

A world map with a yellow and orange color scheme. Several regions are highlighted in a bright yellow color, including parts of North America, Europe, and Asia. The map is set against a light background with a subtle grid pattern.

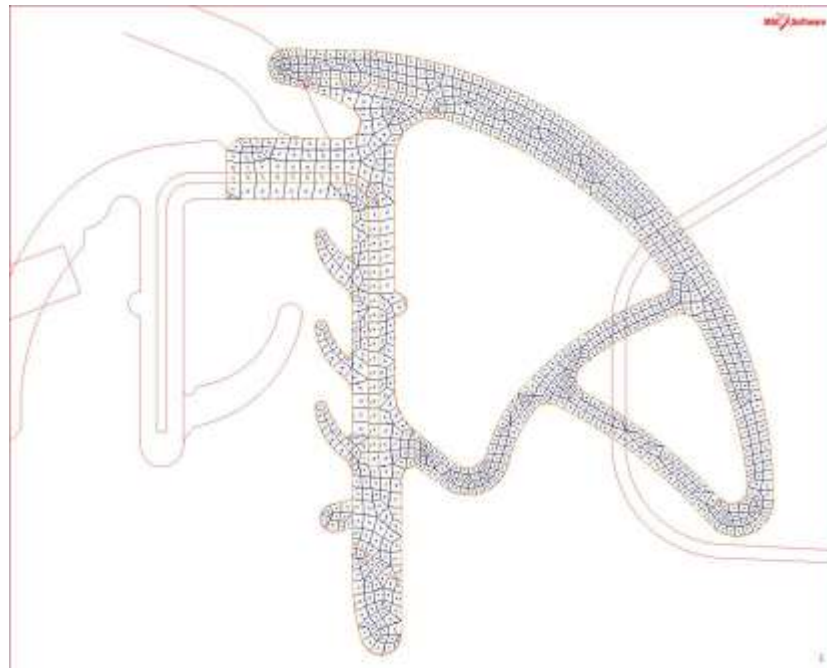
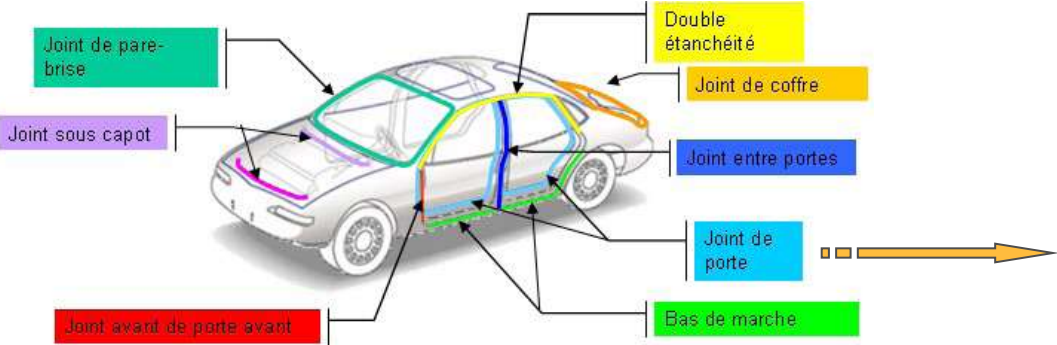
An alternative approach to automotive door seal design using HyperStudy

Maxime Le Moine, Mahmoud Oumohand

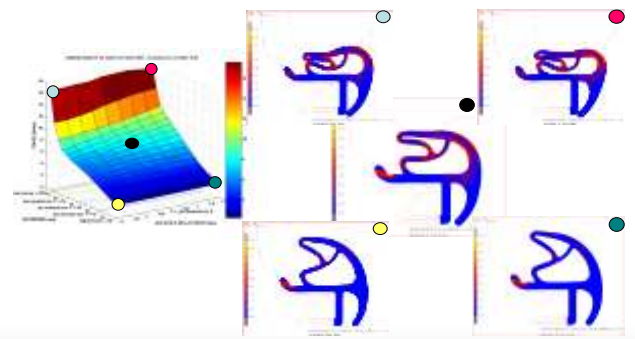


Sealing design: current approach

Sealing systems



Today, seal design and closing effort forces are determined using a nominal seal shape at extreme BIW tolerances.



What is the problem?

✓ When designing a weather-strip seal:

- Match the OEM's requirements
- Find the design of the seal which will **better fulfill** these requirements.

» *Shape optimization*

✓ When manufacturing the weather-strip seal:

- Reduce the impact of small **extrusion tolerance** variation
- Verify that a given design is **less sensible** to these variations

» **Sensibility study**

- Find the design of the product which will both **satisfy** the requirements and be **less sensitive** to small deformations

» *Robust design optimization*

Objectives



What :

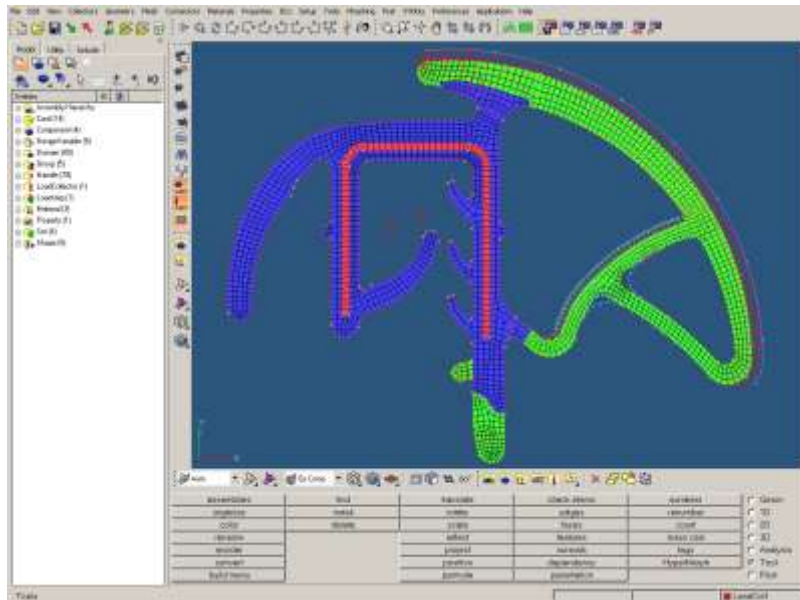
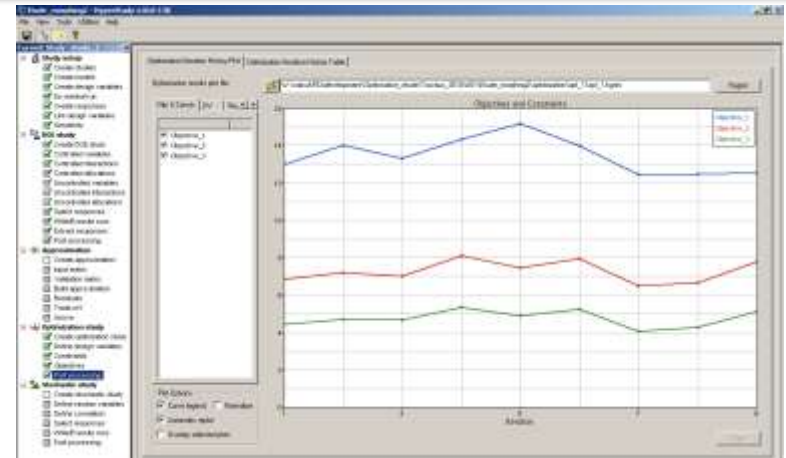
- Design process  Parametric design approach

How :

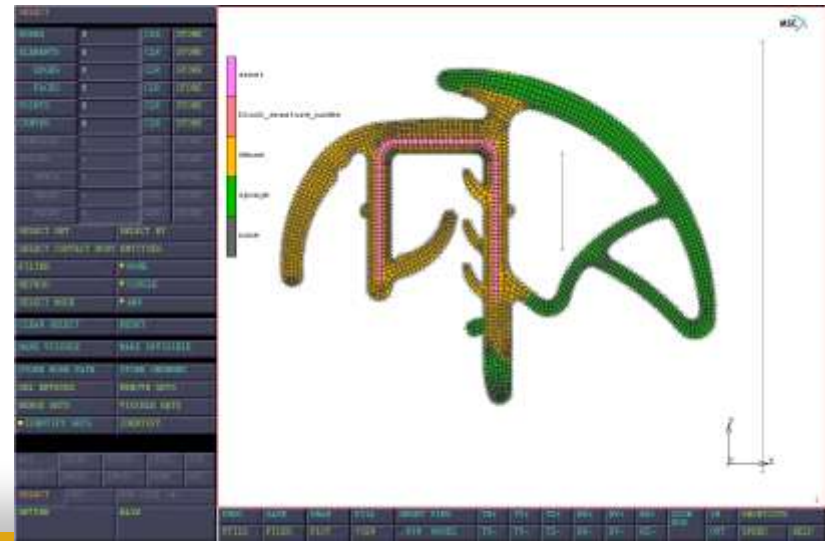
- Identify the numerical tools
- Define a procedure
- Study the effect of size and shape variations in seal design

The numerical tools

HyperStudy: optimization (Altair Engineering)



HyperMesh: Morphing function (Altair Engineering)



Marc & Mentat: FE solver & pre-processor (MSC Software)

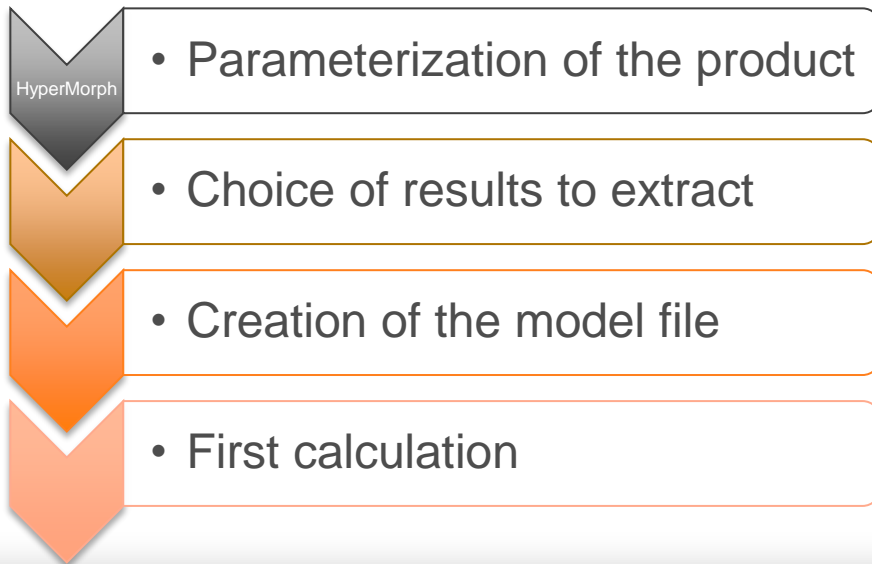
The procedure

- Communication not obvious between the numerical tools
- Data exchange not easy

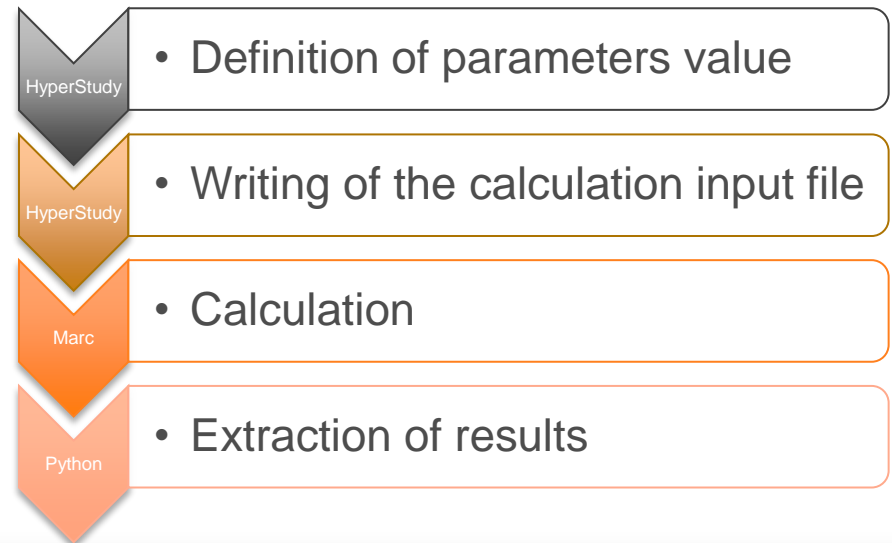
Python routines (in house developments):

- 2 initialization procedures
- 2 analysis procedures
- 5 scripts

Initialisation

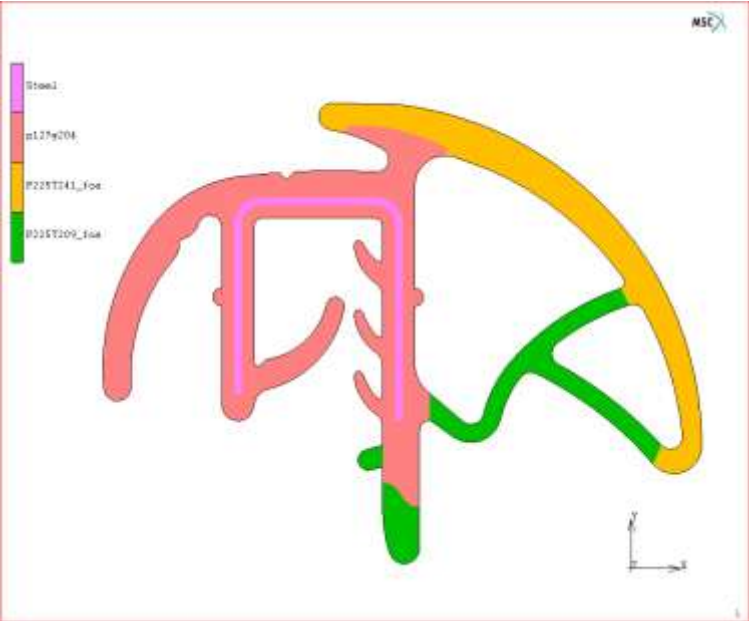


Steps of analysis

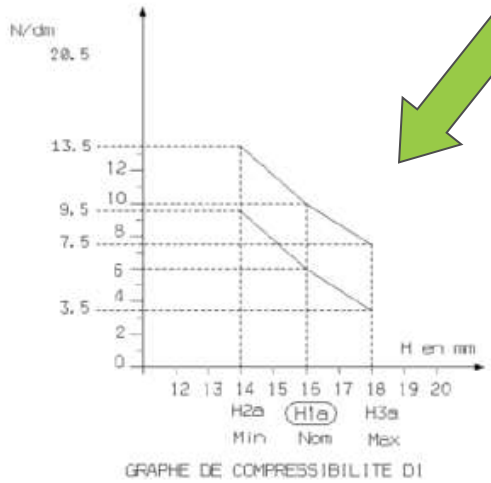
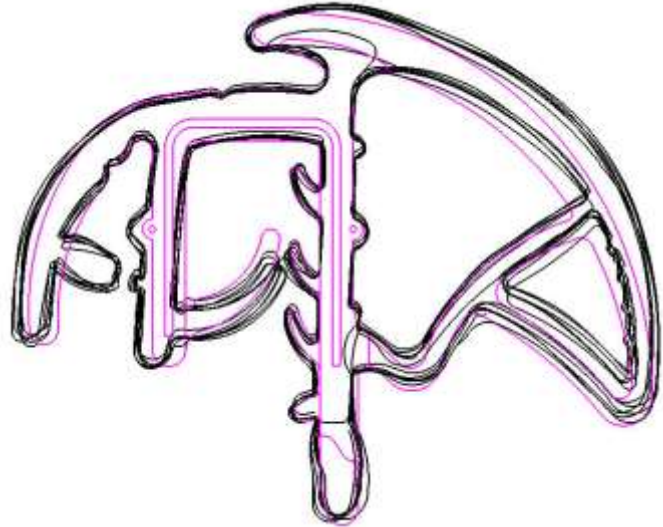


A simple typical design

Ideal (nominal design)



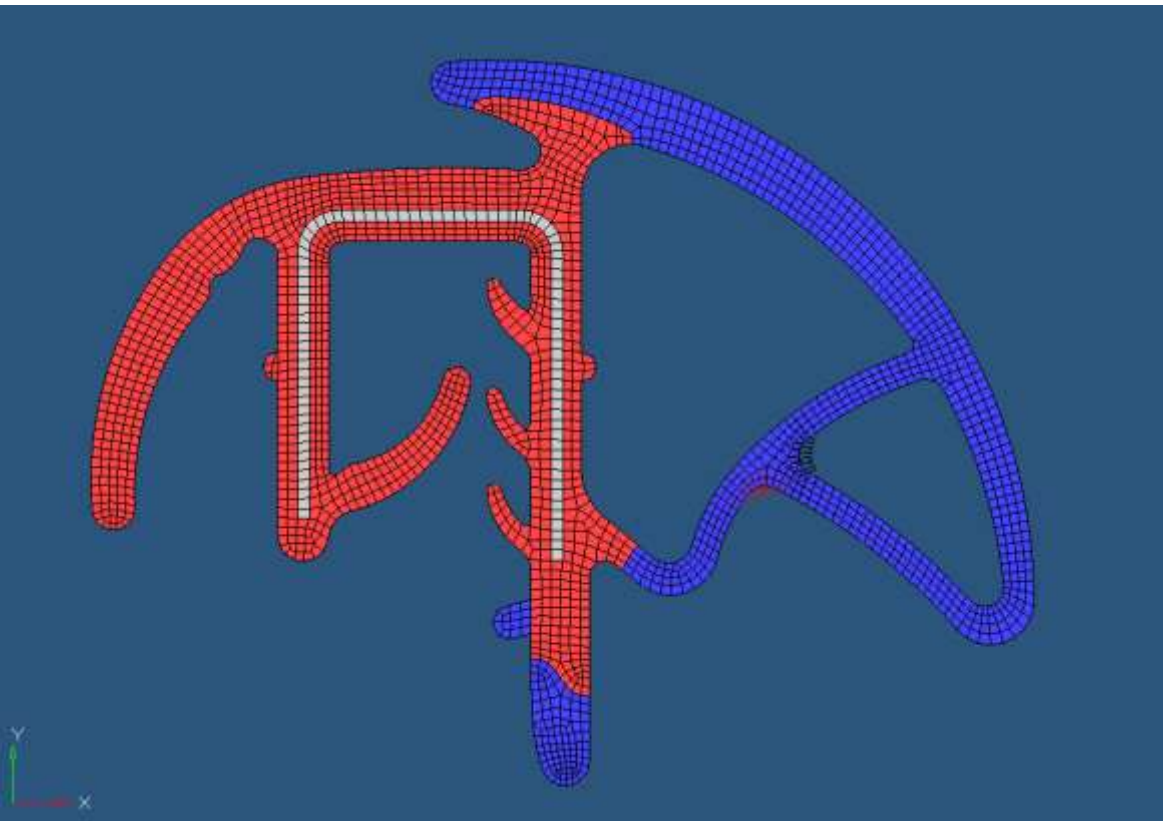
Reality (geometric scatter)



Requirements



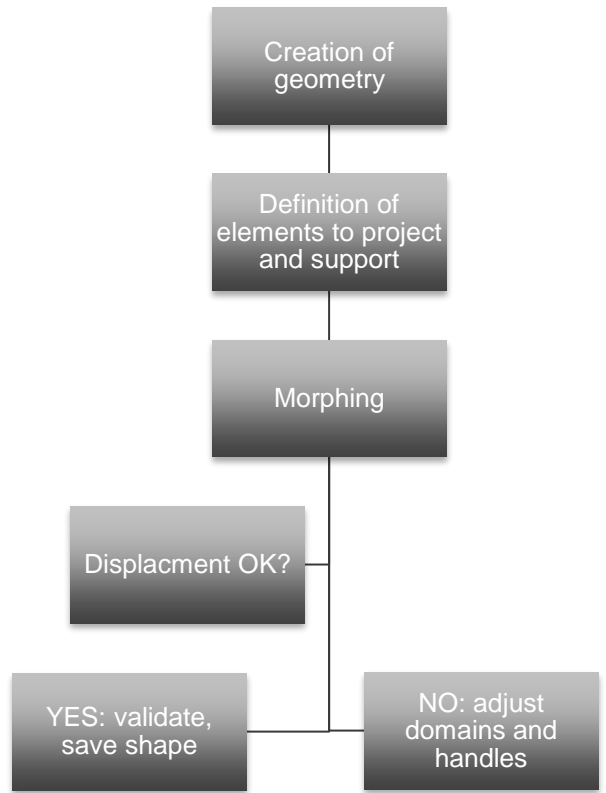
Parameterization of geometric scatter



Parameters

- ✓ Height
- ✓ Thicknesses
- ✓ Radiuses

Process



Initialization of study – export of parameters

- ✓ Accessible from *optimization* panel of HyperMesh
- ✓ Associates to each deformation a variable (initial value and definition interval)
- ✓ Export two files:
 - *.shp* : contains the definition of all deformations as a list of Δx , Δy , Δz associated to the nodes coordinates.
 - *.marc.node.tpl* : definition of parameters et list of nodes coordinates in *Marc* format; the nodes affected by a deformation are indicated by a tag and point to the matching line in the *shp* file.

```
1 {parameter(epaisseur_3,"epaisseur_3",0.00000000e+000,0.00000000e+000,1.00000000e+000)}
15 {coeff1:=read("model_0_7.shp",0,0,1)}
30 {I1:=I1+epaisseur_3*coeff1}

590 .....548...1.0457214282e+001...8.7576297549e+000...0.0000000000e+000
591 .....549{ getvalueatindex("I1",3),%20.10e}{ getvalueatindex("I1",4),%20.10e}{ getvalu
```

Initialization of study – creation of model file

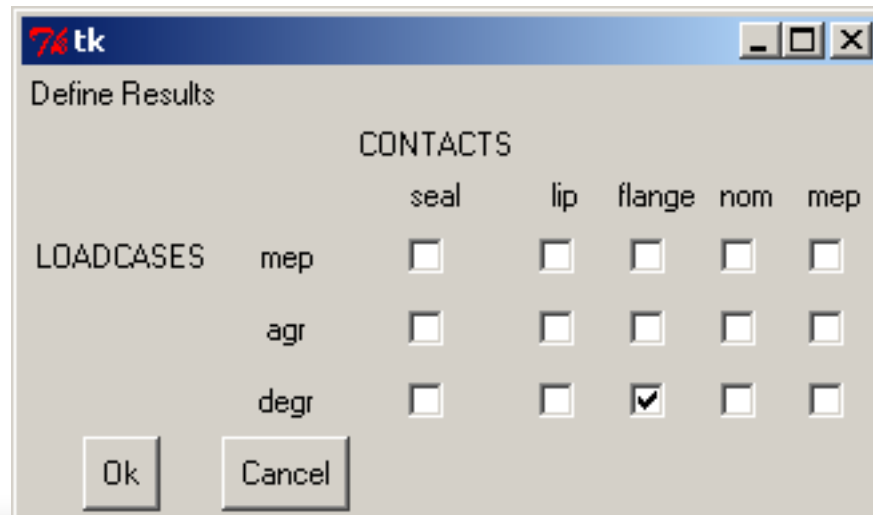
- ✓ Procedure accessible in HyperStudy
- ✓ Ask the user for the location of the *Marc* input file on which the morphing were based, and for the location of the *.marc.node.tpl* file
- ✓ Delete the list of nodes coordinates in the input file and replace it by an inclusion of the *.marc.node.tpl* file

```
1391 coordinates
1392 ..... 3 ..... 1636 ..... 0 ..... 1
1393 {include "W:/calcul/Stagiaires/Maxime_LeMoine/Etude_T9/model_0_7.marc.node.tpl"}
1394 define ..... node ..... set ..... fx-y_nodes
1395 ..... 22 ..... 63
1396 define ..... node ..... set ..... fx-x_nodes
1397 ..... 22 ..... 63
1398 define ..... element ..... set ..... gde-levre
1399 ..... 398 ..... to ..... 735
1400 mooney
1401
```

- ✓ The file created will be used as model (*template*) to HyperStudy

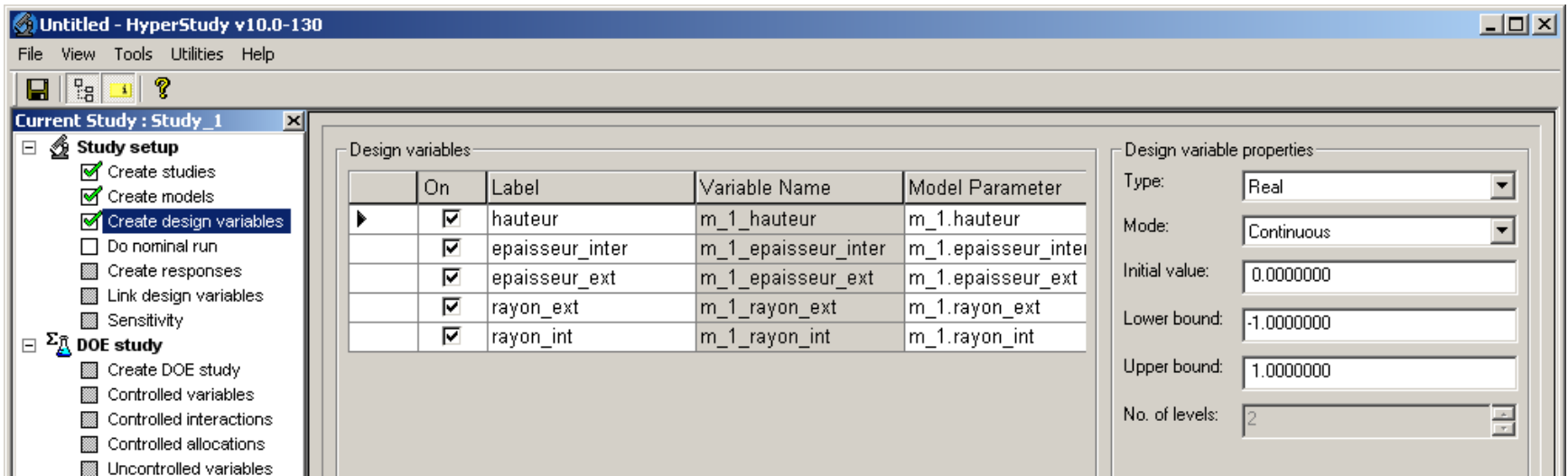
Initialization of study – Definition of output results

- ✓ Procedure accessible from HyperStudy
- ✓ Analyses of the *Marc* input file used for the study
 - Lists all the contacts and loadcases
- ✓ Opens a Python/Tk window where the user chooses the couples *Contacts / Load cases* to be studied



Start of nominal run

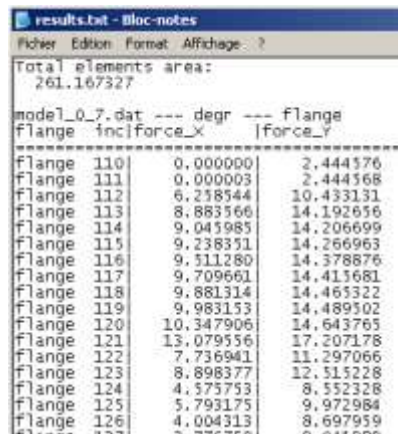
- ✓ The model can now be imported in HyperStudy; the parameters will be recognized automatically.



- ✓ A first calculation (nominal run) must be performed in order to define the responses (numerical values) to study.

Initialization of study – Definition of response

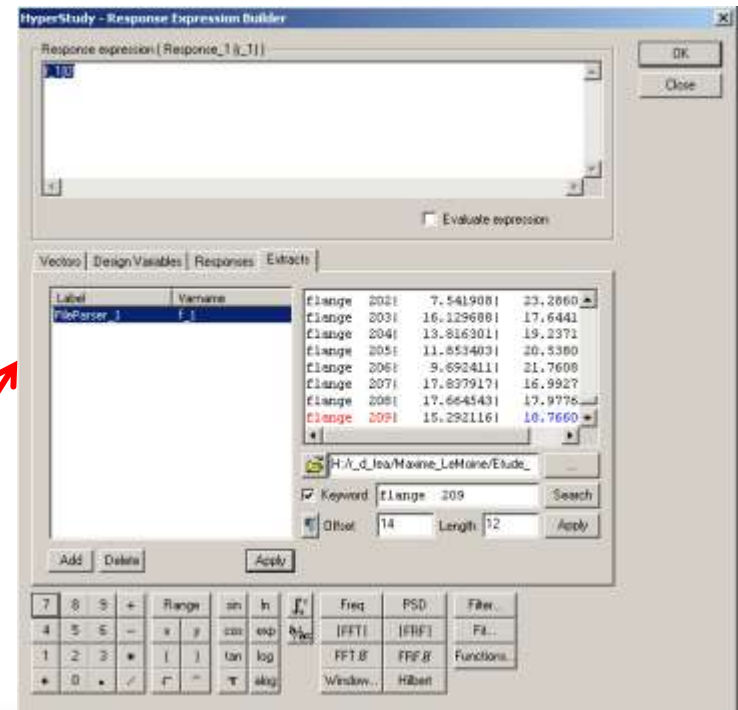
- During initialization: choice of couples *contacts/loadcases* to study
- During a calculation: writing of a text file containing the forces applied to a contact during the associated loadcase, for each increment and both X- and Y- axis



```
results.txt - Bloc-notes
Fichier Edition Format Affichage ?
Total elements area:
261.167327

model_0.7.dat --- degr --- flange
Flange inc force_X | force_Y
-----
Flange 110 | 0.000000 | 2.444576
Flange 111 | 0.000003 | 2.444568
Flange 112 | 6.218544 | 10.433131
Flange 113 | 8.883566 | 14.192656
Flange 114 | 9.045985 | 14.206699
Flange 115 | 9.238351 | 14.266963
Flange 116 | 9.511280 | 14.378876
Flange 117 | 9.709661 | 14.411681
Flange 118 | 9.881314 | 14.465322
Flange 119 | 9.983153 | 14.489502
Flange 120 | 10.347906 | 14.643765
Flange 121 | 13.079556 | 17.207178
Flange 122 | 7.736941 | 11.297066
Flange 123 | 8.898377 | 12.515228
Flange 124 | 4.575753 | 8.552328
Flange 125 | 5.793175 | 9.972984
Flange 126 | 4.004313 | 8.697959
```

- After the nominal run, choice of particular values by a tool in HyperStudy



DOE

| Label | Varname |
|-------|---------|
| Doe_1 | doe_1 |
| Doe_2 | doe_2 |
| Doe_3 | doe_3 |

Controlled factors

DOE Class:

Number of runs:

- ✓ Type of DOE
- ✓ Number of runs
- ✓ Set of possible values for each parameter
- ✓ Set of combinations for all parameters

Design variables

| On | Label | Variable Name | Model Parameter |
|-------------------------------------|-----------------|---------------------|---------------------|
| <input checked="" type="checkbox"/> | hauteur | m_1_hauteur | m_1_hauteur |
| <input checked="" type="checkbox"/> | epaisseur_inter | m_1_epaisseur_inter | m_1_epaisseur_inter |
| <input checked="" type="checkbox"/> | epaisseur_ext | m_1_epaisseur_ext | m_1_epaisseur_ext |
| <input checked="" type="checkbox"/> | rayon_ext | m_1_rayon_ext | m_1_rayon_ext |
| <input checked="" type="checkbox"/> | rayon_int | m_1_rayon_int | m_1_rayon_int |

Design variable properties

Type:

Mode:

Class:

Initial value:

Lower bound:

Upper bound:

No. of levels:

Value table

| | |
|----|------------|
| 1 | -0.9920319 |
| 2 | -0.9840637 |
| 3 | -0.9760956 |
| 4 | -0.9681275 |
| 5 | -0.9601594 |
| 6 | -0.9521912 |
| 7 | -0.9442231 |
| 8 | -0.9362550 |
| 9 | -0.9282869 |
| 10 | -0.9203187 |
| 11 | -0.9123506 |
| 12 | -0.9043825 |
| 13 | -0.8964143 |
| 14 | -0.8884462 |
| 15 | -0.8804781 |
| 16 | -0.8725100 |
| 17 | -0.8645418 |
| 18 | -0.8565737 |
| 19 | -0.8486056 |
| 20 | -0.8406375 |
| 21 | -0.8326693 |
| 22 | -0.8247012 |
| 23 | -0.8167331 |
| 24 | -0.8087649 |
| 25 | -0.8007968 |
| 26 | -0.7928287 |
| 27 | -0.7848606 |
| 28 | -0.7768924 |
| 29 | -0.7689243 |
| 30 | -0.7609562 |
| 31 | -0.7529881 |
| 32 | -0.7450199 |
| 33 | -0.7370518 |
| 34 | -0.7290837 |
| 35 | -0.7211156 |
| 36 | -0.7131474 |

DOE Run Table

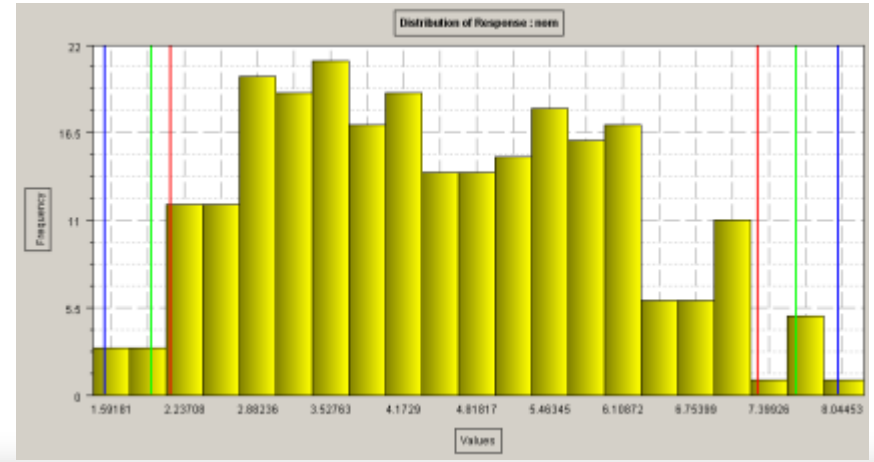
| Runs | State | hauteur | epaisseur_inter | epaisseur_ext | rayon_ext | rayon_int |
|------|-------------------------------------|------------|-----------------|---------------|-----------|-----------|
| 1 | <input checked="" type="checkbox"/> | -0.9820319 | 0.4520778 | 0.5355897 | 0.5043306 | 0.8562273 |
| 2 | <input checked="" type="checkbox"/> | -0.9840637 | 0.2454184 | -0.5206482 | 0.5322153 | 0.1548279 |
| 3 | <input checked="" type="checkbox"/> | -0.9760956 | -0.3823019 | 0.7804363 | 0.8067446 | 0.7019847 |
| 4 | <input checked="" type="checkbox"/> | -0.9681275 | 0.1468894 | 0.6703458 | 0.1468026 | 0.8908048 |
| 5 | <input checked="" type="checkbox"/> | -0.9601594 | -0.1282617 | -0.7484521 | 0.8200756 | 0.0804686 |
| 6 | <input checked="" type="checkbox"/> | -0.9521912 | -0.7748451 | -0.1298676 | 0.4104989 | 0.5876881 |
| 7 | <input checked="" type="checkbox"/> | -0.9442231 | 0.3853056 | -0.0103367 | 0.8177317 | 0.3140878 |
| 8 | <input checked="" type="checkbox"/> | -0.9362550 | -0.5001717 | 0.6094995 | 0.2380605 | 0.0418845 |
| 9 | <input checked="" type="checkbox"/> | -0.9282869 | 0.3030536 | 0.4740803 | 0.5251319 | 0.0917517 |
| 10 | <input checked="" type="checkbox"/> | -0.9203187 | 0.1896325 | -0.7337520 | 0.3751750 | 0.8481170 |
| 11 | <input checked="" type="checkbox"/> | -0.9123506 | -0.2853423 | -0.5391070 | 0.8127536 | 0.9127389 |
| 12 | <input checked="" type="checkbox"/> | -0.9043825 | 0.8576519 | -0.4707254 | 0.1108441 | 0.1923712 |
| 13 | <input checked="" type="checkbox"/> | -0.8964143 | 0.4444601 | -0.4488063 | 0.8873528 | 0.7234095 |
| 14 | <input checked="" type="checkbox"/> | -0.8884462 | -0.3845833 | 0.1702874 | 0.7847725 | 0.6378666 |
| 15 | <input checked="" type="checkbox"/> | -0.8804781 | 0.0020942 | -0.6473793 | 0.4548410 | 0.8278873 |
| 16 | <input checked="" type="checkbox"/> | -0.8725100 | 0.7781939 | -0.2221141 | 0.4445913 | 0.7032206 |
| 17 | <input checked="" type="checkbox"/> | -0.8645418 | -0.1678079 | 0.4381295 | 0.1143301 | 0.7178857 |
| 18 | <input checked="" type="checkbox"/> | -0.8565737 | 0.3582483 | 0.5423557 | 0.0471329 | 0.1128839 |
| 19 | <input checked="" type="checkbox"/> | -0.8486056 | 0.3850594 | 0.7336051 | 0.6684181 | 0.0802343 |
| 20 | <input checked="" type="checkbox"/> | -0.8406375 | 0.1715766 | 0.7986456 | 0.9102580 | 0.3179624 |
| 21 | <input checked="" type="checkbox"/> | -0.8326693 | 0.7457522 | 0.4418625 | 0.5177421 | 0.0214120 |
| 22 | <input checked="" type="checkbox"/> | -0.8247012 | -0.4043445 | 0.5701958 | 0.0100907 | 0.7586588 |
| 23 | <input checked="" type="checkbox"/> | -0.8167331 | 0.3371270 | 0.4113169 | 0.7042651 | 0.1961543 |
| 24 | <input checked="" type="checkbox"/> | -0.8087649 | 0.8377678 | -0.5711079 | 0.1524624 | 0.8849863 |
| 25 | <input checked="" type="checkbox"/> | -0.8007968 | -0.2094085 | 0.6321044 | 0.7167313 | 0.6182036 |
| 26 | <input checked="" type="checkbox"/> | -0.7928287 | 0.3071780 | 0.3878344 | 0.0393900 | 0.7690565 |
| 27 | <input checked="" type="checkbox"/> | -0.7848606 | 0.2580633 | 0.2958470 | 0.2804258 | 0.8314586 |
| 28 | <input checked="" type="checkbox"/> | -0.7768924 | -0.9836340 | -0.9056275 | 0.5808116 | 0.4754597 |
| 29 | <input checked="" type="checkbox"/> | -0.7689243 | -0.0589904 | -0.8598422 | 0.8891748 | 0.0373883 |
| 30 | <input checked="" type="checkbox"/> | -0.7609562 | -0.9804337 | 0.7038889 | 0.8910057 | 0.3896447 |
| 31 | <input checked="" type="checkbox"/> | -0.7529881 | -0.9027885 | 0.0926751 | 0.0376401 | 0.0485275 |
| 32 | <input checked="" type="checkbox"/> | -0.7450199 | -0.1498774 | 0.5433363 | 0.1958437 | 0.7167370 |
| 33 | <input checked="" type="checkbox"/> | -0.7370518 | 0.3808396 | -0.9372479 | 0.7743181 | 0.3443740 |
| 34 | <input checked="" type="checkbox"/> | -0.7290837 | -0.3535107 | -0.8018480 | 0.3033137 | 0.1174221 |
| 35 | <input checked="" type="checkbox"/> | -0.7211156 | 0.1419517 | 0.9388632 | 0.8160110 | 0.6253805 |
| 36 | <input checked="" type="checkbox"/> | -0.7131474 | -0.4070764 | 0.5318536 | 0.2865757 | 0.0873487 |

DOE: results

| Extract | | Post-process | | | | |
|---------|-------|--------------|-------|-----------|-----------|-----------|
| Run | State | Run | State | mini | nom | maxi |
| 1 | ✓ | 1 | ✓ | 1.0450960 | 1.9584940 | 3.7718500 |
| 2 | ✓ | 2 | ✓ | 2.7627400 | 5.1002610 | 8.8145890 |
| 3 | ✓ | 3 | ✓ | 2.3157120 | 4.4913610 | 7.8961890 |
| 4 | ✓ | 4 | ✓ | 1.3643910 | 2.8765670 | 5.8128030 |
| 5 | ✓ | 5 | ✓ | 0.8487170 | 1.6935980 | 3.5082760 |
| 6 | ✓ | 6 | ✓ | 0.8562270 | 1.7538960 | 3.6492560 |
| 7 | ✓ | 7 | ✓ | 2.1665510 | 4.2418960 | 7.9212790 |
| 8 | ✓ | 8 | ✓ | 2.2508740 | 4.2838920 | 8.2077420 |
| 9 | ✓ | 9 | ✓ | 1.8322850 | 3.3979580 | 6.4089000 |
| 10 | ✓ | 10 | ✓ | 0.8175650 | 1.7303670 | 3.6332400 |
| 11 | ✓ | 11 | ✓ | 2.3970070 | 4.6045270 | 8.2081790 |
| 12 | ✓ | 12 | ✓ | 1.4055130 | 2.9954320 | 5.7196890 |
| 13 | ✓ | 13 | ✓ | 2.3412960 | 4.5739770 | 8.0819220 |
| 14 | ✓ | 14 | ✓ | 2.9048180 | 5.4012630 | 9.1522780 |
| 15 | ✓ | 15 | ✓ | 1.0048130 | 2.1831779 | 4.4340620 |
| 16 | ✓ | 16 | ✓ | 2.1296790 | 4.1669670 | 8.0469940 |
| 17 | ✓ | 17 | ✓ | 1.5451010 | 3.2455280 | 6.2678010 |
| 18 | ✓ | 18 | ✓ | 0.9412210 | 2.0798830 | 4.2338840 |
| 19 | ✓ | 19 | ✓ | 2.2684120 | 4.4870000 | 8.2043110 |
| 20 | ✓ | 20 | ✓ | 2.4063590 | 4.5591020 | 7.7964580 |
| 21 | ✓ | 21 | ✓ | 1.8311530 | 3.7364480 | 7.0539880 |
| 22 | ✓ | 22 | ✓ | 1.7632060 | 3.6653630 | 6.7267680 |
| 23 | ✓ | 23 | ✓ | 1.3473890 | 2.9020150 | 5.5002180 |
| 24 | ✓ | 24 | ✓ | 2.8077080 | 4.7514280 | 9.0236110 |
| 25 | ✓ | 25 | ✓ | 1.2058600 | 2.6126870 | 5.0087010 |
| 26 | ✓ | 26 | ✓ | 1.4687310 | 2.7418720 | 5.0353620 |
| 27 | ✓ | 27 | ✓ | 1.7564850 | 3.3954800 | 6.1336110 |
| 28 | ✓ | 28 | ✓ | 1.4343280 | 2.8475530 | 5.1938350 |
| 29 | ✓ | 29 | ✓ | 2.7343300 | 5.2090980 | 8.8973620 |
| 30 | ✓ | 30 | ✓ | 1.9120870 | 3.8826430 | 6.8884200 |
| 31 | ✓ | 31 | ✓ | 2.9444750 | 5.4809000 | 9.0764930 |
| 32 | ✓ | 32 | ✓ | 2.9363880 | 5.4425380 | 9.0654030 |
| 33 | ✓ | 33 | ✓ | 2.4647590 | 4.7866880 | 8.1818700 |
| 34 | ✓ | 34 | ✓ | 1.0791070 | 3.8912090 | 7.0584180 |
| 35 | ✓ | 35 | ✓ | 1.5053830 | 3.0267890 | 5.4639470 |
| 36 | ✓ | 36 | ✓ | 2.2603370 | 4.3666720 | 7.5243160 |
| 37 | ✓ | 37 | ✓ | 1.6132580 | 3.3884080 | 6.1103030 |

| | min | nom | max | hauteur | epaisseur_i~ | epaisseur_e~ | rayon_ext | rayon_int |
|--------------|--------|--------|--------|---------|--------------|--------------|-----------|-----------|
| Forces | | | | | | | | |
| mini | 1 | 0.99 | 0.95 | 0.43 | -0.07 | -0.2 | -0.055 | -0.022 |
| nom | 0.99 | 1 | 0.99 | 0.32 | -0.094 | -0.19 | -0.048 | -0.02 |
| maxi | 0.95 | 0.99 | 1 | 0.2 | -0.099 | -0.18 | -0.044 | -0.024 |
| Variables | | | | | | | | |
| hauteur | 0.43 | 0.32 | 0.2 | 1 | 0.045 | -0.12 | 0.015 | 0.027 |
| epaisseur_i~ | -0.07 | -0.094 | -0.099 | 0.045 | 1 | -0.033 | -0.15 | 0.048 |
| epaisseur_e~ | -0.2 | -0.19 | -0.18 | -0.12 | -0.033 | 1 | 0.048 | 0.001 |
| rayon_ext | -0.055 | -0.048 | -0.044 | 0.015 | -0.15 | 0.048 | 1 | 0.067 |
| rayon_int | -0.022 | -0.02 | -0.024 | 0.027 | 0.048 | 0.001 | 0.067 | 1 |

- ✓ Extraction of results
- ✓ Main and secondary effects
- ✓ Distribution of responses



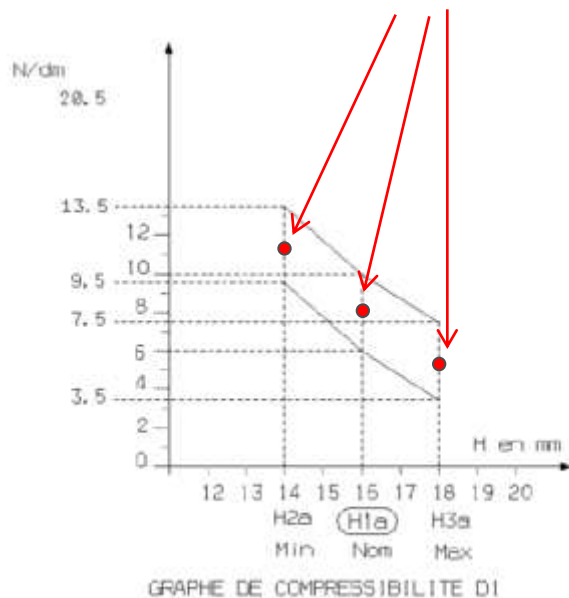
Optimization

Optimization:

| Label | Varname |
|----------------|---------|
| Optimization_1 | opt_1 |
| Optimization_2 | opt_2 |
| Optimization_3 | opt_3 |

Optimization Engine: [ARSM] - Adaptive Response Surface Method

- Choice of the optimization algorithm: ARSM for a shape optimization
- Choice of the objectives: get as close as possible to the requirements



Define objective

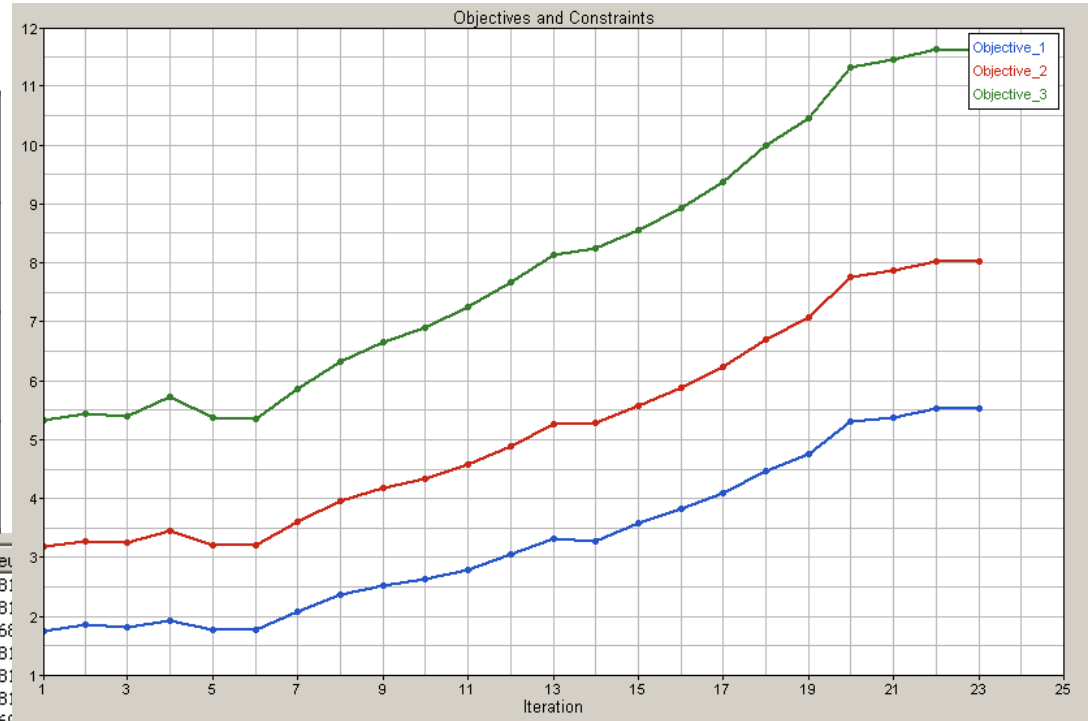
Goal: System Identification

| | On | Label | Varname | Apply On | Evaluate from | Target Value |
|---|-------------------------------------|-------------|---------|----------|---------------|--------------|
| ▶ | <input checked="" type="checkbox"/> | Objective_1 | obj_1 | mini | SOLVER | 5.5000000 |
| | <input checked="" type="checkbox"/> | Objective_2 | obj_2 | nom | SOLVER | 8.0000000 |
| | <input checked="" type="checkbox"/> | Objective_3 | obj_3 | maxi | SOLVER | 11.5000000 |

Optimization: results

Convergence in 23 iterations

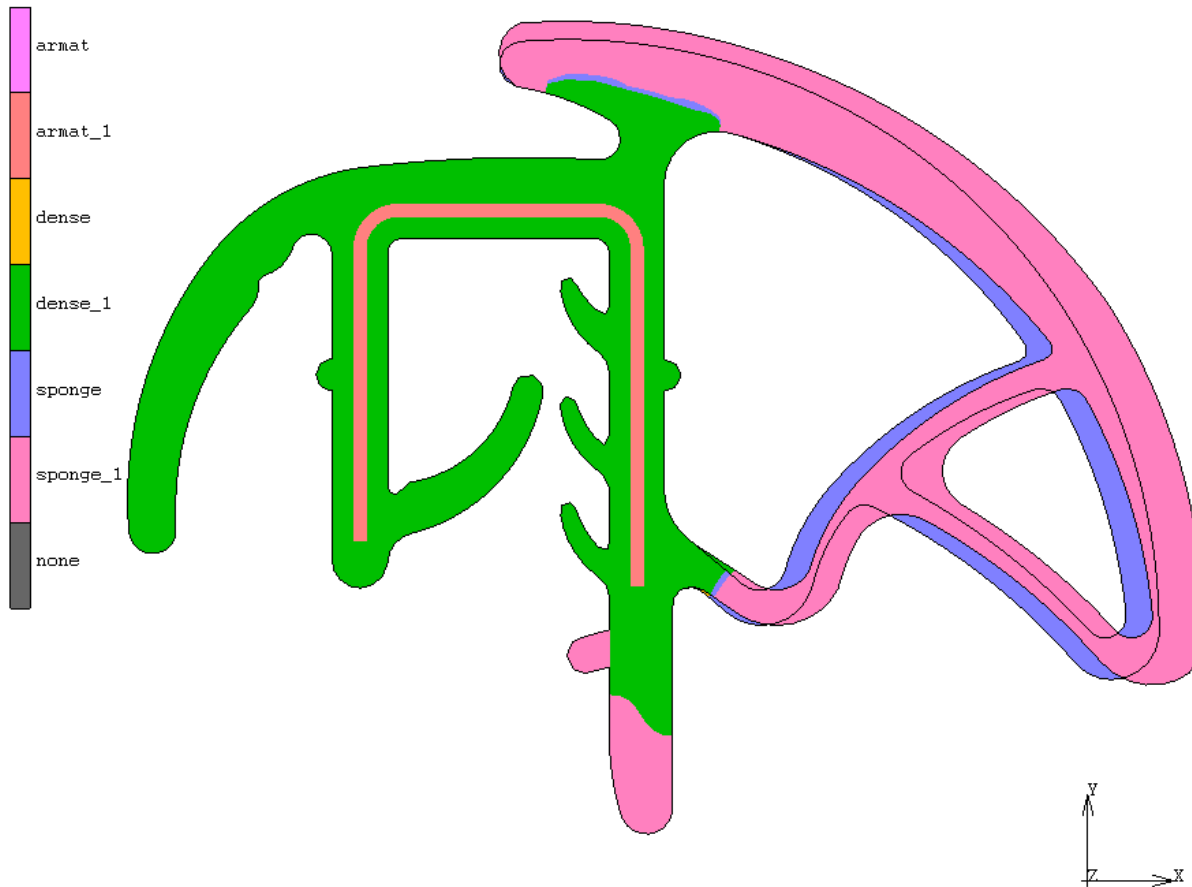
| | Optimized design | Requirements |
|---------------|------------------|--------------|
| Force mini | 5.52 | 5.5 |
| Force nominal | 8.01 | 8.0 |
| Force maxi | 11.60 | 11.5 |



| Iteration | Objective_1 | Objective_2 | Objective_3 | hauteur | epaisseur |
|-----------|-------------|-------------|-------------|-----------|------------|
| 1 | 1.7548590 | 3.1856950 | 5.3329180 | 0.8200000 | -0.81 |
| 2 | 1.8608490 | 3.2841180 | 5.4390250 | 0.9553000 | -0.81 |
| 3 | 1.8184810 | 3.2570870 | 5.4018500 | 0.8200000 | -0.66 |
| 4 | 1.9213130 | 3.4410200 | 5.7186250 | 0.8200000 | -0.81 |
| 5 | 1.7827910 | 3.2164930 | 5.3630400 | 0.8200000 | -0.81 |
| 6 | 1.7672500 | 3.2042940 | 5.3560190 | 0.8200000 | -0.81 |
| 7 | 2.0873300 | 3.5964750 | 5.8583790 | 0.9430000 | -0.66 |
| 8 | 2.3678460 | 3.9506650 | 6.3150310 | 1.0000000 | -0.5910050 |
| 9 | 2.5225420 | 4.1768660 | 6.6601800 | 1.0000000 | -0.6969629 |
| 10 | 2.6403190 | 4.3430700 | 6.9024830 | 1.0000000 | -0.7052751 |
| 11 | 2.7857680 | 4.5709150 | 7.2566520 | 1.0000000 | -0.7109561 |
| 12 | 3.0444790 | 4.8961560 | 7.6731830 | 1.0000000 | -0.6108504 |
| 13 | 3.3290180 | 5.2579190 | 8.1325590 | 1.0000000 | -0.5108504 |
| 14 | 3.2649290 | 5.2951730 | 8.2487290 | 0.8207157 | -0.6108504 |
| 15 | 3.5793150 | 5.5791030 | 8.5487080 | 1.0000000 | -0.4108504 |
| 16 | 3.8228340 | 5.8812700 | 8.9328620 | 1.0000000 | -0.3108504 |
| 17 | 4.0920400 | 6.2281040 | 9.3797400 | 1.0000000 | -0.2108504 |
| 18 | 4.4671130 | 6.7050850 | 9.9973990 | 1.0000000 | -0.1108504 |
| 19 | 4.7656560 | 7.0783960 | 10.460629 | 1.0000000 | -0.0450885 |
| 20 | 5.3059130 | 7.7559700 | 11.308955 | 1.0000000 | 0.0549115 |
| 21 | 5.3823700 | 7.8592270 | 11.445607 | 0.9961363 | 0.0359115 |
| 22 | 5.5289070 | 8.0260790 | 11.625439 | 1.0000000 | 0.1359115 |
| 23 | 5.5220340 | 8.0137000 | 11.603008 | 1.0000000 | 0.1517210 |

Optimization: optimized section

Comparison *Initial CAD section* / *optimized section*



Geometric differences:

Height : +1mm

Thickness_ext : +0.86mm

Thickness_int : +0.15mm

Radius_ext : +0.96mm

Radius_int : +0.97mm

Stochastic study

- ✓ Check for robustness of the optimized design
- ✓ Choice of type of study

Stochastic Study:

| Label | Varname |
|-------|---------|
| Sto_1 | sto_1 |

Sampling

Type: Hammersley

Number of runs: 100

- ✓ Distribution of input variables

Random variable properties

Type: Real

Mode: Continuous

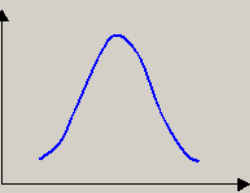
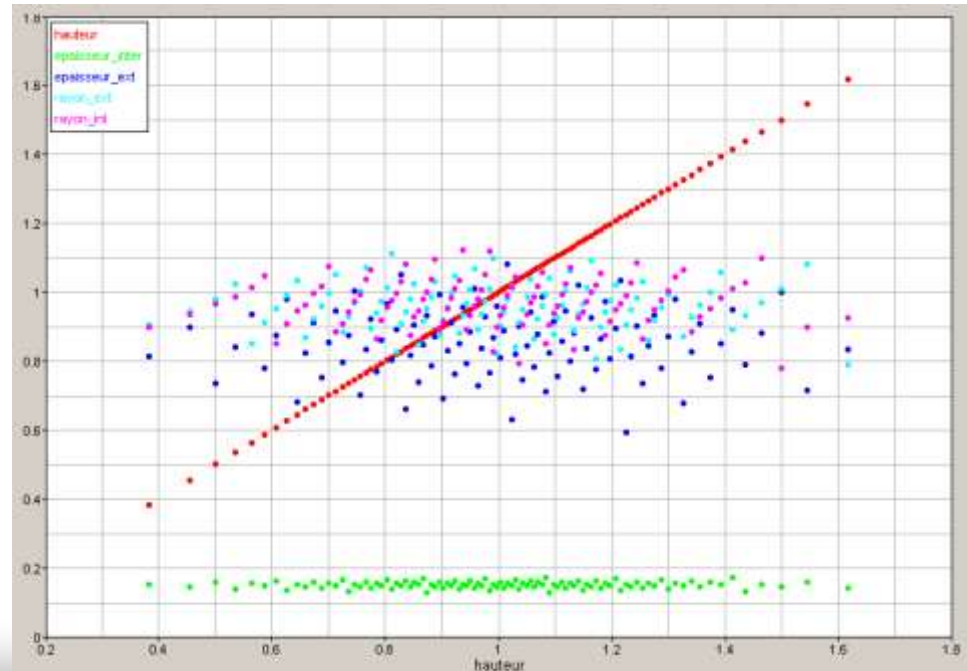
Distribution: Normal

Mean: 1.0000000

Variance: 0.0700000

CoV: 0.2645751

Distribution properties


$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$


Stochastic study: results

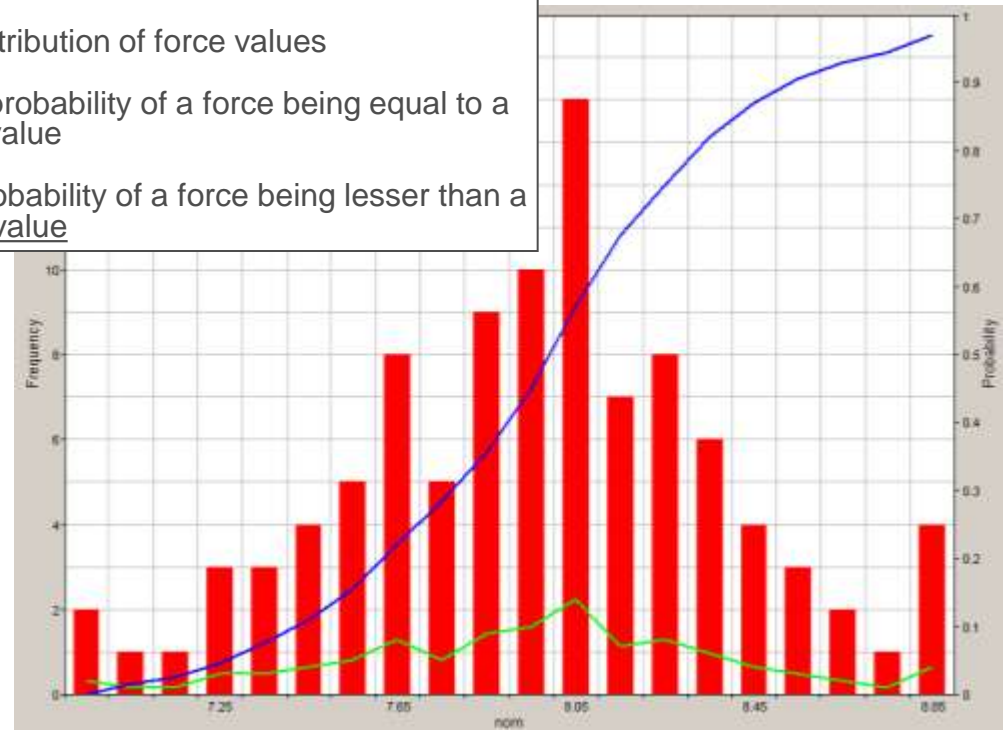
- Probability bar chart
- Statistic indicator

Nominal force

Red : distribution of force values

Green : probability of a force being equal to a specific value

Blue : probability of a force being lesser than a specific value



- Robustness indicator:
- Solution is robust

| | mini | nom | maxi |
|-----------|------------|------------|------------|
| Mean | 5.4662116 | 7.9635887 | 11.545768 |
| Avg. Dev. | 0.3468417 | 0.3344647 | 0.4010990 |
| Std. Dev. | 0.4348599 | 0.4210807 | 0.5110038 |
| Variance | 0.1891031 | 0.1773089 | 0.2611249 |
| CoV | 0.0795542 | 0.0528757 | 0.0442590 |
| Skewness | -0.0800649 | -0.0689962 | -0.0185944 |
| Median | 5.4683095 | 7.9502505 | 11.572595 |
| RMS | 5.4833093 | 7.9746022 | 11.556957 |
| Min | 4.3875740 | 6.9787310 | 10.346871 |
| Max | 6.4297900 | 8.8894300 | 12.789698 |
| Range | 2.0422160 | 1.9106990 | 2.4428270 |

| | Response | Bound Type | Bound Value | Reliability | Probability of Failure |
|---|----------|------------|-------------|-------------|------------------------|
| ► | mini | <= | 6.2162870 | 0.9500000 | 0.0500000 |
| | nom | <= | 8.6524290 | 0.9500000 | 0.0500000 |
| | maxi | <= | 12.359195 | 0.9500000 | 0.0500000 |

Conclusions



- ✓ New design approach
- ✓ Effect of extrusion tolerance on the design response investigated
- ✓ Optimal response predicted using numerical model
- ✓ Design of optimal solution is robust
- ✓ The approach used is valid for shape definition that meets specified design requirements.
- ✓ Can be extended to define manufacturing tolerances of the design

A world map with a yellow and orange color scheme. The map is semi-transparent and shows the outlines of continents. Several regions are highlighted in a bright yellow color, including parts of North America, Europe, and Asia. The background of the map is a light yellowish-green.

Merci
Thank you

