MULTI-ATTRIBUTE VEHICLE PERFORMANCE OPTIMIZATION: AMESIM AND MODEFRONTIER INTERFACE

A Joint Webinar by ESTECO and SIEMENS

June 26, 2014
Agenda

• Introduction (5 min)
• Overview of modeFRONTIER (10 min)
• Overview of Imagine.Lab AMESim (10 min)
• Example 1: Optimization of a Check Valve (10 min)
• Example 2: Parallel Hybrid Vehicle (10 min)
• Conclusions (5 min)
• Q & A (10 min)
Team Introduction

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Introduction modeFRONTIER
ESTECO is a pioneer in **numerical optimization** solutions

Perfecting engineering and reducing complexity in the design process is our vision.
Complexity Across Domains

Different teams create more detailed and domain specific models but need to be able to verify them against a cohesive view of the system.
Introducing modeFRONTIER

modeFRONTIER is an integration platform for **multi-objective and multi-disciplinary optimization**. It provides seamless coupling with third party engineering tools, enables the **automation** of the design simulation process, and facilitates **analytic decision making**.
What can you do with modeFRONTIER?

- Integration and Process Automation
- Optimization
- Robust Design and Reliability
- Design Space Exploration
- Analytics and Visualization
- Decision Making
The modeFRONTIER workflow guarantees formalization and management of all logical steps of an engineering process. Its powerful integration capabilities allow product engineers and designers to integrate and drive multiple Computed Aided Engineering (CAE) tools.

modeFRONTIER offers over 40 direct integration nodes to couple with the most popular engineering solvers, in which communication is guaranteed by APIs or automatic file exchange. Other wizard style tools are available for building a bridge between modeFRONTIER and any commercial or in-house codes.
ESTECO’s expertise in numerical solutions equips designers with a complete array of optimization algorithms covering deterministic, stochastic and heuristic methods for single and multi-objective problems.

Besides the traditional methods, modeFRONTIER provides fine-tuned hybrid algorithms combining the strengths of single approaches.

<table>
<thead>
<tr>
<th>LOCAL REFINEMENT</th>
<th>GRADIENT-BASED</th>
<th>DETERMINISTIC</th>
<th>HEURISTIC</th>
<th>EVOLUTIONARY</th>
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<tr>
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<td>LEVENBERG-MARQUARDT</td>
<td>SIMPLEX</td>
<td>SIMULATED ANNEALING</td>
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<td>B-BFGS</td>
<td>GAME THEORY</td>
<td>PARTICLE SWARM</td>
<td>EVOLUTION STRATEGY</td>
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Virtual optimization using response surfaces

**RSM-based, or virtual optimization** is a valid strategy which serves as a surrogate for heavy simulation processes, allowing engineers to fast-run the classic optimization process.

### How does it work in modeFRONTIER?

1. **RSMs are trained** from an available database of real designs and validated one against another.

2. The best model is used to **compute** the outputs of the system; this process is called **virtual optimization**.

3. The best designs obtained through virtual optimization are then **evaluated by the real solver**.

### Main advantages

- ✓ perform thousands of design evaluations in short time
- ✓ accelerate the optimization step
- ✓ use small amounts of data efficiently
- ✓ smart exploitation of available computational resources
The input parameters’ **uncertainty** is reflected in the outputs of the system: modeFRONTIER multi-objective robust design optimization (MORDO) algorithms generate a **scatter of samples** (noise factors) around the design, in order to verify how sensitive the design is to variations, i.e. whether the values of the outputs are still within the user-defined limits.
modeFRONTIER offers a number of sophisticated and efficient DOE methods:

- **Space Filler DOEs** serve as the starting point for a subsequent optimization process or a database for response surface training;

- **Statistical DOEs** are useful for creating samplings for the sensitivity analysis thus allowing in-depth understanding of the problem by identifying the sources of variation;

- **Robustness and reliability DOEs** help create a set of stochastic points for robustness evaluation;

- **Optimal Designs DOEs** are special purpose techniques used for reducing the dataset in a suitable way.
Analytics and Visualization

To maximize product performance, a **full and rapid understanding** of the design space is essential for extracting the most relevant information from a database of experiments.

modeFRONTIER provides a **complete and comprehensive environment for data analysis and visualization**, enabling statistical assessment of **complex datasets**. Its sophisticated **post-processing tools**, such as Sensitivity Analysis, Multi-Variate Analysis, and Visual Analysis, allow results from multiple simulations to be **visualized in a meaningful manner** and **key factors** to be identified.
ESTECO Enterprise Suite

- Collaboration
- Web-Based Access
- Project Versioning
- Multiple DOE & Optimization Strategies
- Distributed Execution
- Analysis of Results & Reporting

- Integration & Process Automation
- Robust Design & Reliability
- Virtual Optimization Using RSMs
- Advanced Analytics & Data Visualization
- Decision Making

SOMO

mode FRONTIER

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Introduction AMESim
Multi-Attribute Vehicle Performance Optimization: AMESim and modeFRONTIER interface

Siemens Introduction
June 26, 2014
The Siemens Vision: Provide Answers to the Great Challenges of our Time

Siemens – the pioneer in

- Energy efficiency
- Industrial productivity
- Affordable and personalized healthcare
- Intelligent infrastructures
Siemens Organization: Four Sectors Covering the Global Challenges

Industry

- Industry Automation
- Drive Technologies
- Customer Services

Infrastructure & Cities

- Rail Systems
- Mobility and Logistics
- Low and Medium Voltage
- Smart Grid
- Building Technologies
- Osram

Energy

- Fossil Power Generation
- Wind Power
- Solar & Hydro
- Power Transmission
- Oil & Gas
- Energy Service

Healthcare

- Imaging & Therapy
- Clinical Products
- Diagnostics
- Customer Solutions
Industry Automation: Boosting Industrial Productivity

We help boost productivity and improve resource efficiency along the entire product development and production process to enhance the competitiveness of our customers.
The Next Level of Productivity
Integrated product and production lifecycles

Overcome diminishing return of productivity
Improve Productivity

Seamless Integration
Shared data models

Best of Breed
Products
Linked by data import and export

Productivity

Integrated Product and Production Lifecycles

2000 2010 2020 2030

Product
Production

PDM
PLM
cPDM
Adoption of “systems Engineering”
Superior Product Innovation and Managing increasing complexity

“Systems Engineering”

“System of Systems Engineering”

The “Smart Products” of the Future

The “Smart Industry Solutions” of the Future

Design  System Validation  Simulate & Test  Build  Operate

Functional Performance Engineering to Drive PLM & Superior Innovation
Integrating multi-disciplinary activity...

Adopting Model Based Product Development
In all Stages of Development

…enabled by closed-loop performance verification
LMS Imagine.Lab Solutions
From Physics Based Authoring … … to Model Based System Engineering

Automotive & Ground Vehicles
- Internal Combustion Engine
- Transmission
- Thermal Systems
- Vehicle Dynamics
- Electrical Systems

Aerospace & Defense
- Landing Gear & Flight Controls
- Engine Equipment
- Environmental Control Systems
- Fuel Systems
- Aircraft Engine
- Electrical Aircraft

Mechanical Industries
- Pumps & Compressors
- Electro-Hydraulic Valves
- Fluid Actuation Systems
- Heat Exchangers
- Heat Pumps / Refrigerators
- Electrical Systems

Open and Customizable
- Scripting / Customization
  - MODELICA
  - VBA
  - AutoSAR
- Interfaceing
  - To Simulink/Matlab
  - To numerous 3D CAE
  - “FMI” Interface for
  - Mechatronic Co-simulation

Fluids
- Thermodynamics
- Energy
- Control
- Mechanical
- Internal Combustion Engine

Electrical Systems
- 30 Libraries / 4,000 Multi-physics Models
  - Validated and maintained
  - Supporting multiple levels of complexity

High-fidelity Plant Modeling
- Model reduction for Real-time – SIL, HIL
- Supporting Multiple SIL/HIL Platforms
- Interlock “Mechanical” and “Controls” Engineering
- Enable ISO 26262

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Automotive Engineering Challenges
Balancing Emissions, Cost, and Brand Performance

Eco-Driven Powertrain Concepts

Innovative and Lightweight Design

Creating Brand Value through Performance

Creating Brand Value through Systems
Current Engineering Practice: Struggling to Control Complexity

Dramatic Growth of Electronics Systems

- Cost of Software
  - 2000: €25b
  - 2010: €95b
  - 2015: €126b

Exploding Requirements and Test Cases

- Multiple Variants and System Architectures
- Multiple Sites, Multiple Participants

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What If You Could Optimize These Attributes Across the Organization?

- Performance
- Comfort
- Energy Management
- Fuel Economy
- Drivability / Safety

Multi-attribute balancing Vehicle integration

Attributes:
- Multi-attribute balancing
- Vehicle integration
- Drivability
- Comfort
- Performance
- Drivability
- Energy Management
- Powertrain
- Full Vehicle
- E&E
- Chassis and Suspension
- Body
The LMS Imagine.Lab Platform

The innovative Model-Based Systems Engineering approach for Mechatronic System Development

LMS Imagine.Lab AMESim
Software environment for multi-physics, multi-level, mechatronic system modeling, simulation and analysis

LMS Imagine.Lab SysDM
Solution for the organization and management of mechatronic data, from mechanical to controls engineering

LMS Imagine.Lab System Synthesis
Software tool to support configuration management, systems integration and architecture validation.
LMS Imagine.Lab AMESim (1/2)

The Open and Productive Development Environment
Simulate and analyze multi-physics controlled systems

**INTUITIVE GRAPHICAL INTERFACE**
- User-friendly modeling environment
- Seamless connection between various validated and predefined components
- Display of the system throughout the simulation process
- Several customization and scripting tools

**ADVANCED ANALYSIS TOOLS**
- Fast Fourier Transform
- Plotting facilities, 2D/3D post-processing tools
- Spectral map & Order Tracking
- Linear analysis (eigenvalues, modal shapes, root locus, and transfer function representation)

**UNRIVALLED NUMERICAL CORE**
- Capability to robustly execute inhomogeneous dynamic systems
- Advanced numerical techniques (ODE, DAE)
- Dynamic selection of calculation methods
- Discrete partitioning, parallel processing and co-simulation

**OPEN-ENDED PLATFORM**
- Efficient integration with 3rd party software for SiL, MiL, HiL, real-time simulation, MBS, process integration and design optimization
- Generic co-simulation interface to couple to dynamic 3D models
- Modelica-compliant platform
LMS Imagine.Lab AMESim (2/2)

The Validated, Off-the-Shelves Physical Libraries
Chose after 4500 multi-domain models

**FLUIDS**
- Hydraulic, Hydraulic Component Design
- Hydraulic Resistance, Filling
- Pneumatic, Pneumatic Component Design
- Gas Mixture, Moist Air

**THERMODYNAMICS**
- Thermal, Thermal Hydraulics
- Two-Phase Flow

**MECHANICS**
- 1D mechanical, Planar mechanical Transmission, Cam & Followers
- Finite-Elements Import
- Vehicle Dynamics

**ENGINE**
- IFP Drive, IFP Engine
- IFP Exhaust
- IFP C3D, CFD-1D

**ELECTRICS**
- Electrical Basics, Electromechanical
- Electrical Motors & Drives
- Electrical Static Conversion
- Automotive Electrics, Electrochemistry

**CONTROLS**
- Signal and Control
- Engine Signal Generator
Multi-Domain simulation in AMESim

Electrical domain

Controller

Hydraulics

Mechanics

Pneumatics
Closed loop powertrain model for drivability

Overview

Powertrain model including:
- HF 4 cylinder engine model (crank angle degree resolution)
- 6 gear Automatic transmission
- 2D longitudinal vehicle + Driver and mission profile definition
- 3D engine bloc and mounts

Simulink interfaces

Automatic transmission (6 gears)

Driver and mission profile

Longitudinal 2D vehicle carbody
LMS Imagine.Lab AMESim – The integrated platform for multi-domain system simulation

**VEHICLE INTEGRATION**
- Conventional, EV, HEV
- Exhaust
- Underhood Thermal Systems
- Air Conditioning
- Cabin
- Electrical Networks
- Chassis Systems

**INTERNAL COMBUSTION ENGINE**
- Engine Controls
- Air Path
- Combustion
- Engine Cooling, Lubrication
- Fuel Injection and Valvetrain

**DRIVELINE**
- Torsional Analysis
- Dual-mass Flywheel
- Torque Vectoring

**CHASSIS SUBSYSTEMS**
- Braking
- Steering
- Suspension/ Anti-rol

**TRANSMISSION**
- Manual
- Automatic
- Continuously Variable
- Dual Clutch
- Hybrid Architectures
Example 1

DEMO CHECK VALVE
Example 1: Optimization of a Check Valve
Check Valve: Workflow Description

Workflow Components:

- **Input Variables**: Stroke, Spring_Preload, Spring_Stiffness, Seat_Diam, Ball_Diam
- **Process Flow**: DOE, SIMPLEX, AMESim
- **Output Variables**: Diff_Diam, Qerr
- **Objectives/Constraints**: Diam_Constraint, MinQerr

Direct Integration to AMESim
Check Valve: Workflow Building Example
Check Valve: Problem Definition

5 Input Variables:
- Stroke Length $\in [1, 10]$ mm
- Spring Preload $\in [0, 100]$ N
- Spring Stiffness $\in [1E-5, 100]$ N/mm
- Seat Diameter $\in [1, 25]$ mm
- Ball Diameter $\in [1, 30]$ mm

Constraint:
- Ball diameter must be greater than the seat diameter

Objective:
- Minimize the **sum of squares error (SSE)** between the target and simulation flow rate responses (model correlation/calibration study)
modeFRONTIER offers over 15 optimization algorithms

2 algorithms used for this case:

- **Levenberg-Marquardt Algorithm (LMA)**
  - Gradient based method used for curve fitting problems
  - Starting point: baseline design
- **FAST Strategy**
  - Uses Response Surface Models (RSM) and real evaluations
  - Optimization uses RSM
  - Best designs are validated
  - RSM adapted using new validation runs
  - Optimization repeated

- **FAST-SIMPLEX**: Mono-Objective SIMPLEX algorithm used as optimizer
  - Start population: 6 Uniform Latin Hypercube (ULH) Designs of Experiments (DOE)
  - Robust convergence
Hardware:
• Dell Latitude w/ Intel Core i7

Software:
• modeFRONTIER v4.5.4
• AMESim v13.0

Run times:
• Number of parallel evaluation: 2
• Number of total evaluations: 36
• Average single evaluation time: 5 sec
• Total runtime: 2 min
Levenberg-Marquardt started from baseline design:

- **Baseline flow rate curve**
- **Target flow rate curve**
- **Error between the curves**
Check Valve: LMA Convergence

- Black line is the target flow rate curve.
- Only showing latest 10 designs.
LMA optimization history:

Forward finite difference runs;
Relative perturbation $1E^{-4}$

Converged to optimum in 5 moves
Check Valve: LMA Result

Optimized flow rate comparison:

![Graph showing baseline and optimized flow rate curves.](image-url)
Check Valve: LMA Result

Optimized flow rate comparison:

Visually line-on-line fit to target
Python interface available to access advanced AMESim API features

Constraints added to ensure slopes of three linear segments of the curve are within ±20% of target (speed-up convergence);
FAST-SIMPLEX started from 6 Uniform Latin Hypercube (ULH) DOE points

Resulting DOE flow rate curves

Check valve does not open, 0 cumulative volumetric flow
Check Valve: FAST-SIMPLEX Convergence

- Black line is the target flow rate curve
- Only showing latest 10 designs
FAST-SIMPLEX history:

Most unfeasible designs violate ± 20% slope constraints
FAST-SIMPLEX history (showing improved designs):

Converged to optimum in 308 evaluations.
Check Valve Optimization: LMA

Optimization convergence:
Optimized flow rate comparison:

Visually line-on-line fit to target
### Check Valve: Result Comparison

#### Levenberg-Marquardt

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring Preload, $N$</td>
<td>2.33</td>
</tr>
<tr>
<td>Spring Stiffness, $N/mm$</td>
<td>0.450</td>
</tr>
<tr>
<td>Stroke Length, $mm$</td>
<td>2.00</td>
</tr>
<tr>
<td>Ball Diameter, $mm$</td>
<td>12.9</td>
</tr>
<tr>
<td>Seat Diameter, $mm$</td>
<td>4.04</td>
</tr>
<tr>
<td>SSE</td>
<td>2.34</td>
</tr>
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</table>

#### FAST-SIMPLEX

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring Preload, $N$</td>
<td>2.32</td>
</tr>
<tr>
<td>Spring Stiffness, $N/mm$</td>
<td>1.01</td>
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<tr>
<td>Stroke Length, $mm$</td>
<td>1.59</td>
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<tr>
<td>Ball Diameter, $mm$</td>
<td>25.8</td>
</tr>
<tr>
<td>Seat Diameter, $mm$</td>
<td>4.04</td>
</tr>
<tr>
<td>SSE</td>
<td>2.96</td>
</tr>
</tbody>
</table>

**Multiple local optimums**
Example 2

DEMO PARALLEL HYBRID VEHICLE
Example 2: Parallel Hybrid Vehicle
Parallel Hybrid: Problem Description

4 Input Variables:
- Suspension Stiffness $\in [5000, 15000]$ N/m
- Tire Adherence Coefficient $\in [0.5, 1.5]$
- Wheel Inertia $\in [0.35, 4.0]$ kg·m$^2$
- Vehicle Mass $\in [1250, 1550]$ kg

Objectives:
- Minimize the total fuel consumption
- Minimize the maximum jerk
Parallel Hybrid Vehicle: Workflow

Pure multi-objective optimization defined
2 approaches used for this case:

- **DOE + Statistical Analysis**
  - 100 ULH DOE points
  - Correlation
  - Main effect
  - Smoothing-spline ANOVA (SS-ANOVA)
    - ANOVA decomposition applied to smoothing spline fit to data

- 3 optimization algorithms used:
  - **FAST-NSGA-II**: FAST strategy using non-dominated sorting genetic algorithm (NSGA) used as optimizer
  - **HYBRID**: Combination of gradient based and genetic algorithm optimizers
  - **NSGA-II**: Regular NSGA used as optimizer
  - Starting population: 10 ULH DOE points and ran a total of 1000 evaluations
Example 2: Parallel Hybrid Vehicle Statistical Analysis
Correlation values:

- Values represent the slope of a normalized linear regression fit
- Max value 1.0, Min value -1.0

Slope of the linear regression fit is the correlation value
Parallel Hybrid Vehicle: Statistical Analysis

**Correlation values:**
- Values represent the slope of a normalized linear regression fit
- Max value 1.0, Min value -1.0

- Suspension stiffness highly **inversely** correlated with jerk
- Mass highly **directly** correlated with fuel consumption
Parallel Hybrid Vehicle: Statistical Analysis

Main effect sizes:
- Main effect size is the difference between the means of the lower half and higher half of the distributions.
Main effect sizes:

- Main effect is the difference between the means of the lower half and higher half of the distributions.

Mass and suspension stiffness factors have the most effect on fuel consumption and jerk respectively.
SS-ANOVA:
• ANOVA decomposition applied to smoothing spline fit
• All factor effects sum to 1

Mass contributes over 80% of the total effect on fuel consumption

Suspension stiffness contributes over 95% of the total effect on jerk
Example 2: Parallel Hybrid Vehicle Optimization
Parallel Hybrid Vehicle: Optimization Run Statistics

Hardware:
• Dell Latitude w/ Intel Core i7

Software:
• modeFRONTIER v4.5.4
• AMESim v13.0

Run times:
• Number of parallel evaluation: 1
• Number of total evaluations: 1000
• Average single evaluation time: 6-7 sec
• Total runtime: ≈3 hrs.
Parallel Hybrid Vehicle: Optimization Convergence

NSGA-II History:
Parallel Hybrid Vehicle: Optimization Results

Pareto designs for the 3 optimization algorithms:
Parallel Hybrid Vehicle: Optimization Results

Pareto designs for the 3 optimization algorithms:
Parallel Hybrid Vehicle: Optimization Results

Trade-off analysis:

![Graph showing trade-off analysis for parallel hybrid vehicle optimization results.](image-url)
Trade-off analysis:

Parallel Hybrid Vehicle: Optimization Results
Parallel Hybrid Vehicle: Optimization Results

Trade-off analysis:
Parallel Hybrid Vehicle: Optimization Results

Trade-off analysis:

Designs resulting from low mass and low suspension stiffness (statistical analysis conclusion)
Conclusions

- modeFRONTIER provides an easy to use interface to integrate AMESim models for (collaborative) MDO
- Get more out of your AMESim models by exploring the full design space and visualize all options
- Automate your simulation process by integrating AMESim with other analytical tools
- Very suitable for Model Based Systems Engineering
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