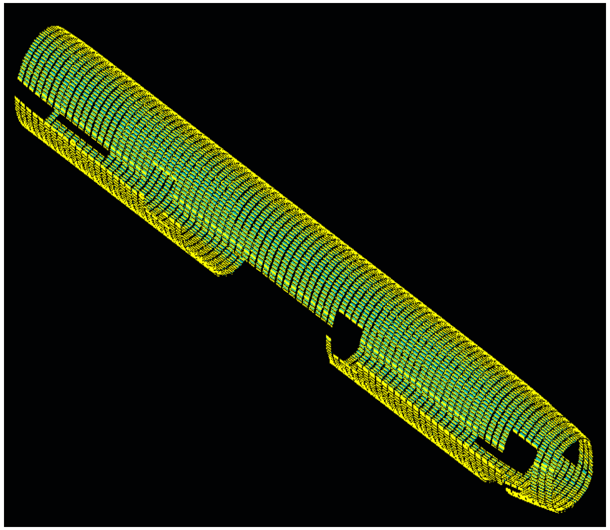
- For any new load RFs are evaluated using piecewise-linear interpolation

PROBLEM:
- **too huge size** of the PRESTO Data Base,
- **non-smooth** approximation

Problem statement

Requirements to Surrogate Models:

- relative prediction **error is smaller than 5% for 95% of observations**
- **model size is at least 9-10 times smaller** than the size of data base
- It should take **no more than a few seconds to construct** a new model



Test Case:

- 7 RFs
- 47 pairs of t, A

That is 329 models in total

For each (pair t, A + failure mode) training sample is defined as

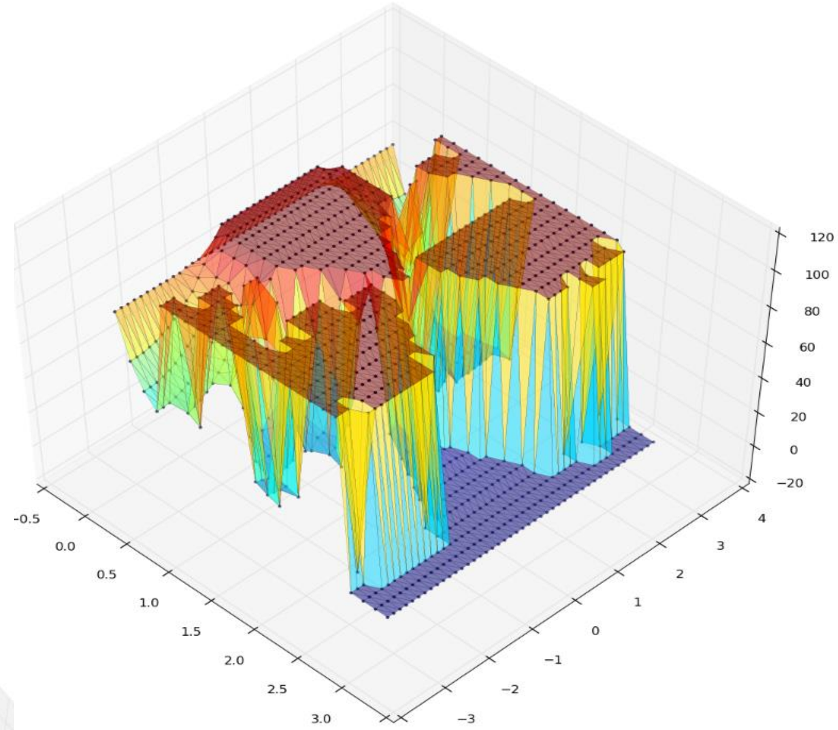
- inputs (DoE) = 2D grid of **23 x 45 = 1035 points**
- outputs = values of the corresponding RF

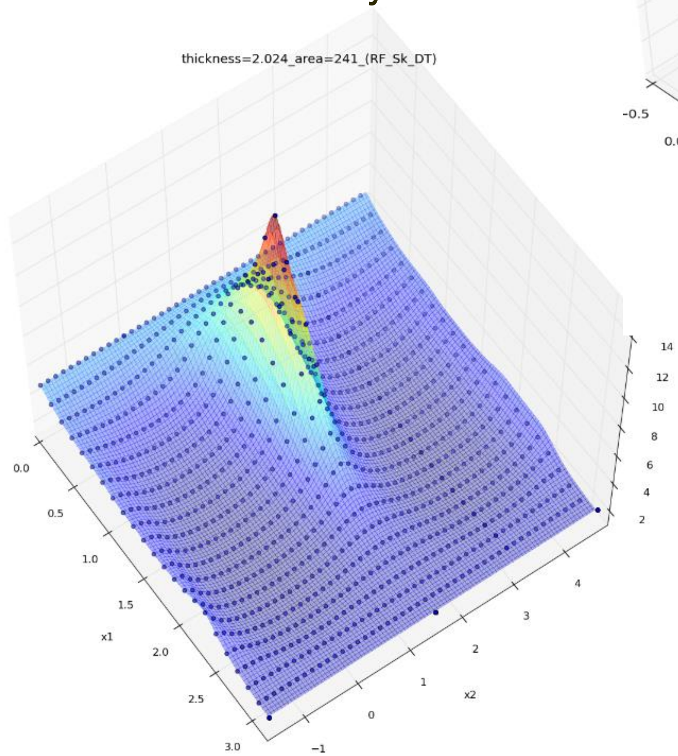
Challenges

- nonlinear 2D/3D function

- discontinuities and large gradients

- strict limitations on model size,
  model construction time and accuracy





Examples of functions to approximate

Algorithm

Steps of model construction:

1. Construct classifier for “nan” points
2. Transform data *(box-cox transformation of y gives better accuracy)*
3. Build separate model on filtered sample *(“nan” points with y>100 removed)* for each output using MACROS techniques TA/iTA
4. Merge separate models and classifier into one model for catalog *(in form of C99 code)*

TCDB size

Comparison of TCDB size:

Size RFDB: 11553792 octets

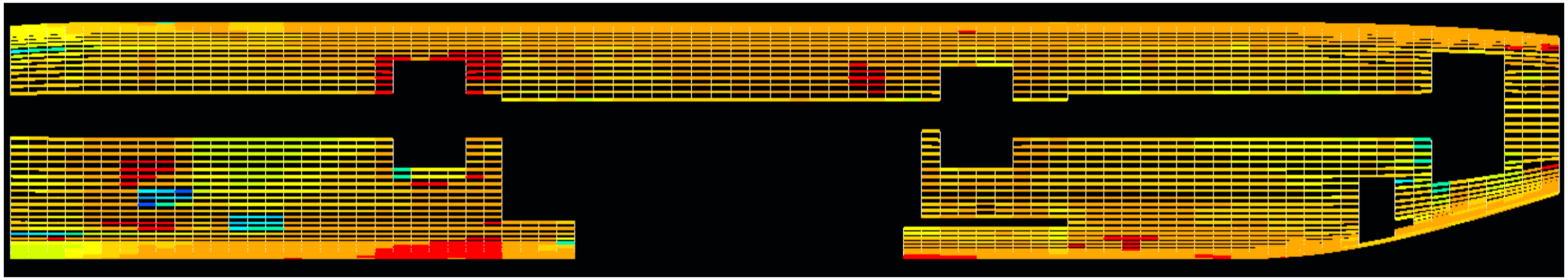
Size MACROS surrogate: 1284480 octets

Ratio = RFDB / Surrogate ~ 9

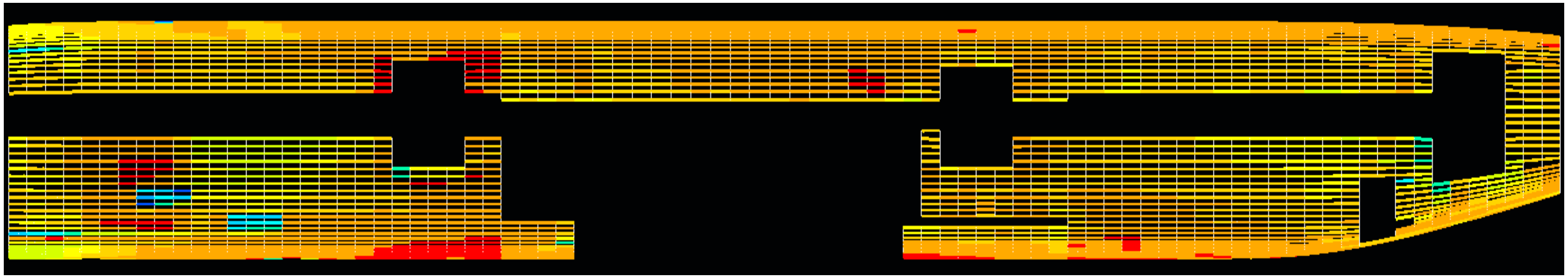
Comparison of RF values

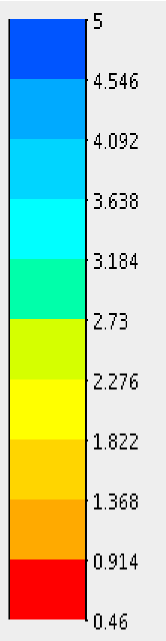
Comparison of critical RF values

MACROS:



RFDB:

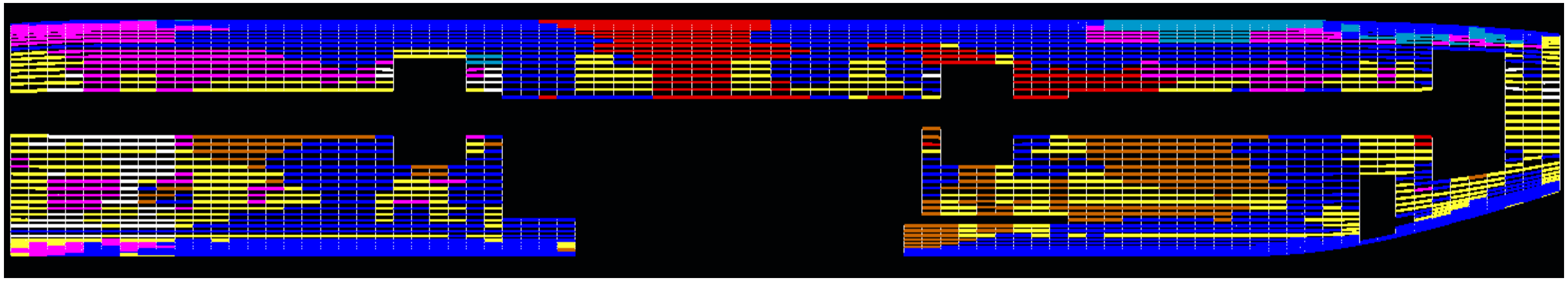




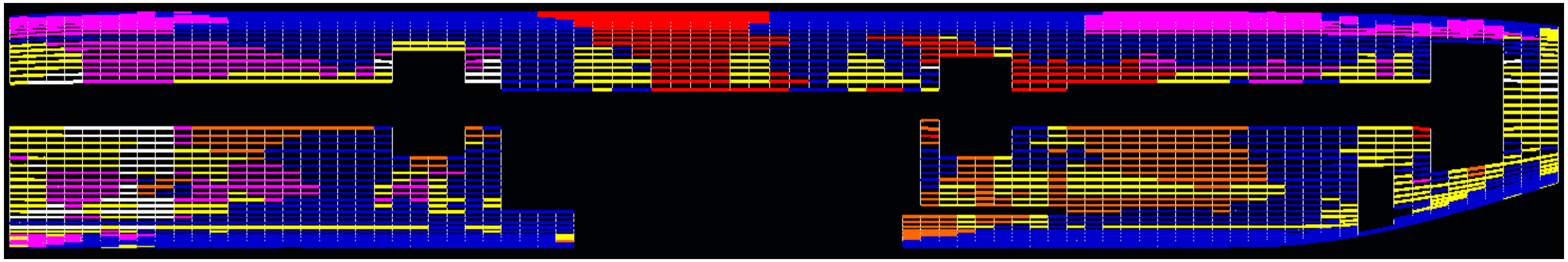
Comparison of RF values

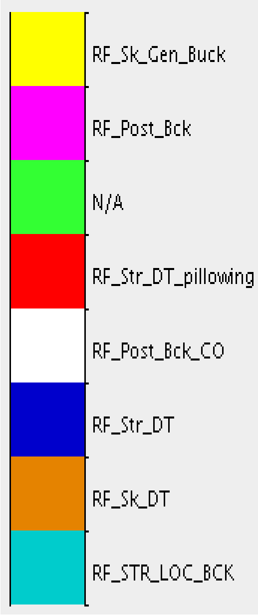
Comparison of critical RF types (failure modes)

MACROS:



RFDB:





Conclusions

Results of tests of MACROS surrogate model for CFRP fuselage stiffened panels (LMS-SAMTECH) showed that MACROS surrogate models give good accuracy with respect to the RF databases with a reduction factor of about 10 for the data storage.

- **Thus the use of MACROS is beneficial for data compression within PRESTO**

Following activities are planned:

- Integration of MACROS surrogate modeling techniques into PRESTO *(to allow construction of surrogate models on the side of LMS-SAMTECH)*

- Research on approaches to reduction of design of experiments (*to further reduce space storage size for the models)*