Meta Modeling
and
Multi Objective Optimization

By: Srinivasan K (ENB2)
Robert Bosch Engineering and Business Solutions, India

Mentors: Mr. Schirrmacher Roland (CR/ARH2)
Mr. Allgeier Christian (ED/ETS1)
Robert Bosch GmbH, Germany
Meta-Modeling and Multi Objective Optimization

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• Scanning Design space
• Stochastic sampling: Why?
• LHS Sampling
• DOE: Sensitivity study
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Scanning Design Space

- Output variability and input sensitivities
- Input parameter significance and multivariate dependencies
- Minimum number of designs should cover the input space optimally and avoid clustering
- For each design/sample the outputs are calculated/measured

Source: Dynardo
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Stochastic Sampling: Why?

- Deterministic designs use maximum 3 levels for each variable
- LHS has for each variable N levels
  - If we reduced the variable space be removing unimportant variables, deterministic designs loose the information of these variables, but with LHS this is not the case

- Example: 4 minor and 1 major important input variables:

  ![Graph 1](image1)
  ![Graph 2](image2)

LHS, 100 samples

Full factorial, 243 designs

Source: Dynardo
**Latin Hypercube Sampling**

- Improved Monte Carlo Simulation
- Cumulative distribution function is subdivided into N classes with same probability
- Reduced number of required samples for statistical estimates
- Reduced unwanted input correlations
- Add optimal samples to an existing set of LHS samples (ALHS)

Source: Dynardo
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DOE: Sensitivity Study

- DOE helps for following
  - To find out the effect of the input parameter variation over the output responses and to rank the important parameters with respect to the output.
  - It is the base data to generate meta models, which are helpful to minimize the actual sample runs and minimize overall optimization lead time.
- Procedure for DOE is to generate LHS (Latin Hypercube) sample and run for the DOE analysis
- Sensitivity co-efficient are calculated during DOE run and important parameters are identified.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>dr</td>
<td>20 to 27.5 mm</td>
</tr>
<tr>
<td>d1</td>
<td>...</td>
</tr>
<tr>
<td>L</td>
<td>...</td>
</tr>
</tbody>
</table>
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Sensitivity based on Linear correlation coefficient
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Meta-model of Optimal Prognosis (MOP)

- Approximation of solver output by fast surrogate model
- Reduction of input space to get best compromise between available information (samples) and model representation (number of input variables)
- Advanced filter technology to obtain candidates of optimal subspace (significance and CoI filters)
- Determination of most appropriate approximation model (polynomials with linear or quadratic basis, MLS, ..., Box-Cox)
- Assessment of approximation quality (CoP)

- MOP solves three important tasks:
  - Best variable subspace
  - Best meta-model
  - Determination of prediction quality

Source: Dynardo
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COP: Example

- The COP value for the meta models are good and these models can be used for further optimization

protocol.txt

<table>
<thead>
<tr>
<th>Response</th>
<th>meta model</th>
<th>no. parameter</th>
<th>CoD adj.</th>
<th>CoD</th>
</tr>
</thead>
<tbody>
<tr>
<td>RecdB</td>
<td>Partially Quadratic Regression</td>
<td>3</td>
<td>0.9520</td>
<td>0.9484</td>
</tr>
<tr>
<td></td>
<td>Important variables: L, dss, bys</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Linear Regression</td>
<td>3</td>
<td>0.9820</td>
<td>0.9806</td>
</tr>
<tr>
<td></td>
<td>Important variables: L, dss, bys</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Linear Regression</td>
<td>3</td>
<td>0.9820</td>
<td>0.9806</td>
</tr>
<tr>
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<td>Important variables: L, dss, bys</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Linear Regression</td>
<td>3</td>
<td>0.9820</td>
<td>0.9806</td>
</tr>
<tr>
<td></td>
<td>Important variables: L, dss, bys</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**Model of optimized prognosis**

<table>
<thead>
<tr>
<th>response name</th>
<th>meta model</th>
<th>no. parameter</th>
<th>CoD adj.</th>
<th>CoD</th>
</tr>
</thead>
<tbody>
<tr>
<td>RecdB</td>
<td>Quadratic (no mixed)</td>
<td>3</td>
<td>0.9983</td>
<td>0.9882</td>
</tr>
<tr>
<td></td>
<td>Linear Regression</td>
<td>3</td>
<td>0.9920</td>
<td>0.9906</td>
</tr>
</tbody>
</table>

---

**Relative frequency of importance**

- d1: 0 ±
- L: 100 ±
- d1: 0 ±
- dss: 100 ±
- bss1: 0 ±
- bss2: 0 ±
- bss1: 0 ±
- bss: 67 ±
- bss: 0 ±
- bss: 0 ±

Source: Dynardo
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Generic Data Processing for MOO

Parameter file → Optislang

- Geometry Processing Script
  - Pre-processing script - dynamic
  - Pre-processing script - static

Geometry → Pre-Processor → FE Solver → Output Files

ETK Output file

Post-processing Tool (ETK)
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ETK (Extraction Tool Kit)

- Import of ABAQUS, ANSYS, Adams and Edyson result files
- GUI- and Batch modus
- Visualisation as xy-Plots (field and history data)
- Manipulation of results by mathematical functions and own macros
- Export of scalar, vector and signal data to OptiSLang-Problemfile (*.pro), ASCII (*.out), Excel (*.xml)
- Usage for optimization and analysis

Source: Mr. Schirrmacher Roland (CR/ARH2)
CASE STUDY
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Optimization Problem

» Design Variable:
  • Height and thickness of 8 ribs.

» Response Variables:
  • V.mises stress at 8 ribs
  • 1st bending frequency
  • Total reaction force at mounting points.

» Objectives:
  • Minimizing overall dB target 1 < 120 dB (800-1100Hz)
  • Minimizing overall dB target 2 < 116 dB (1100-2000Hz)
  • Stresses at the ribs < 50 MPa

» Constraints:
  • First bending > 150 Hz

» Optimization method:
  • Pareto-Optimization

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1_H</td>
<td>0.5 to 20 mm</td>
</tr>
<tr>
<td>R1_W</td>
<td>0.5 to 3.5 mm</td>
</tr>
<tr>
<td>R2_H</td>
<td>0.5 to 20 mm</td>
</tr>
<tr>
<td>R2_W</td>
<td>0.5 to 3.5 mm</td>
</tr>
<tr>
<td>R3_H</td>
<td>0.5 to 20 mm</td>
</tr>
<tr>
<td>R3_W</td>
<td>0.5 to 3.5 mm</td>
</tr>
<tr>
<td>R4_H</td>
<td>0.5 to 20 mm</td>
</tr>
<tr>
<td>R4_W</td>
<td>0.5 to 3.5 mm</td>
</tr>
<tr>
<td>R5_H</td>
<td>0.5 to 20 mm</td>
</tr>
<tr>
<td>R5_W</td>
<td>0.5 to 3.5 mm</td>
</tr>
<tr>
<td>R6_H</td>
<td>0.5 to 20 mm</td>
</tr>
<tr>
<td>R6_W</td>
<td>0.5 to 3.5 mm</td>
</tr>
<tr>
<td>R7_H</td>
<td>0.5 to 20 mm</td>
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<tr>
<td>R7_W</td>
<td>0.5 to 3.5 mm</td>
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<tr>
<td>R8_H</td>
<td>0.5 to 20 mm</td>
</tr>
<tr>
<td>R8_W</td>
<td>0.5 to 3.5 mm</td>
</tr>
</tbody>
</table>
Definition of steps and output

- Static analysis
  - Static perturbation step using two load cases
  - Output of displacements and v.Mises stress as field output
  - Extraction of maximum v.Mises stresses at ribs, mounting points and inner part by ETK

- Dynamic analysis
  - Modal perturbation step up to 4 kHz
  - Steady State Dynamics (modal) step from 800 Hz to 2000 Hz
  - Tabular modal damping between 0.02 and 0.05
  - Output of reaction forces at mounting points as history output
  - Extraction and conversion of reaction forces at mounting points and shaft by ETK
Correlation matrix of training data (1/2)

- R1_H has the biggest influence of the bending frequency; high R1_H means high frequency.
- No clear correlation to the v.Mises stress at the mounting points and inner part.
- V.Mises stress at the ribs are mostly influenced by the geometry of each rib; there are mostly no global effects between the ribs. High Rx_H and Rx_W mean low v.Mises stresses.
- R1_H, R1_W and R3_H have the biggest influence on the reaction forces in both frequency ranges, but with positive / negative correlation coefficient.

Bending frequency

V.Mises stress at mounting points and inner part

V.Mises stress at rib 1 to 8 for loadcase 1 and 2

Reaction force in frequency range 1

Reaction force in frequency range 2
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Correlation matrix of training data (2/2)

High values of the integral reaction forces mean high values of the maximum reaction force in the frequency range 1 (800 – 1100 Hz).

High values of the integral reaction forces mean high values of the maximum reaction force in the frequency range 2 (1100-2000 Hz).

High values of the integral reaction forces in the frequency range 2 mean low values of the bending frequency.

High values of the integral reaction forces in the frequency range 1 mean low values in the frequency range 2.
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DOE: Observations

- The sensitive parameters are identified for different output variables.
  - R1, R2, R3, R4 ribs are mainly influencing the overall dB
- All the rib dimensions are directly related to the stress increase. So if the dimensions of the ribs reduced the respective stress increases.
- It is also observed that the overall dB in the 800-1100Hz requirements are in contrast with the overall dB requirement in the 1100-2000Hz range.
- To meet the contradicting requirements Pareto-optimization needs to be used.
- Due to limitations in time, s/w and h/w, meta models are preferred to speed up the optimization process.
Meta model

- These meta models have been tested and the accuracy of the meta model is shown in the below graph as % error.
- From the graph it is inferred that meta models are good for studying the dynamic behavior and the static stress at the ribs.
Optimization results (1/2)

results based on ASCMO-analysis

No design fulfills the dynamic targets of max. 120 dB (800-1100 Hz) and max. 116 dB (1100-2000 Hz).
## Meta-model Runs

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Name</th>
<th>Algorithm</th>
<th>Start population</th>
<th>Best Design</th>
<th>Total runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Pareto Optimization 1</td>
<td>EA</td>
<td>1000</td>
<td>3987</td>
<td>5608</td>
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<tr>
<td>2</td>
<td>Pareto Optimization 2</td>
<td>EA</td>
<td>1000</td>
<td>3498</td>
<td>4400</td>
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<tr>
<td>3</td>
<td>Pareto Optimization 3</td>
<td>PSO</td>
<td>1000</td>
<td>9340</td>
<td>10000</td>
</tr>
<tr>
<td>4</td>
<td>Pareto Optimization 4</td>
<td>EA</td>
<td>1000</td>
<td>1216</td>
<td>1284</td>
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<td>5</td>
<td>Pareto Optimization 5</td>
<td>EA</td>
<td>1000</td>
<td>212</td>
<td>788</td>
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<tr>
<td>6</td>
<td>Nature inspired Optimization 1</td>
<td>EA</td>
<td>1000</td>
<td>1051</td>
<td>1284</td>
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<tr>
<td>7</td>
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<td>EA</td>
<td>1000</td>
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<td>8</td>
<td>Nature inspired Optimization 1</td>
<td>EA</td>
<td>1000</td>
<td>592</td>
<td>788</td>
</tr>
</tbody>
</table>

### Overall dB Reduction

<table>
<thead>
<tr>
<th></th>
<th>V1</th>
<th>V2</th>
<th>V3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>122.4</td>
<td>117.6</td>
<td>117.9</td>
</tr>
</tbody>
</table>
## Verification Results Comparison

<table>
<thead>
<tr>
<th>Load1 case</th>
<th>Reaction dB</th>
<th>Acceleration dB</th>
<th>Mass in kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Meta</td>
<td>CAE</td>
<td>Meta</td>
</tr>
<tr>
<td>BASE</td>
<td>-</td>
<td>137.5</td>
<td>-</td>
</tr>
<tr>
<td>V1</td>
<td>125</td>
<td>125</td>
<td>56.5</td>
</tr>
<tr>
<td>V2</td>
<td>119.4</td>
<td>119.4</td>
<td>54.7</td>
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<tr>
<td>V3</td>
<td>128.9</td>
<td>128.9</td>
<td>59.8</td>
</tr>
<tr>
<td>V4</td>
<td>-</td>
<td>126.1</td>
<td>-</td>
</tr>
<tr>
<td>V5</td>
<td>-</td>
<td>121.2</td>
<td>-</td>
</tr>
<tr>
<td>V6</td>
<td>-</td>
<td>126.4</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load2 case</th>
<th>Reaction dB</th>
<th>Acceleration dB</th>
<th>Mass in kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Meta</td>
<td>CAE</td>
<td>Meta</td>
</tr>
<tr>
<td>BASE</td>
<td>-</td>
<td>108.6</td>
<td>-</td>
</tr>
<tr>
<td>V1</td>
<td>-</td>
<td>105.5</td>
<td>-</td>
</tr>
<tr>
<td>V2</td>
<td>-</td>
<td>101.8</td>
<td>-</td>
</tr>
<tr>
<td>V3</td>
<td>-</td>
<td>107.2</td>
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<tr>
<td>V4</td>
<td>104.8</td>
<td>104.8</td>
<td>57.5</td>
</tr>
<tr>
<td>V5</td>
<td>101.4</td>
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<td>55.6</td>
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<tr>
<td>V6</td>
<td>105</td>
<td>105</td>
<td>57.6</td>
</tr>
</tbody>
</table>
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Design Selection: Multi-Objective
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Summary

→ Meta model has been created based form the DOE samples
→ Process to create meta models is established and it has been tested for different projects.
→ Best meta models are obtained based on COP and accuracy of the models are evaluated on the output response.
→ Meta models are used for multi-objective optimization and Different optimizations procedures have been tried with meta models.
→ Optimized designs derived from the meta models are verified using the actual models and found in good match.
→ Generic data processing scheme for the entire process is standardized.
Thank You!