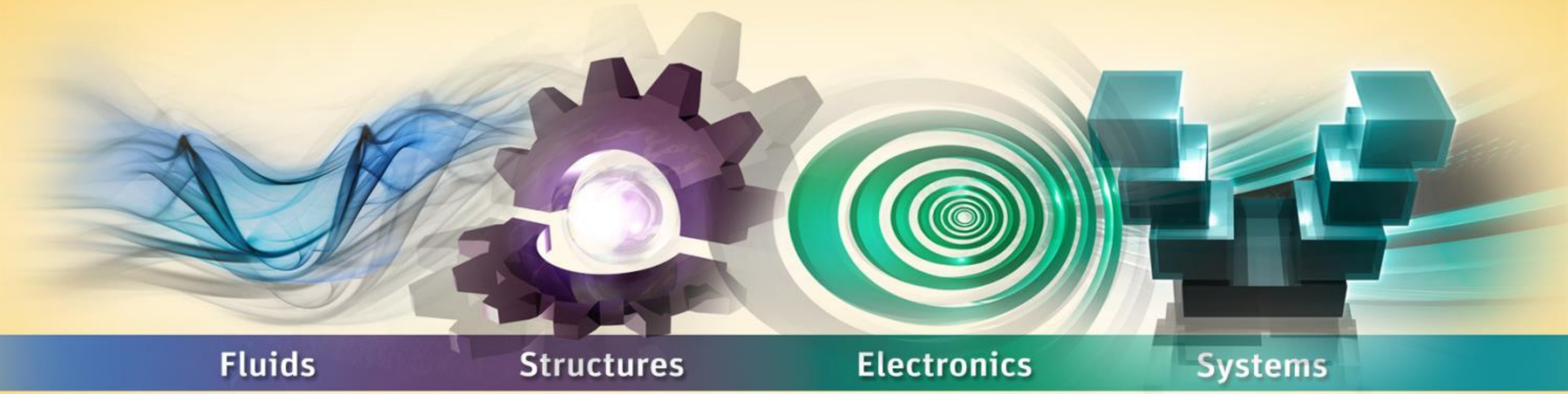
ANSYS

Realize Your Product Promise®

## NAFEMS – Séminaire Simulation des Systèmes - 3 juin 2015

## Hôtel Novotel – Marne la Vallée – Noisy le Grand




# An Integrated Approach for Model-Based Systems and Software Engineering
# ROMs-Based Systems Analysis

**03/06/2015**

***Jacques DUYSENS***

# Our Strengths

## FOCUSED

This is all we do.
Leading product technologies in all physics areas
Largest development team focused on simulation

## TRUSTED

**96** of the top 100
FORTUNE 500 Industrials

ISO 9001 and NQA-1 certified

## CAPABLE

**2,600+** employees

**75** locations

**40** countries

## PROVEN

Recognized as one of the world's **MOST INNOVATIVE AND FASTEST-GROWING COMPANIES***

## INDEPENDENT

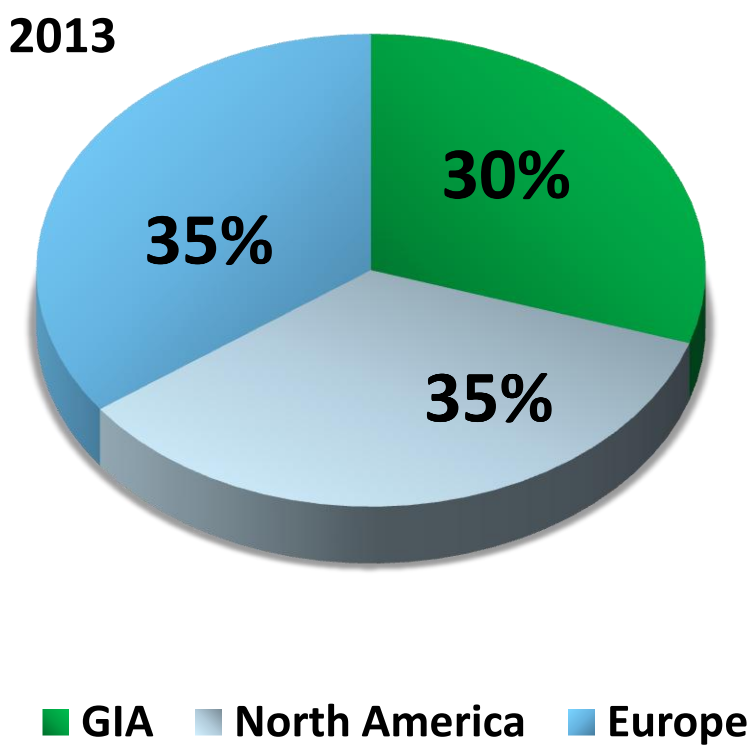
Long-term financial stability
CAD agnostic

**BusinessWeek, FORTUNE*

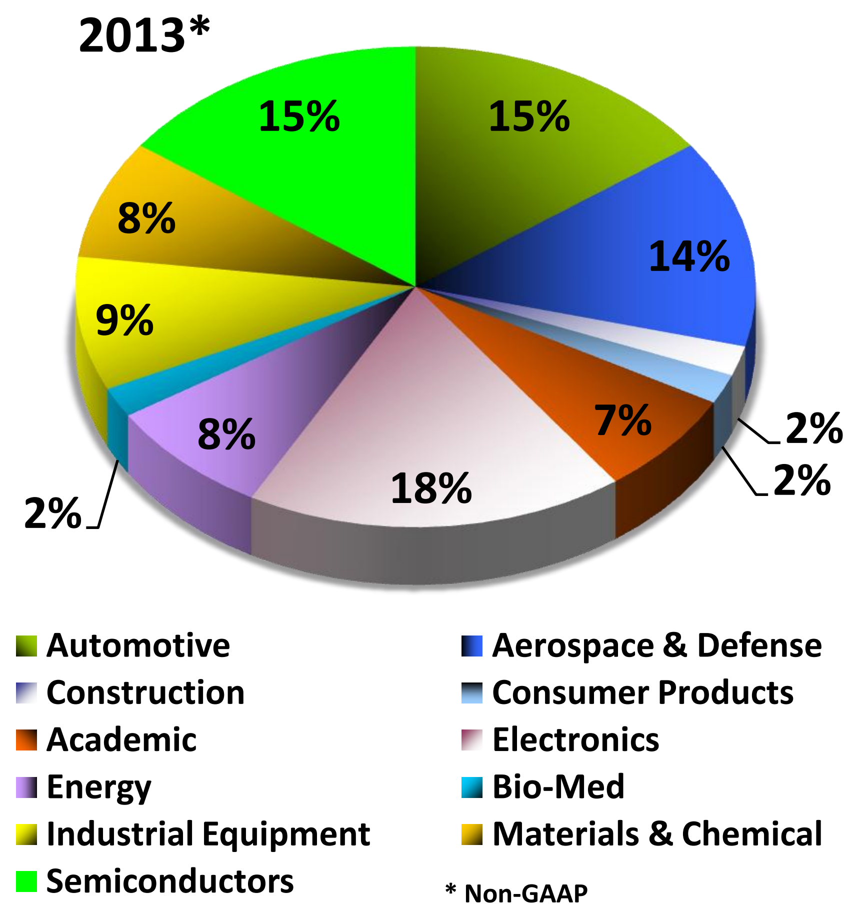
 

# Diversified Portfolio Structured for Success

## Sales by Geography

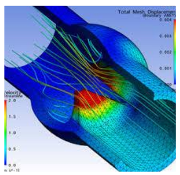



## Sales by Industry

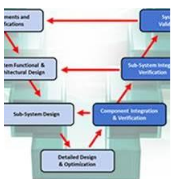


# Scaling the deployment of simulation requires a platform strategy

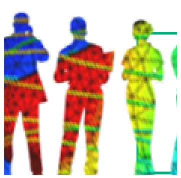
## Simulation Trends



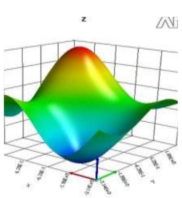
**Multiphysics Simulation**



**Systems Engineering**

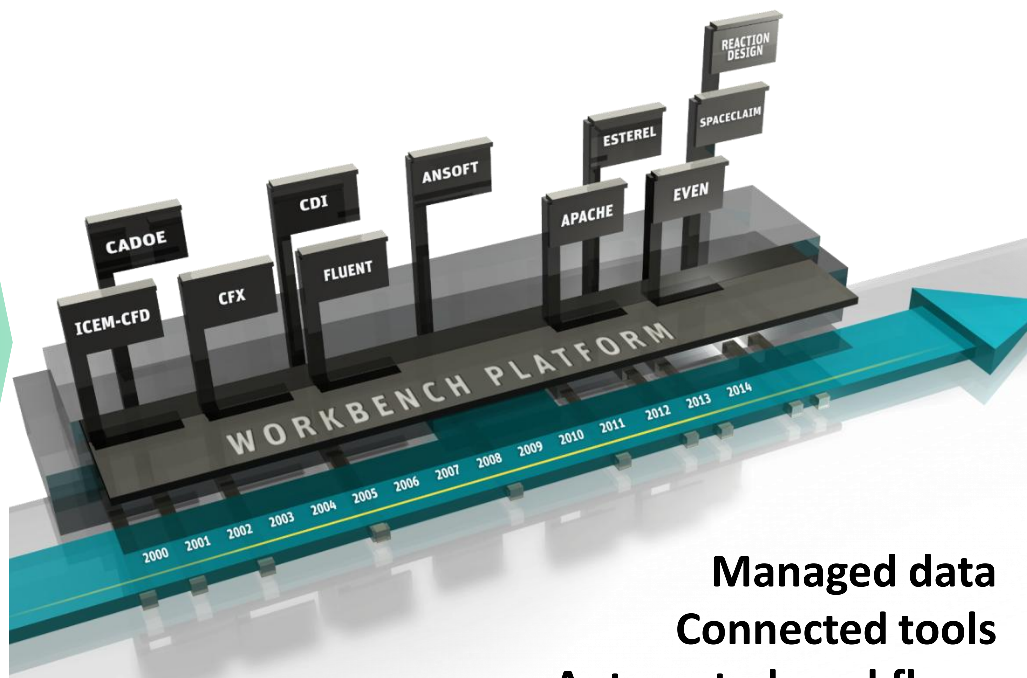


**Simulation Democratization**



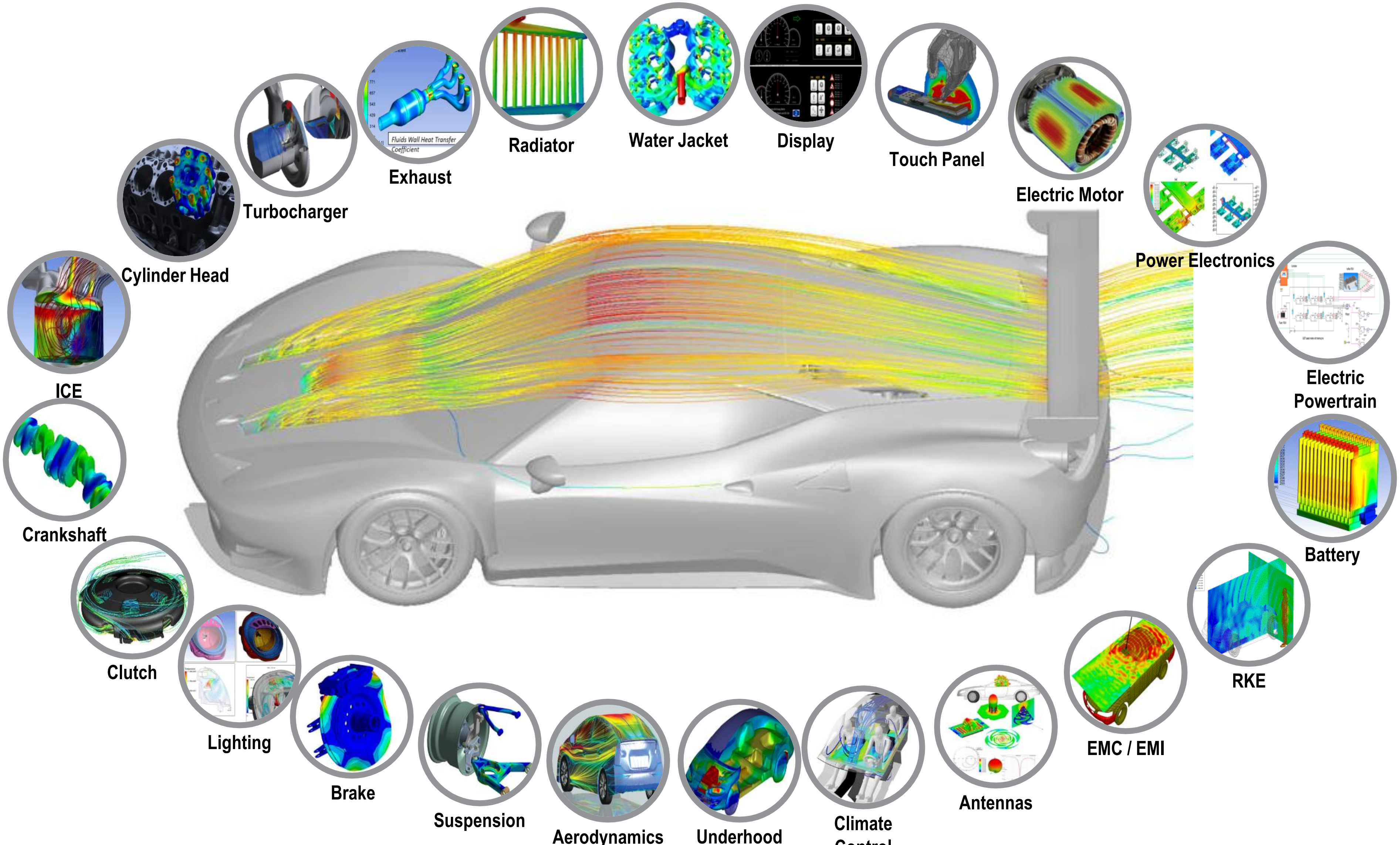
**Robust Design**

## Integrated Platform




**Managed data**
**Connected tools**
**Automated workflows**
**Parametric**
**Open & extendable**

# Example: ANSYS in the Automotive Industry

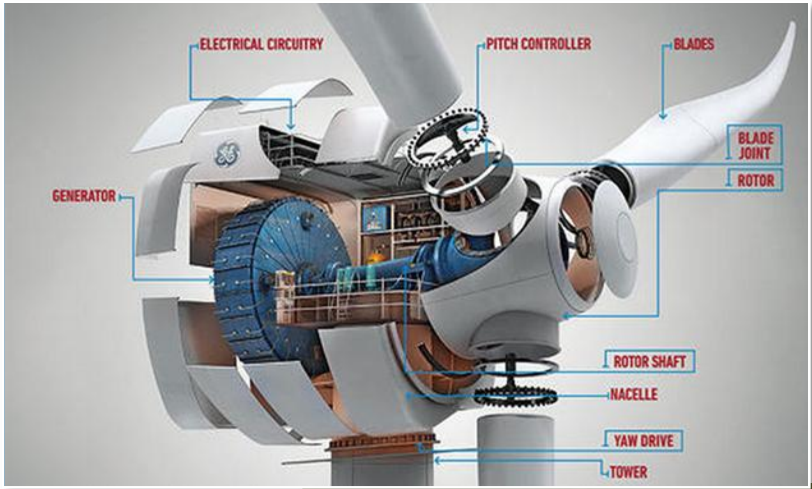



*Courtesy of Ferrari AF Corse*

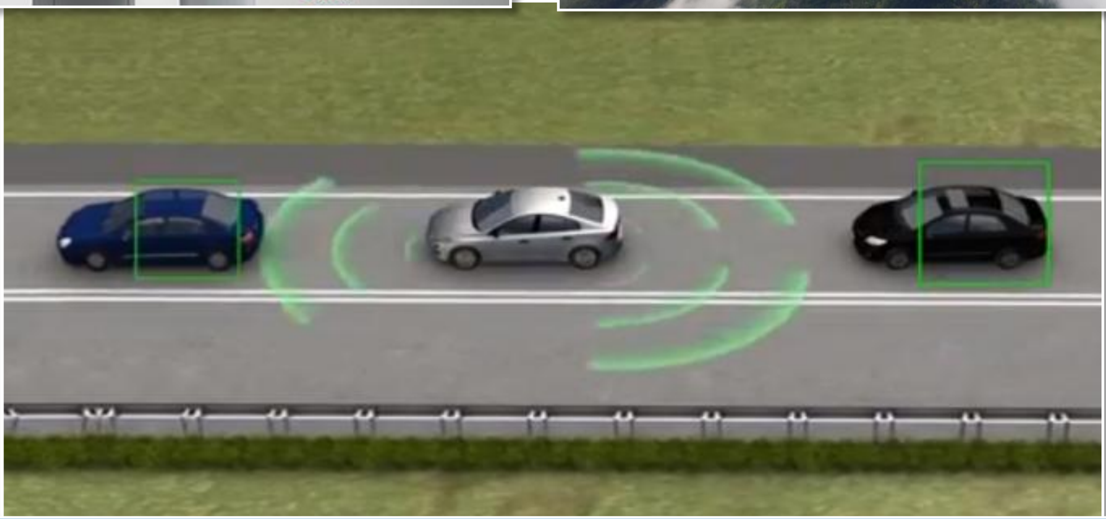
 

# Model Based Systems & Software Engineering

# Why Care about Systems?



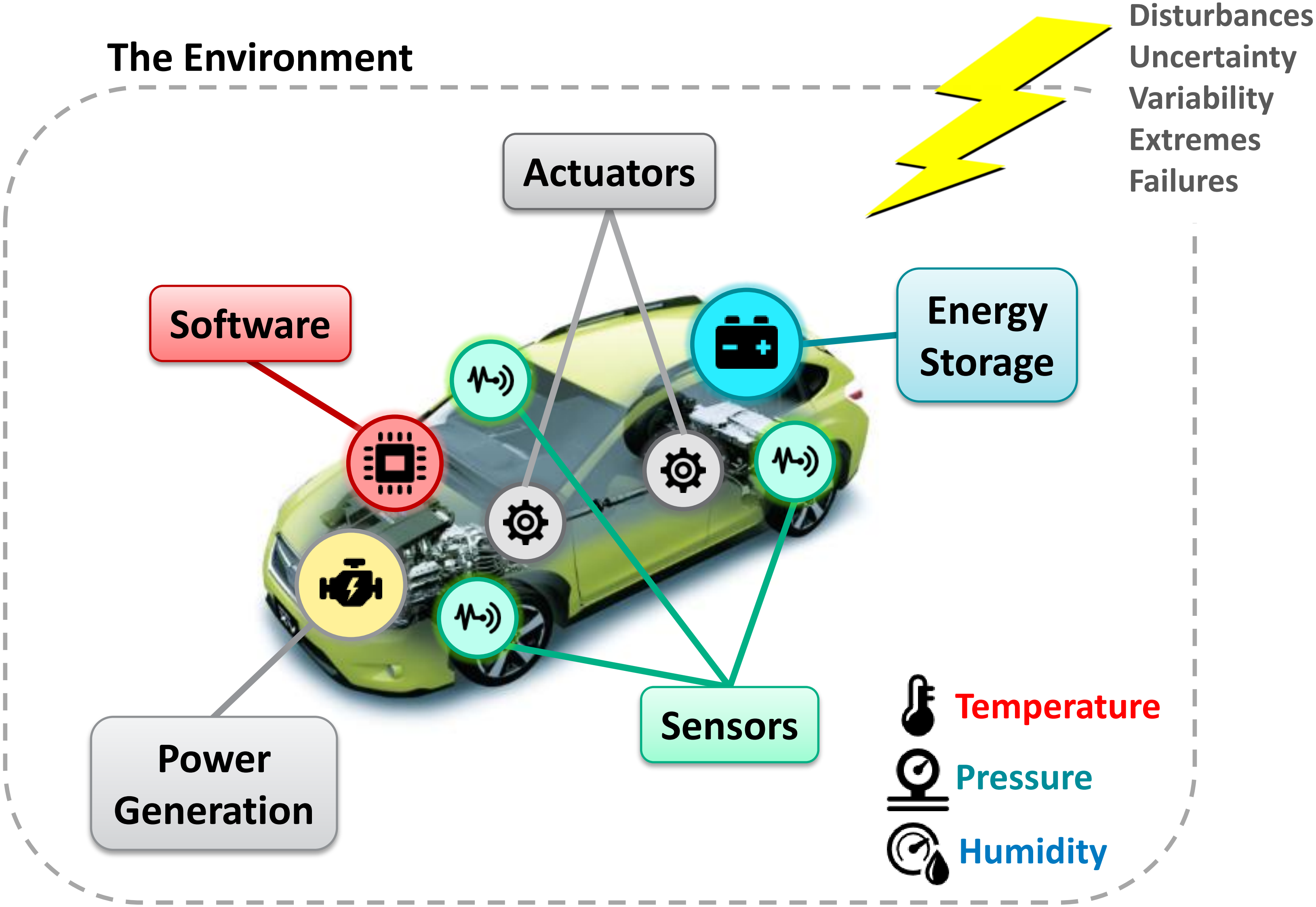




**In every industry major innovations are based on electronics and embedded software.**

# What is a System?

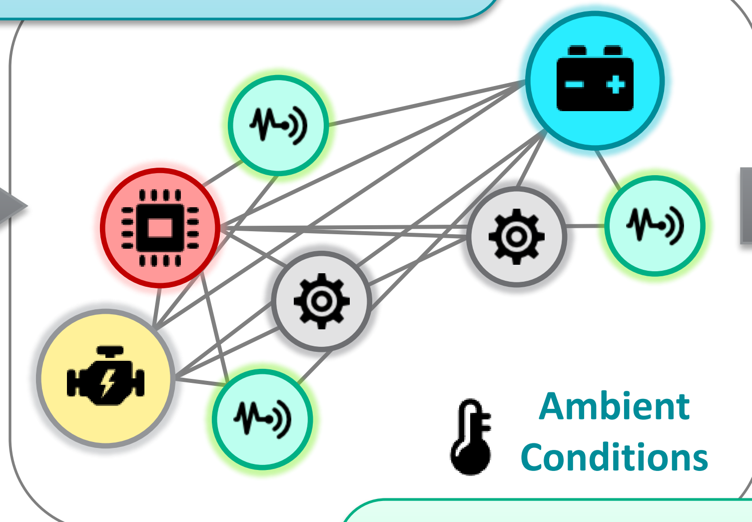


# Modeling & Simulating a System

**System Modeling**
- Mathematical descriptions of behavior
- Captured in a formal modeling language
- Connected together (so they can interact)

**Inputs**

- *Turn on / off*
- *Speed up*
- *Follow a Profile*
- *...*



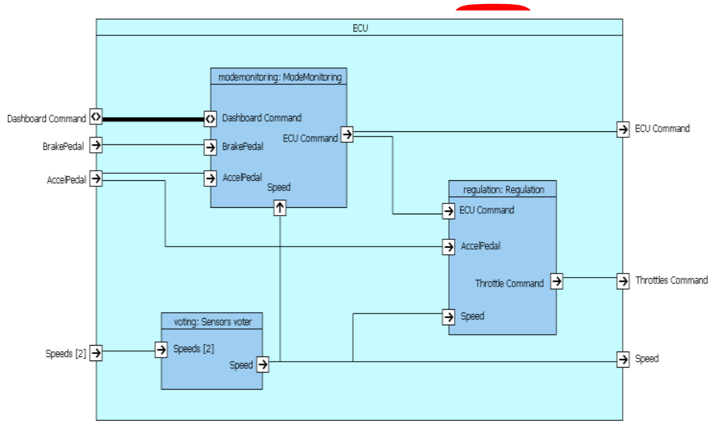

**Outputs**

- *How fast?*
- *How accurate?*
- *How efficient?*

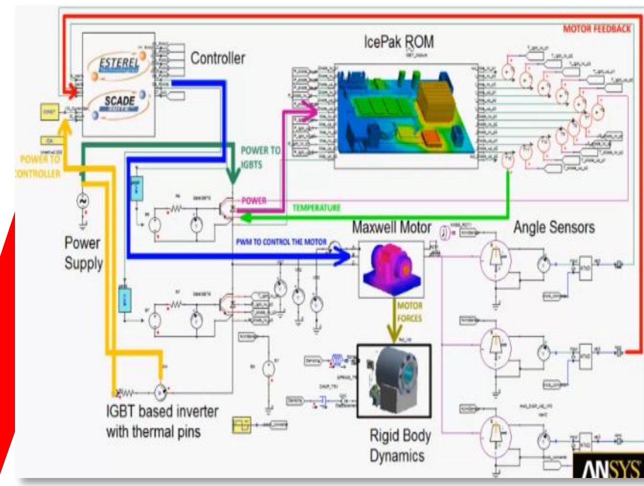
**System Simulation**
- Injects inputs and sets conditions
- Calculates the response of the system
- Produces outputs to evaluate performance

# Complete Model Based Engineering Solution

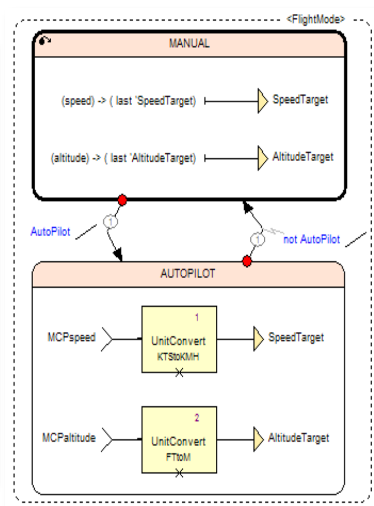
## Functional & Architectural Design (SCADE System)




## Complete Virtual Prototypes of E/E Systems (Simplorer)

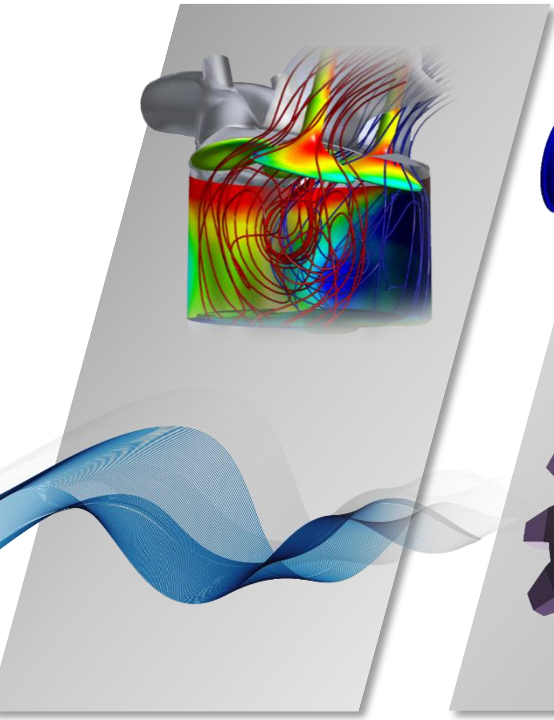



## Model Based Embedded Software Development (SCADE Suite, Display, Test & LifeCycle)

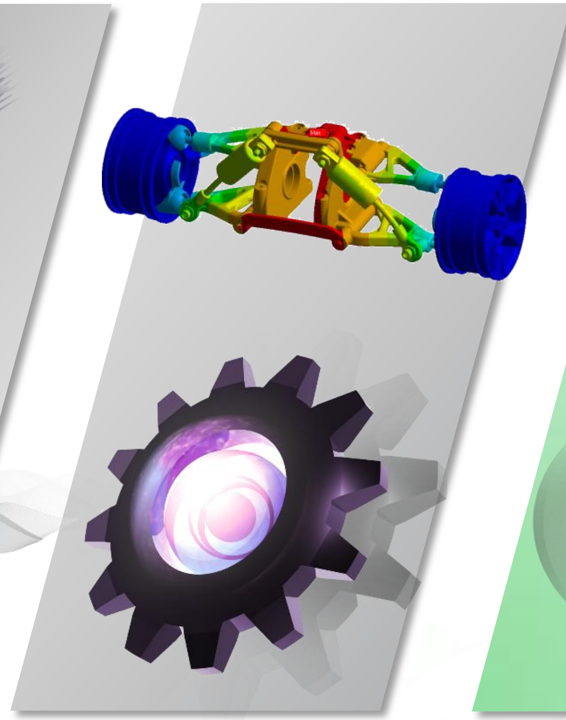



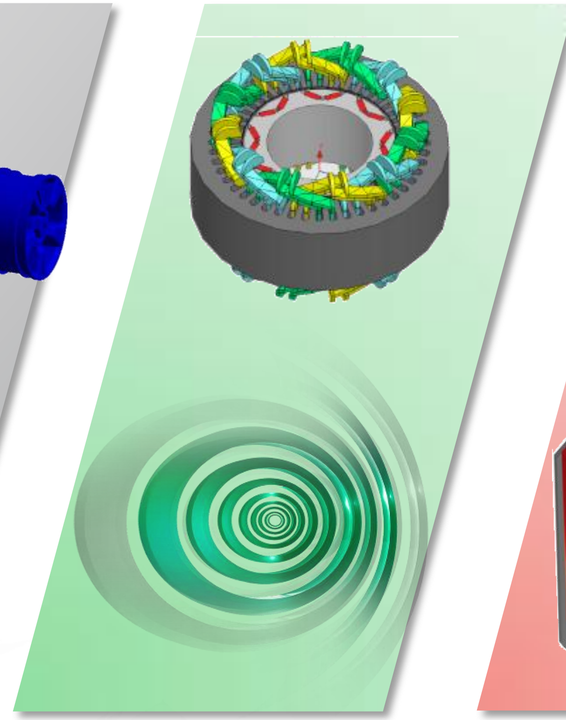
# Comprehensive Component-Level Design



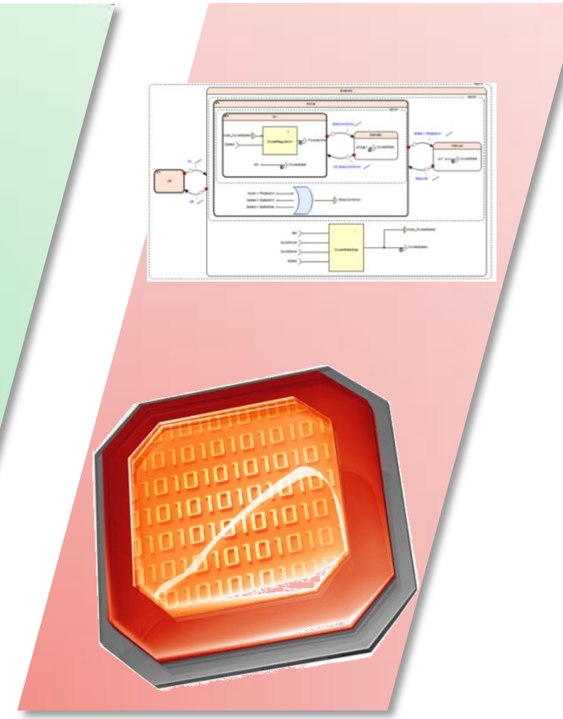
Fluids



Structures



Electronics



Software

# ANSYS Solutions for Detailed Design

Need to optimize & verify interactions of multi-domain components and embedded software

## Fluids

## Structures

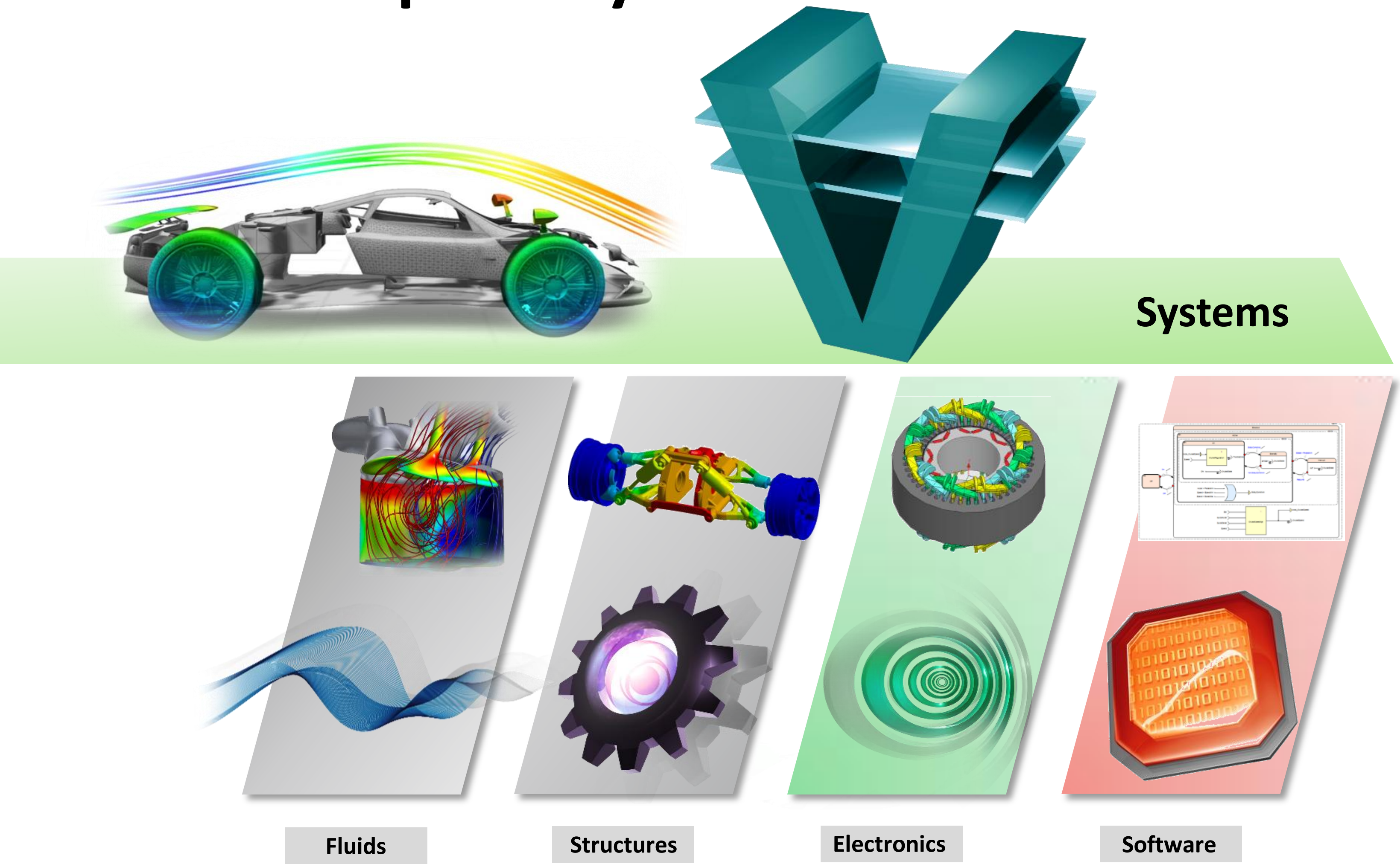
## Electronics

## Embedded Software

SCADE SUITE®

SCADE DISPLAY®

# The Next Level: Virtual Prototypes of Complete Systems



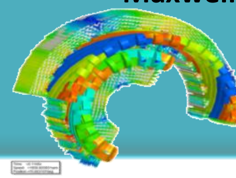

 

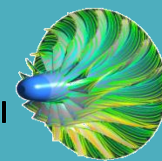
# Our Systems Vision

ANSYS

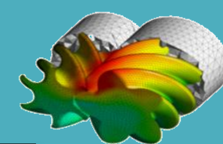
## Detailed 3D Multiphysics

ANSYS Maxwell





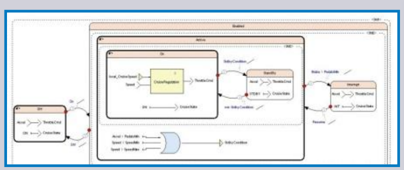
ANSYS Fluent



ANSYS Mechanical

ROM

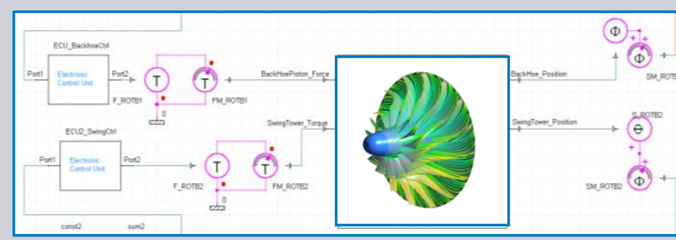
## Software Engineering



SCADE SUITE

SCADE DISPLAY

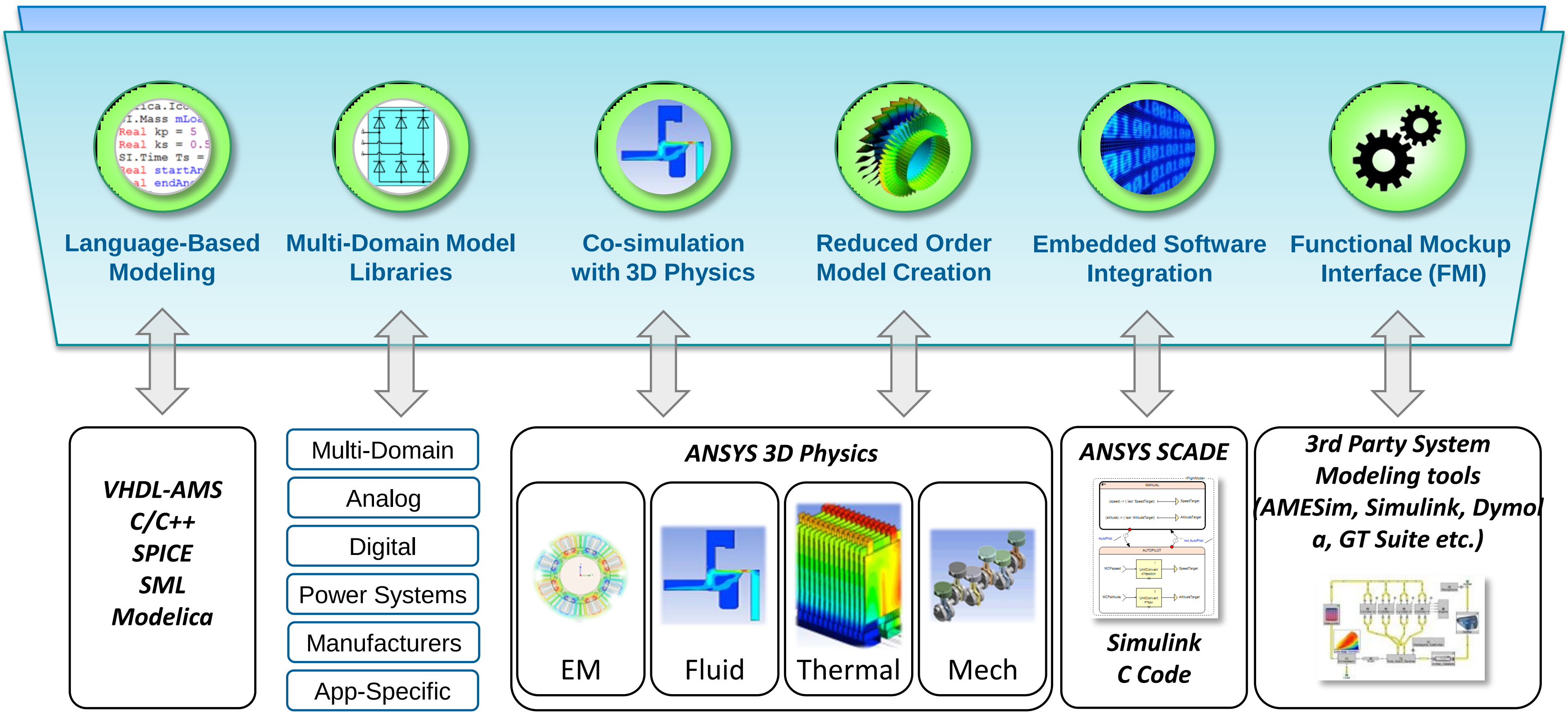
## System Simulation



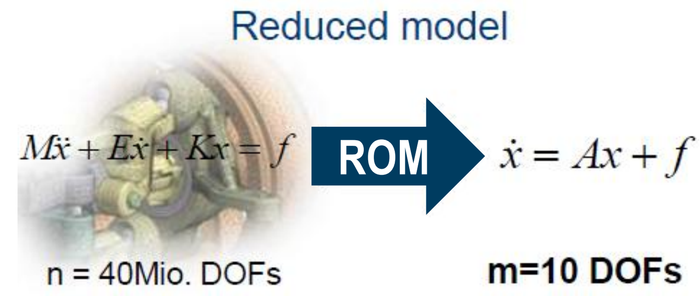
ANSYS Simplorer

# Modeling the System

*Powerful Capabilities for Assembly and Reuse*



# ROM Introduction




**The Webster Definition:**

***A methodology to transform a high dimensional subspace of ordinary differential equations (typically arising from FEM, FVM, etc) with a low-dimensional approximation for the purpose of reducing solution time or solving a larger or more complex model.***

- **The accuracy trade-off for ROMs is to obtain the time response of large systems which otherwise would be computationally impractical**
- **ROMs are compute and license intensive to create but very fast to simulate once they are built**
- **ROMs are design specific and multiple ROMs are required for a single design**

# Modèles Réduits

## Philosophie

**Construire le modèle de plus petite dimension qui capture l'effet dominant du système étudié**

## Ce n'est pas:

- **Le modèle le plus simple**
- **Un modèle à fidélité variable**
- **Le modèle ayant le maillage le plus grossier**
- **Un modèle obtenu par sous-structuration**

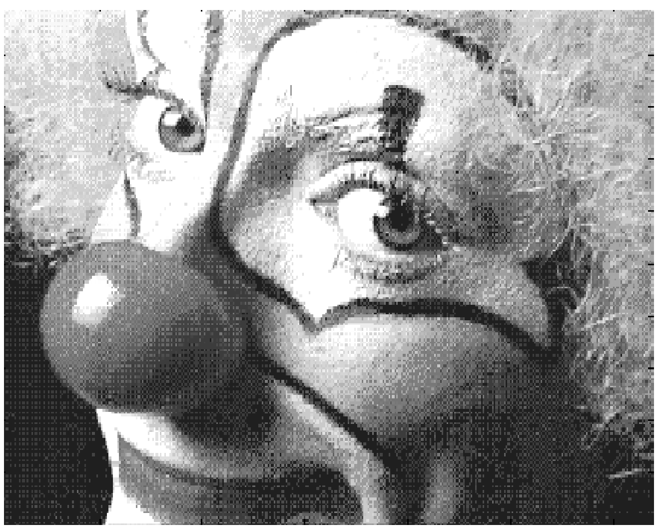


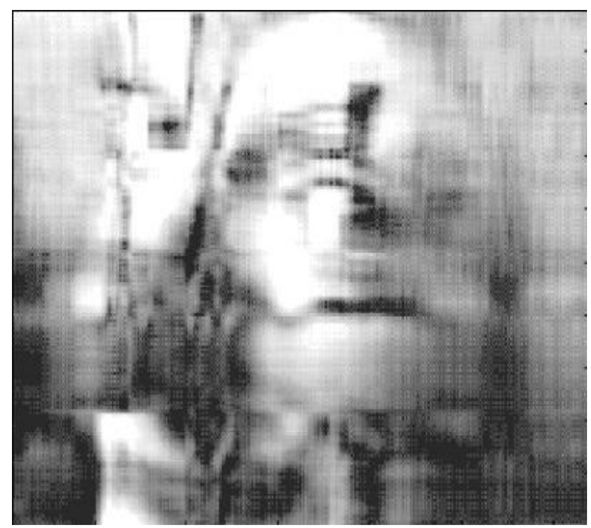
 

# Modèles Réduits

## Philosophie

**Construire le modèle de plus petite dimension qui capture le comportement dominant du système en projetant le modèle haute fidélité sur un sous-espace bien choisi**





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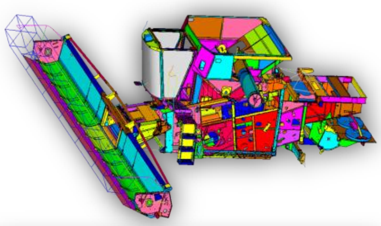
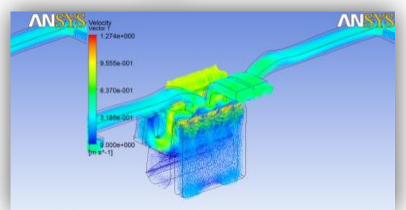
# Three Types or ROM Usage

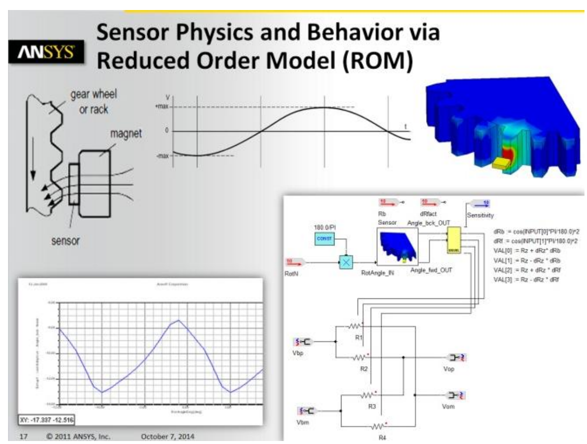
## ROM Usage Types

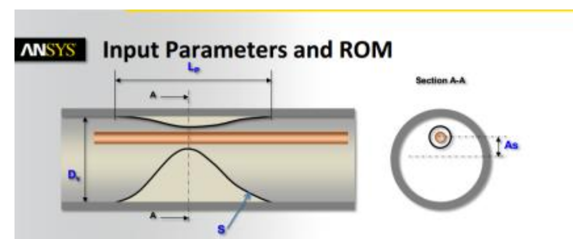
| Single Discipline ROMs | System Simulation ROMs | Simulation Democratization ROMs |
|---|---|---|
| A system of ROMs which are largely homogeneous with respect to an engineering discipline, e.g. mechanical, electronics, or thermal management. | A system of interconnected heterogeneous ROMs (and other component models) where both the system and interface responses are of interest. | A ROM created for non-traditional users to explore the design space. System response and internal field data if of interest. |






**Electronics Example**




| Input Parameters | Description | Variation range |
|---|---|---|
| $D_v$ | Inner diameter (mm) | 3.464 - 6.062 |
| $L_p$ | Plaque length (mm) | 40 - 190 |
| RL | Residual lumen | 0.65 - 0.95 |
| As | Asymmetry coefficient | 0 - 1 |
| S | Sharpness | 0.1 - 1 |
| %ID | Percentage inner diameter | 0.85 - 1.15 |
| %Stretch | Percentage initial stretching | 0. – 0.20 |

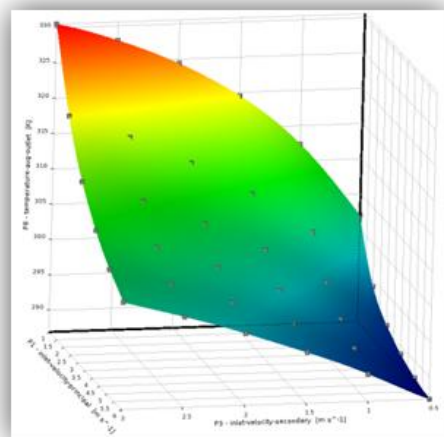
Parametric Simulation Results Based on Reduced Order Modeling
Validation using hundreds design points

# Methodology - Design of experiments

Table de Schéma B2: Plan d'expériences (Personnalisé + remplissage : Nombre total de points = 20)

| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Nom | P1 - inlet -velocity -principal (m s^-1) | P2 - inlet -temperature -principal (C) | P3 - inlet -velocity -secondary (m s^-1) | P4 - inlet -tempera... -secondary (C) | P5 - pressure -drop -principal (Pa) | P6 - pressure -drop -secondary (Pa) | P7 - tempera... -max -outlet (K) | P8 - tempera... -avg-outlet (K) | P9 - temperature -point-outlet (K) |
| 2 | 1 | 3,5 | 5 | 3,5 | 60 | 13024 | 12850 | 321,67 | 298,4 | 319,76 |
| 3 | 2 | 5,9006 | 9,6517 | 1,1516 | 79,393 | 8165,6 | 10938 | 330,88 | 290,47 | 330,48 |
| 4 | 3 | 5,7226 | 0,027105 | 1,0477 | 78,264 | 7313,6 | 9808,1 | 326,15 | 281,3 | 325,7 |
| 5 | 4 | 5,8995 | 0,32343 | 1,2792 | 40,448 | 8886,2 | 11851 | 301,85 | 278,32 | 301,63 |
| 6 | 5 | 1,2177 | 9,7172 | 5,7538 | 40,102 | 11945 | 5939,5 | 307,67 | 302,93 | 296,64 |
| 7 | 6 | 5,4229 | 9,9254 | 5,9732 | 79,814 | 34683 | 32514 | 338,08 | 310,26 | 335,27 |
| 8 | 7 | 5,9893 | 0,14884 | 5,8574 | 76,168 | 37042 | 36832 | 333,68 | 300,98 | 331,42 |
| 9 | 8 | 1,1292 | 9,4721 | 1,0421 | 77,542 | 1260,7 | 1282 | 335,86 | 306,4 | 332,91 |
| 10 | 9 | 5,9489 | 9,8079 | 5,7246 | 42,937 | 35913 | 35971 | 309,26 | 294,9 | 308,25 |
| 11 | 10 | 5,722 | 9,6062 | 1,1193 | 41,703 | 7700,1 | 10306 | 304,89 | 286,29 | 304,71 |
| 12 | 11 | 1,1901 | 8,7326 | 1,088 | 40,263 | 1384,9 | 1413,1 | 306,55 | 292,83 | 305,21 |
| 13 | 12 | 1,318 | 0,23442 | 5,564 | 40,576 | 11810 | 6114,3 | 305,1 | 299,39 | 292,52 |
| 14 | 13 | 1,5358 | 0,47407 | 5,7684 | 79,703 | 13473 | 7258,7 | 335,08 | 323,43 | 313,71 |
| 15 | 14 | 5,8859 | 0,42115 | 5,8085 | 40,941 | 36142 | 35419 | 305,42 | 288,36 | 303,79 |
| 16 | 15 | 1,2046 | 0,29695 | 1,0611 | 47,395 | 1365,3 | 1410,1 | 310,35 | 289,46 | 308,45 |
| 17 | 16 | 1,1244 | 9,576 | 5,693 | 79,866 | 11330 | 5515,4 | 341,18 | 329,82 | 313,97 |
| 18 | 17 | 1,8403 | 1,2284 | 1,1031 | 78,849 | 2155,8 | 2484 | 335,99 | 295,12 | 334,71 |
| 19 | 18 | 5,6622 | 5,1409 | 3,4435 | 79,261 | 20332 | 23548 | 337,52 | 298,35 | 336,7 |
| 20 | 19 | 5,9416 | 5,229 | 1,0888 | 60,731 | 7880,8 | 10579 | 315,97 | 284,15 | 315,65 |
| 21 | 20 | 3,4149 | 9,8548 | 3,2845 | 77,009 | 11885 | 11912 | 336,06 | 307,16 | 333,69 |
| * | Nouveau point de conception | | | | | | | | | |

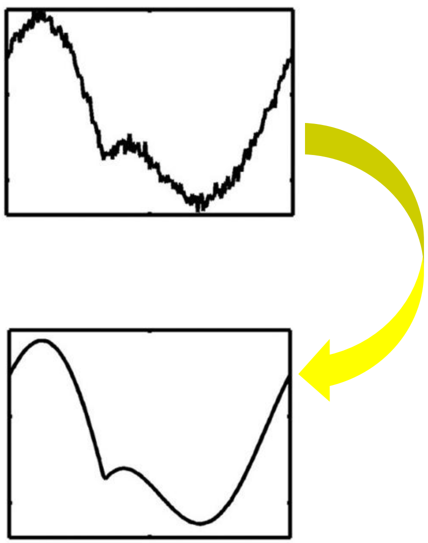
The values of output parameters as a function of input parameters are obtained on **the design points** defined in the **design of experiments**



In order to get the values of output parameters for any value of the input parameters, ANSYS DesignXplorer gives access to a large number of **interpolation methods**

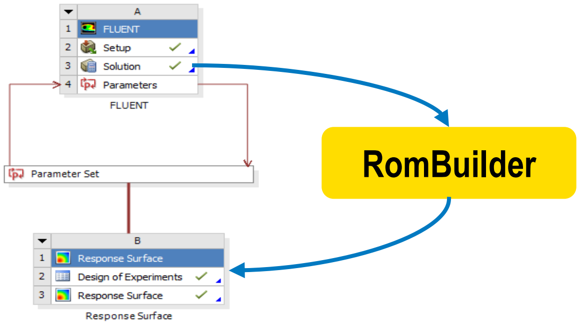
# ROM Technology - A new approach

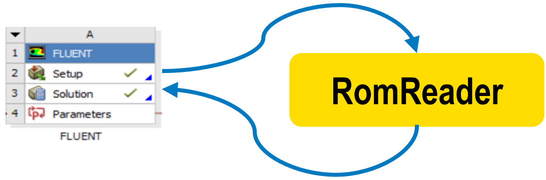
- We will propose you a different usage of the calculations done to overcome today's limitations
- **Data compression and interpolation** based on **Singular Value Decomposition (SVD)**
- SVD works more or less like a Fourier Reconstruction of a signal :
  - The model is a summation of modes
  - The lower modes contains most of the signal energy
  - The higher modes contains noise



# In Practice …

- Two working stages :
  - Offline stage: from a few calculated design points, it is possible to extract a few solution modes (from SVD)
  - Online stage: for any given parameter values of the DoE, the full solution can be "instantaneously" shown as a linear combination of the basis modes



# RomBuilder - The general model - POD

- The solution $U$ is expressed as :

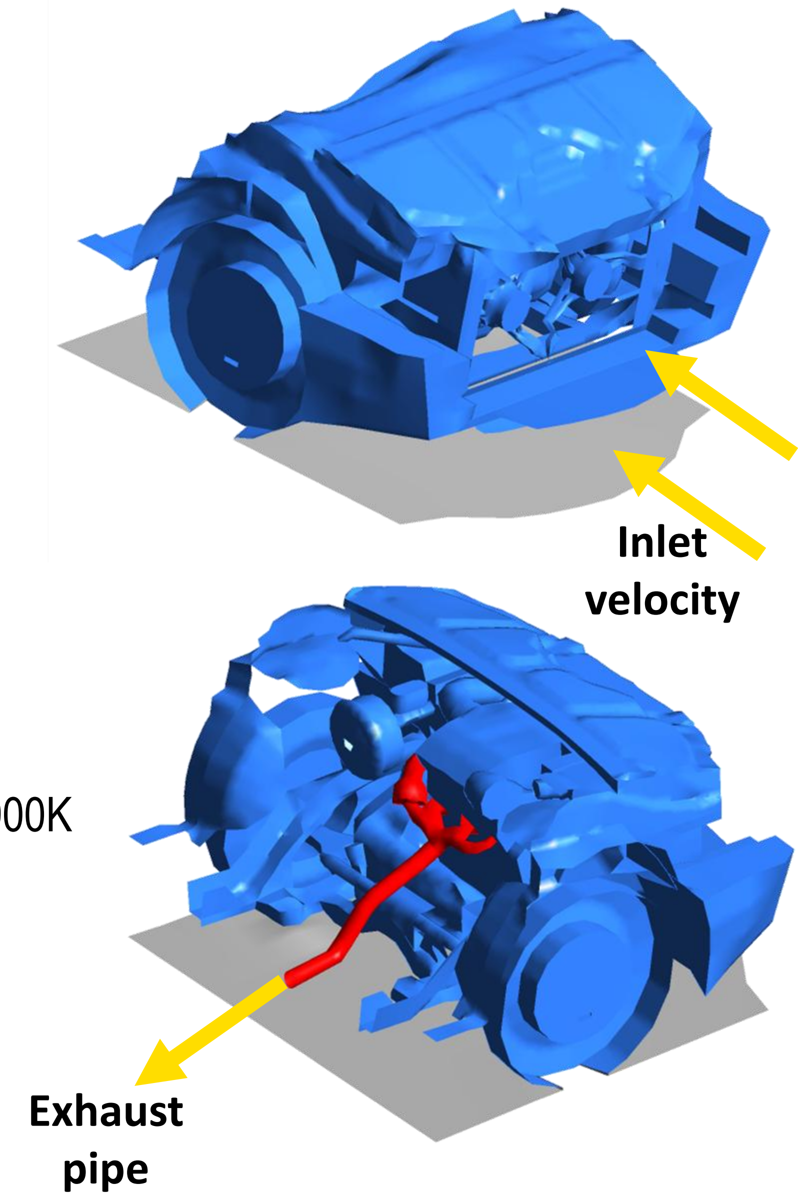
$$U(\mu) = \sum_{i=0}^{n} x_i(\mu)\, Q_i$$

where:

- $n$ is the size of the reduced basis
- $Q_i$ is the ith element of a reduced basis
- $x_i$ is the corresponding coefficient
- $\mu$ is the parameters vector, it may include the time for 4D models

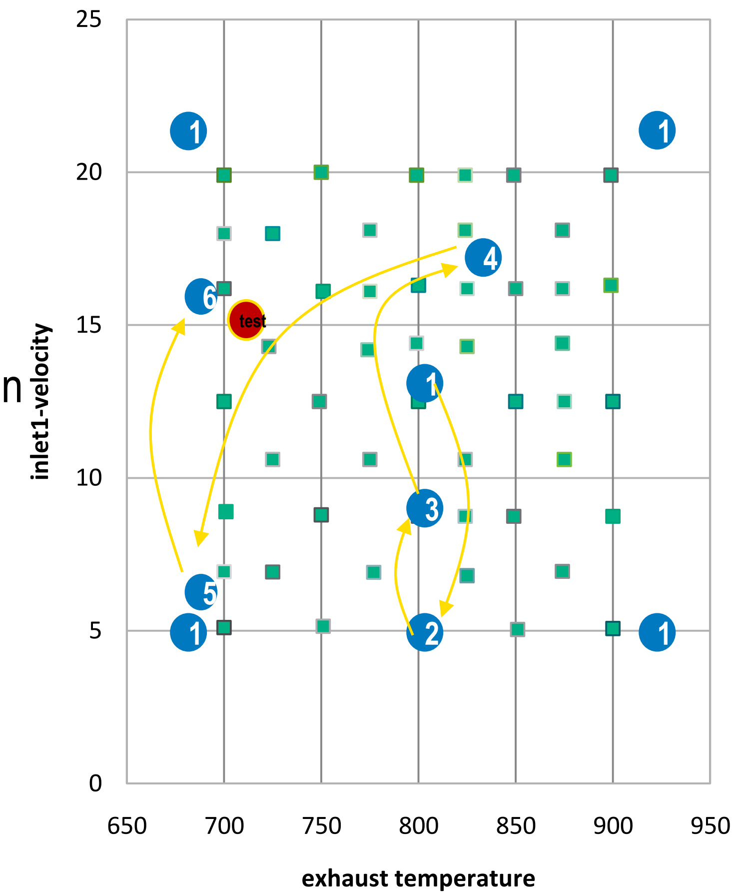
# Generic underhood test case

- 3D thermoaerodynamic coupled with radiation
- DO model for radiation
- 500,417 tetraedral cells without boundary layers
- Standard k-e model with standard wall-functions
- 2 parameters :
  - Inlet velocity from 5 m/s to 20 m/s
  - Exhaust Temperature from 700K to 900K



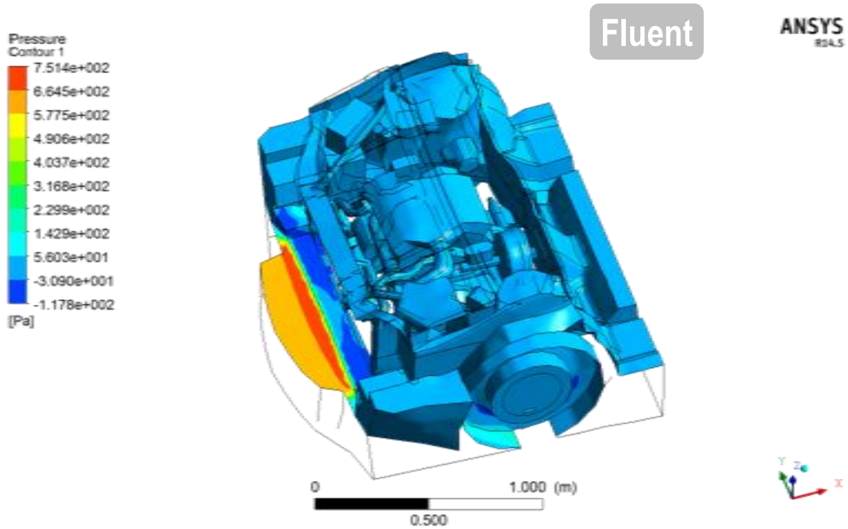
# Reduced Model Generation Process

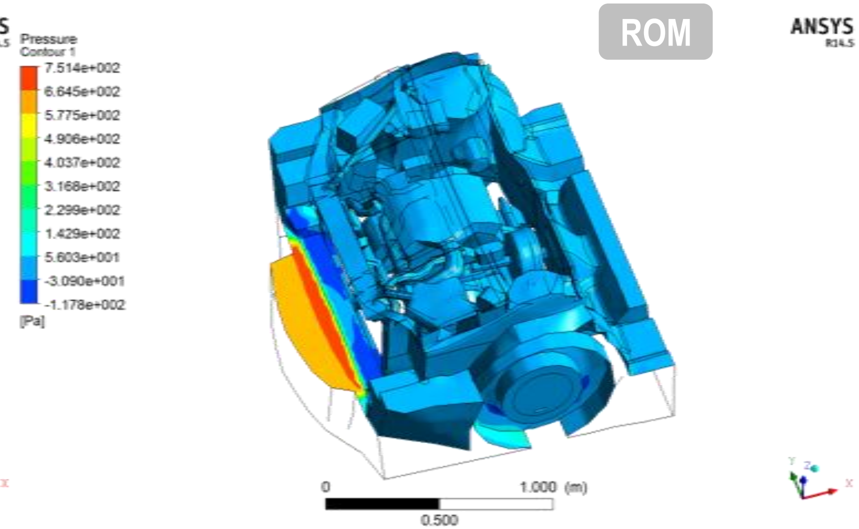
- 50 calculation were done
  - 10 were used to create the model
  - 40 other were made to verify its precision
- ROM Model creation is 9 seconds
- ROM Model is precision is access by comparison with the 40 verification points
- Average error on velocity : 0,06 m/s
- Average error on temperature : 0,49 K




- Quantitative differences in between Fluent calculation and ROM model are presented on the worse verification point

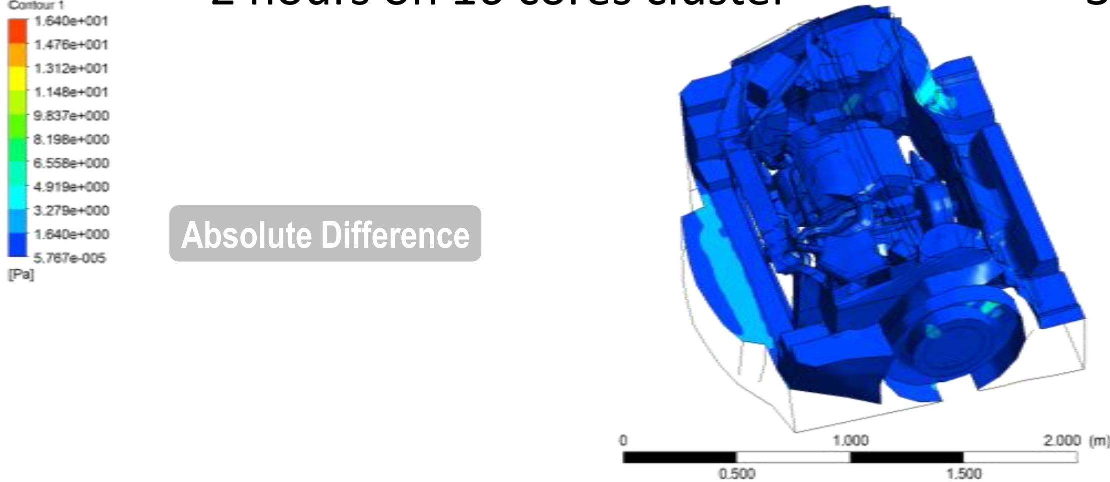
# Static Pressure Comparison




2 hours on 16 cores cluster

3 seconds on this laptop




$T_{exhaust}$ = 723K
$V_{car}$ = 14,3 m/s

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# Methodologies - Summary

- **DOE + meta-modeling techniques (response surface, Kriging, …) including the non-linear scalar case.**
- **Linear Case – LTI method (modal approach – Linear Time Invariant)**
- **LTI + LPV (Linear Parameter Varying)**
- **Modal approach for non-linear steady-state case (intrusive) + limitation to quasi-linear transcient case**
- **Parametrized field-data compression and interpolation**
- **Reseach  on transcient ROM building methods during a learning transcient simulation**

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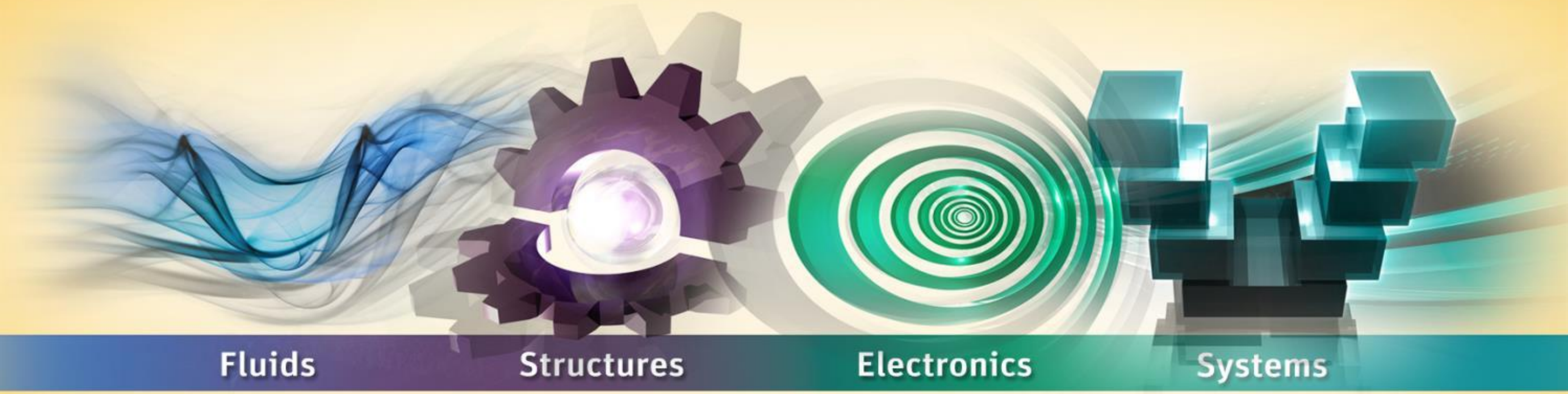
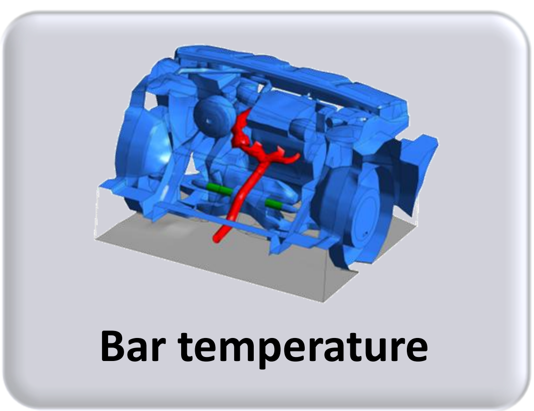
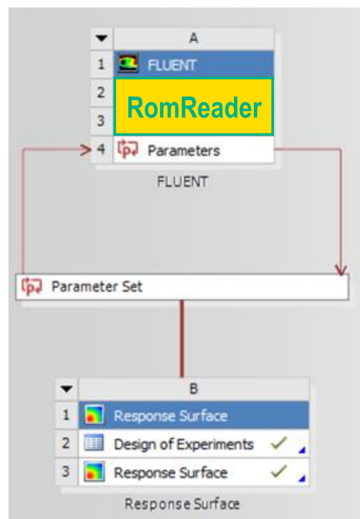
# ROM open door to future Design Exploration

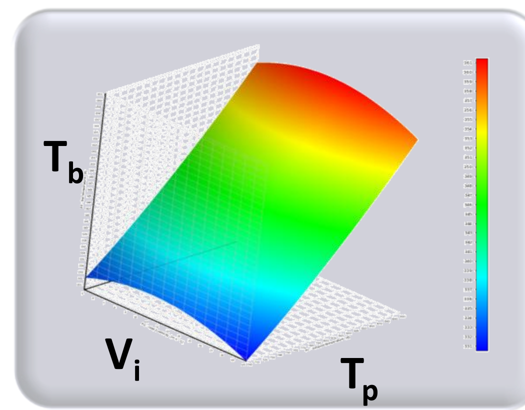


# Rom can replace solver everywhere

- Fluent is used as a platform for the created ROM
- With 10 points classical composite design :
  - 21 hours on 16 cores with Fluent Solver
  - 9 minutes on one laptop with ROM

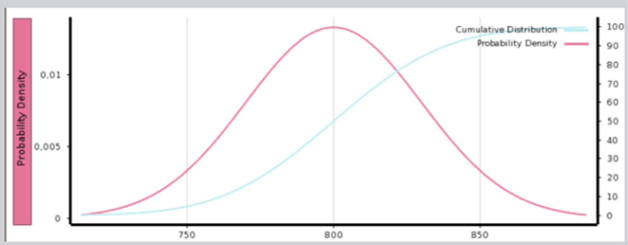


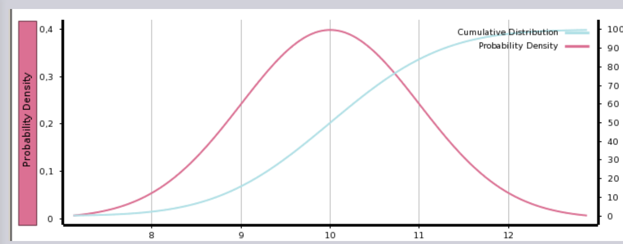



# 6σ in Design Explorer

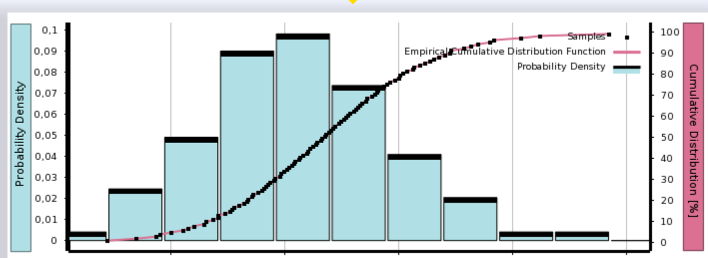
- Fluent is used as a platform for the created ROM
- 2 normal distribution on input parameters :
  - 23 hours on 16 cores with Fluent Solver
  - 13 minutes on one laptop with ROM



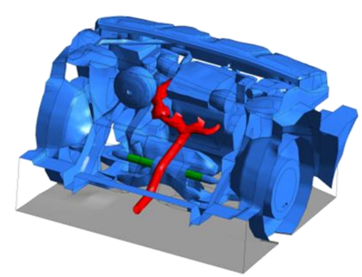

Inlet velocity




Exhaust temperature




Bar temperature



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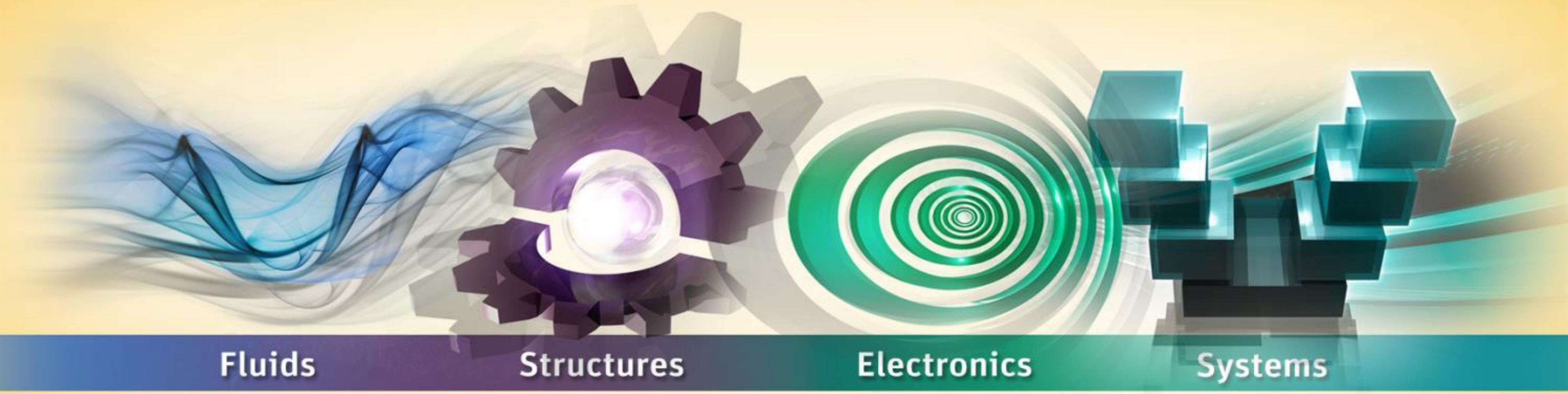
# ROMs-Based Systems Models Industrial Applications



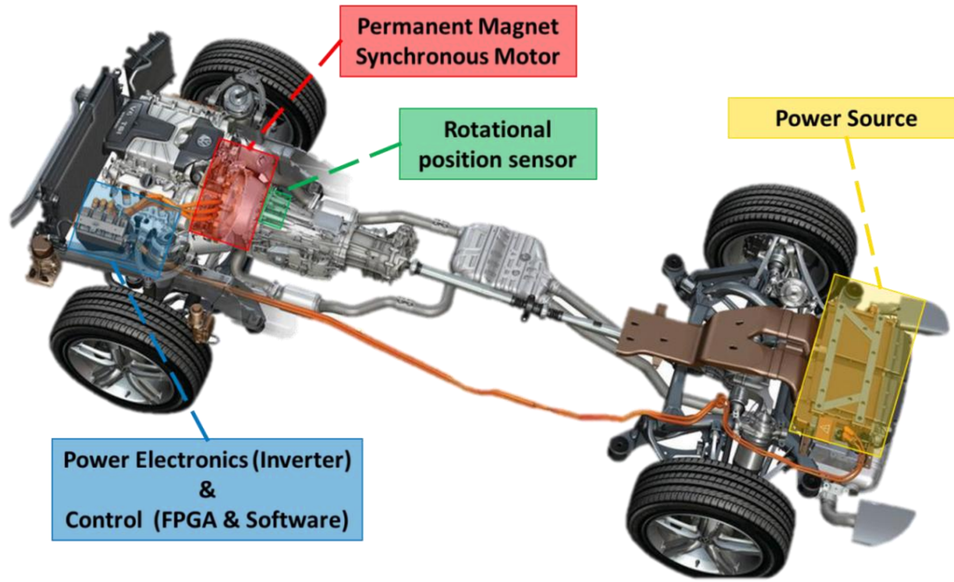
# Hybrid Electric Powertrain Control

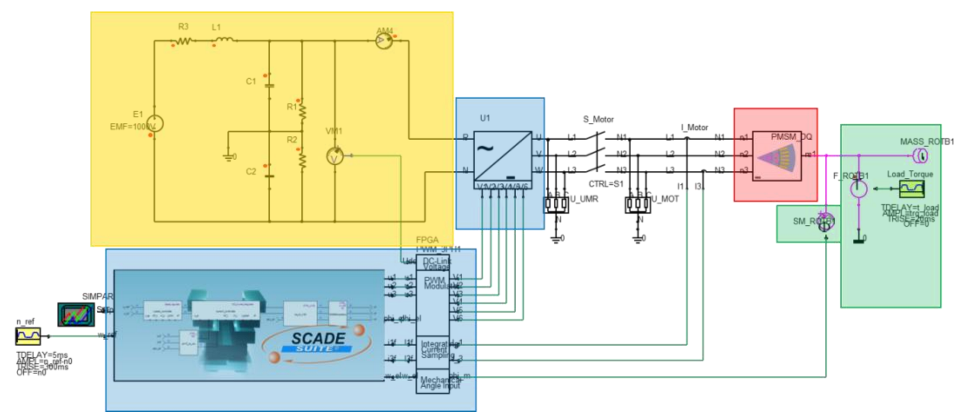
## Key System-Level Models

- ***Maxwell***: Permanent magnet synchronous machine extracted as ROM
- **Q3D**: high-voltage bus bar parasitics
- ***SCADE***: Motor control software
- ***Simplorer***: High-power electronics (inverter), behavioral multi-domain sensors

## System-Level Value

- Evaluate architectural selections and component choices to optimize fuel economy and cost
- Verify control strategies and calibrate control parameters
- Assess system reliability (worst-case analysis, fault injection)

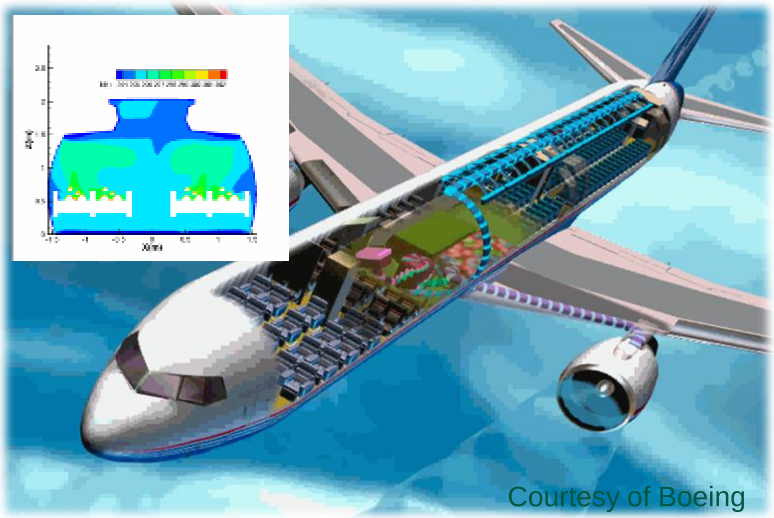


# Aircraft Environmental Control System

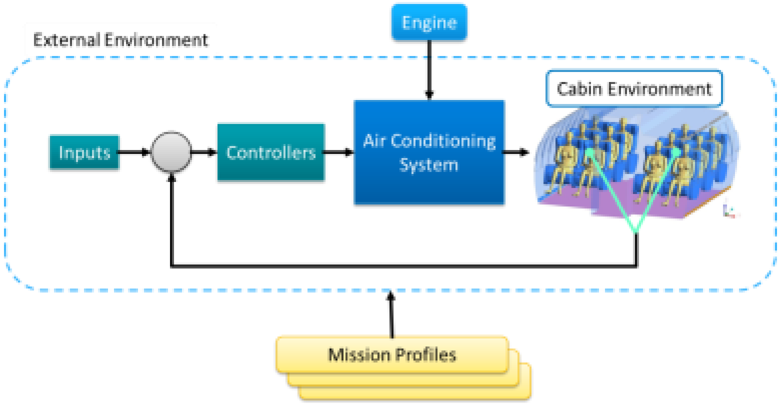
## System-Level Objectives

- Optimize component selection, sensor placement, and control strategies to improve fuel efficiency (lower emissions)
- Tune & optimize controller parameters to improve passenger comfort across a range of mission profiles and conditions




## Key System-Level Models

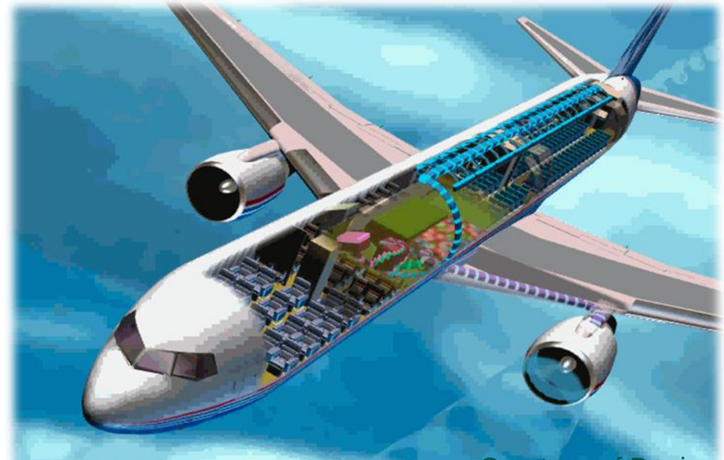
- ***Fluent***: Detailed cabin airflow model extracted as ROM
- ***SCADE***: Cabin pressure / temperature control software
- ***Modelica***: A/C system components (actuators, sensors, etc.)
- ***Simplorer***: External conditions, mission profiles



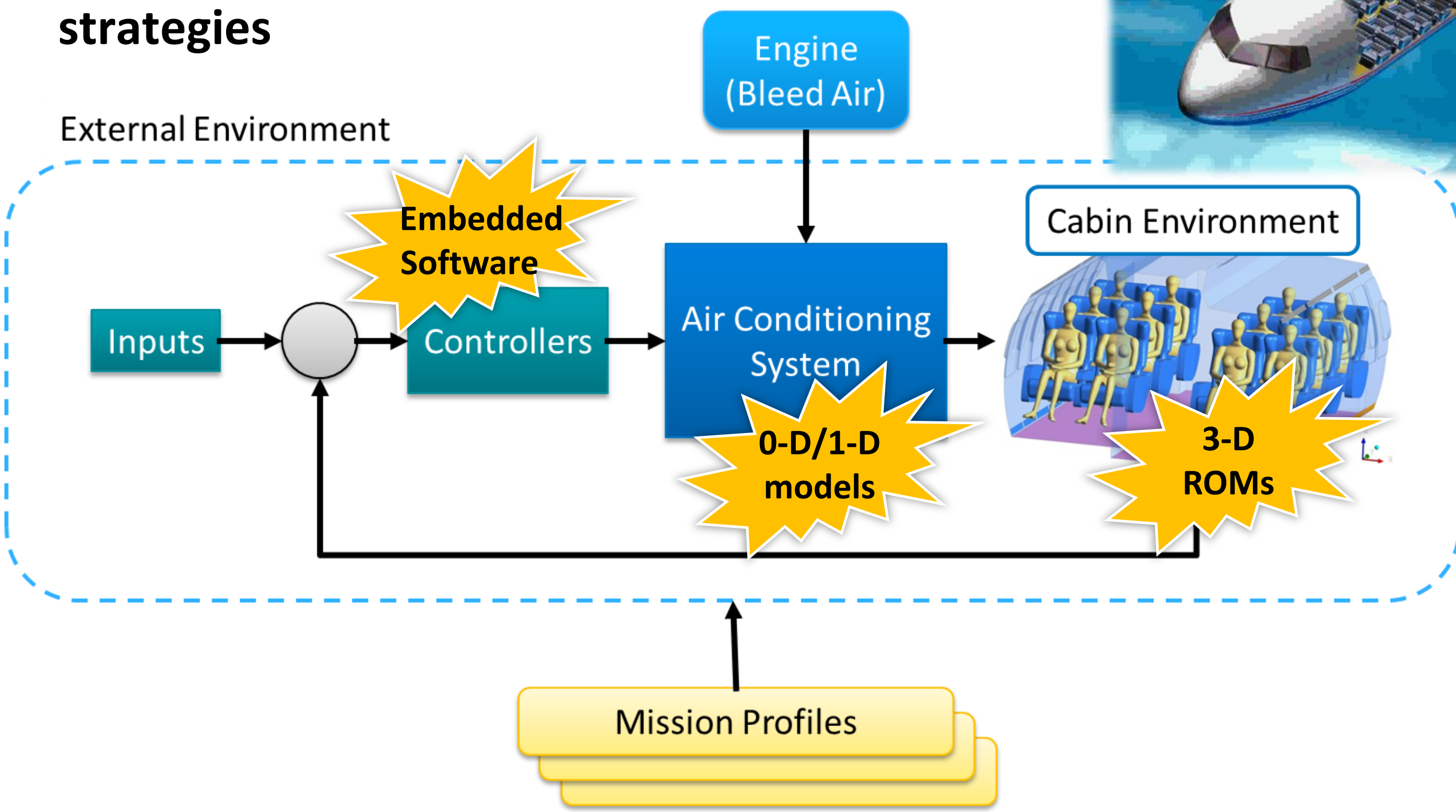
# Complete System Virtual Prototyping

## *Environmental Control Systems*



Courtesy of Boeing

**Optimize component selection, sensor placement, and control strategies**



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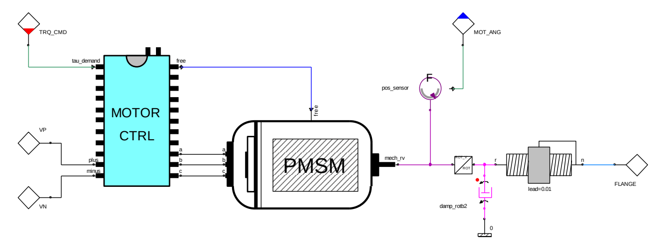
# Electromechanical Flight Controls

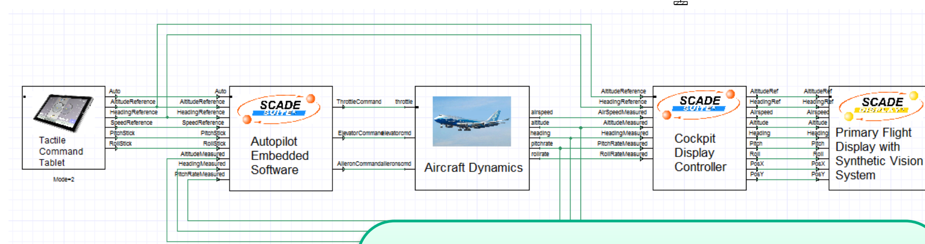
## Key System-Level Models

- ***Maxwell***: Permanent magnet synchronous machine extracted as ROM
- ***SCADE***: Autopilot control software, cockpit display
- ***Simplorer***: Behavioral multi-domain sensors, mechanical assemblies

## System-Level Value

- Verify control strategies and calibrate control parameters
- Optimize performance and robustness to external disturbances
- Assess system reliability (worst-case analysis, fault injection)


**Other Electrified Aircraft Systems:**

- Electric Green Taxiing
- Electric Braking
- Electric Engine Start

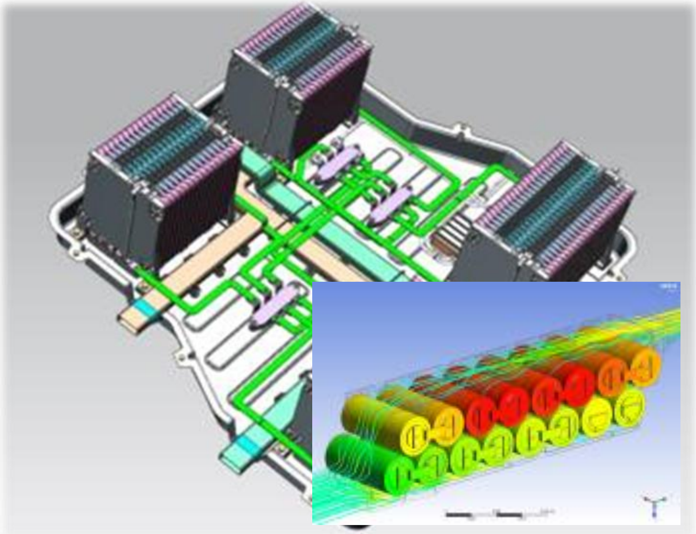
# Automotive Battery Performance

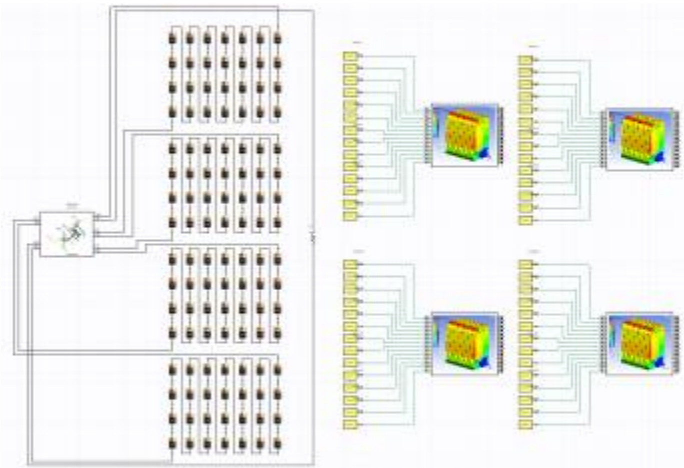
## System-Level Objectives

- Predict and optimize battery life based on electrical and thermal performance
- Assess battery pack safety across a range of mission profiles

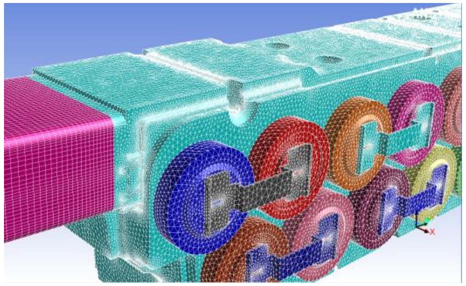
## Key System-Level Models

- ***Fluent***: equivalent electrical circuits and thermal behavior of cells extracted as ROMs
- ***Modelica***: ...
- ***Simplorer***: Electronics and multi-domain sensors
- ***SCADE***: Power management and control



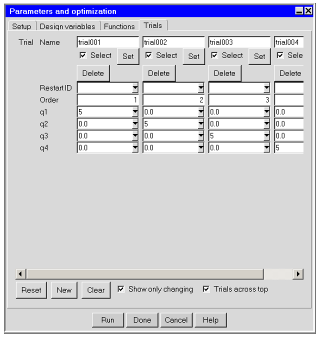


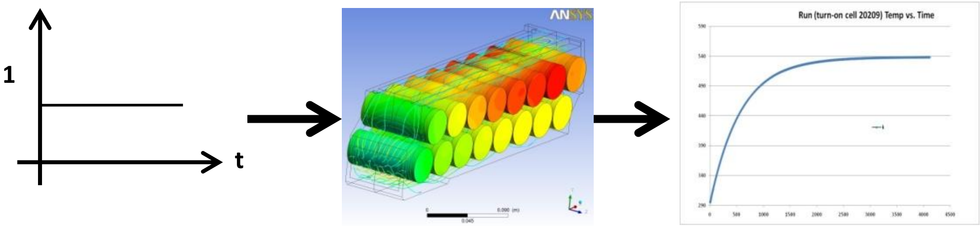
# Model Order Reduction Creation



→ **Create CFD Model**

→ **Generate Step Responses**



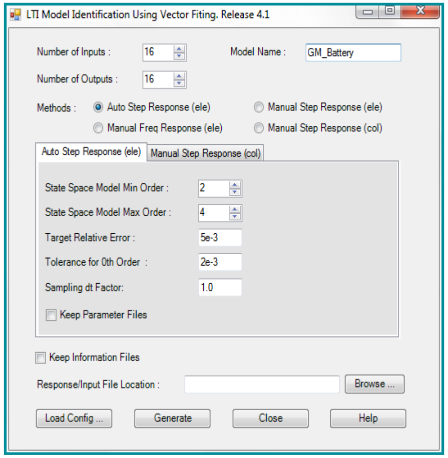

Step Input

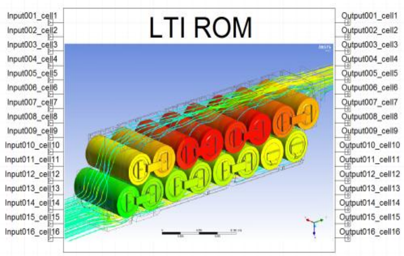
Step Response

→ **Extract ROM**

| | A |
|---|---|
| 1 | LTI ROM Builder |
| 2 | Battery LTI ROM Automation Setup |
| 3 | Results |

LTI ROM Builder

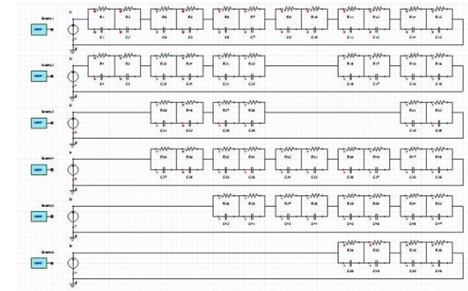


# Model Order Reduction Types

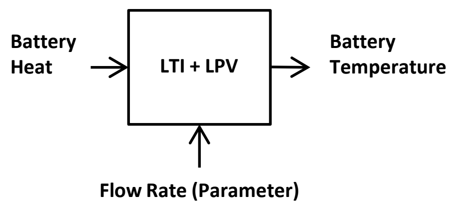
## → Foster Network – LTI (Linear Time Invariant)

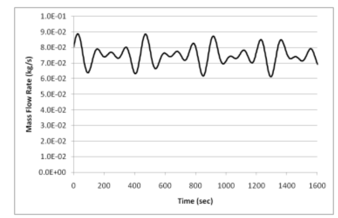
- Average or local temperatures
- One single flow rate
- Physical comprehension

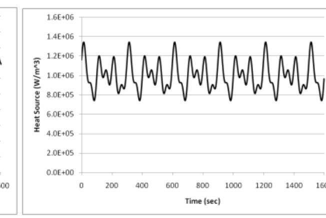


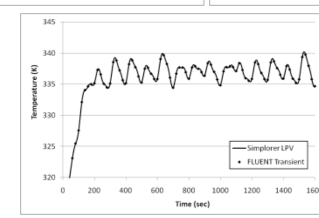
## → LTI+LPV (Linear Parameter Varying) ROM

- Average or local temperatures
- Varying flow rates



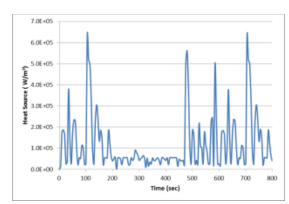



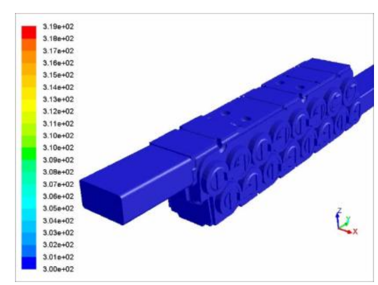




## → SVD (Singular Value decomposition)

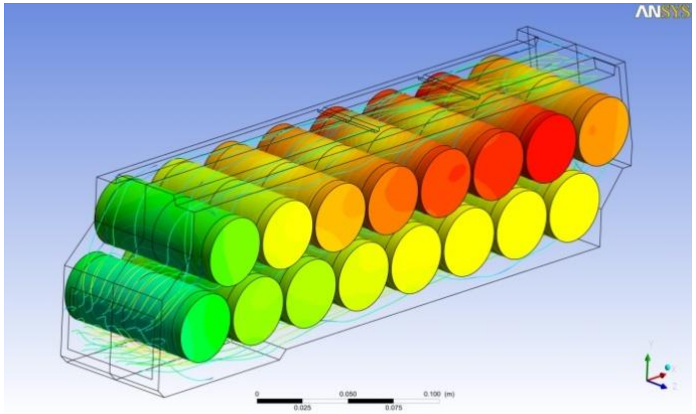
- allows for quick temperature distribution

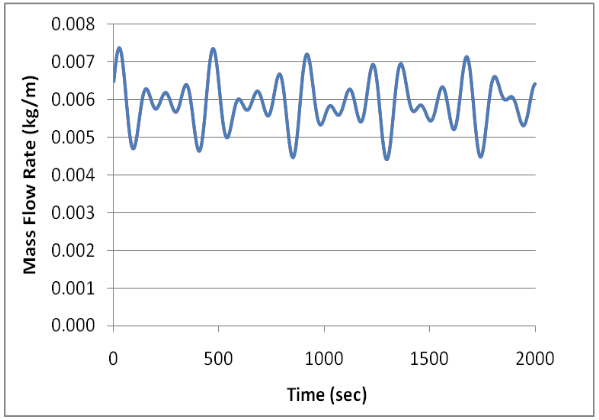


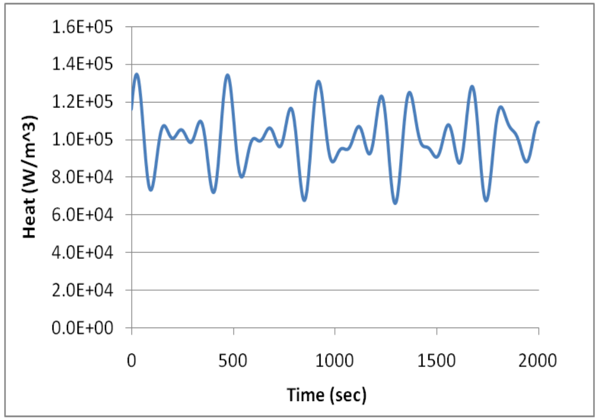


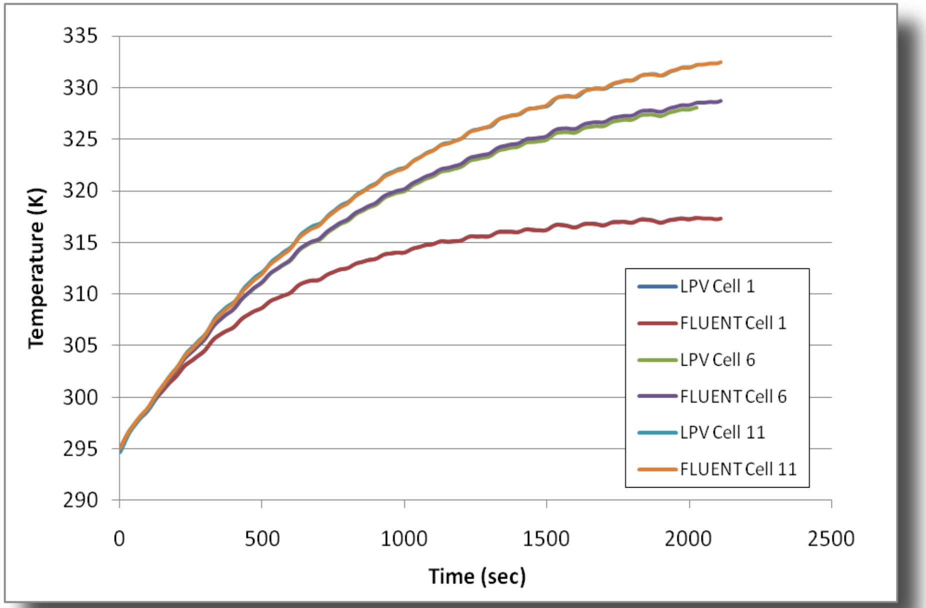
 

# LPV ROM for GM Battery Module





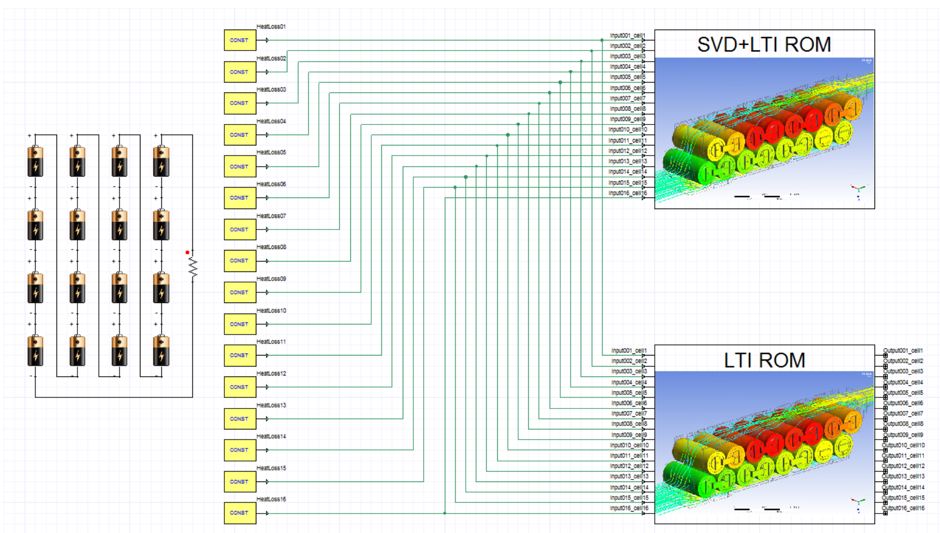



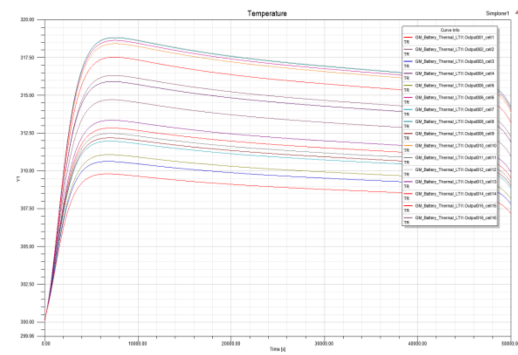




The model gives similar results as CFD. The model runs in less than 20 seconds while the CFD runs a couple of days on 6 CPUs.

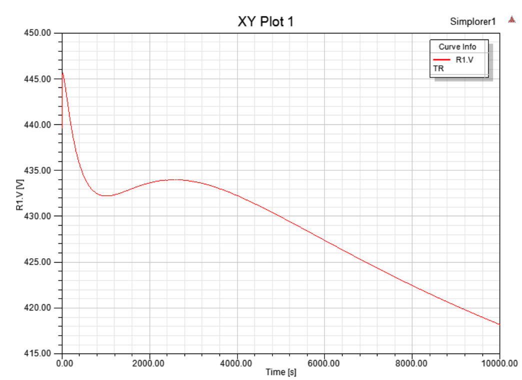
# GM Battery Module – ECM Coupled with ROMs

- ECM calculates heat source and sends it to the two ROMs
- LTI ROM calculates average temperature and sends it to ECM
- SVD+LTI ROM calculates temperature distribution



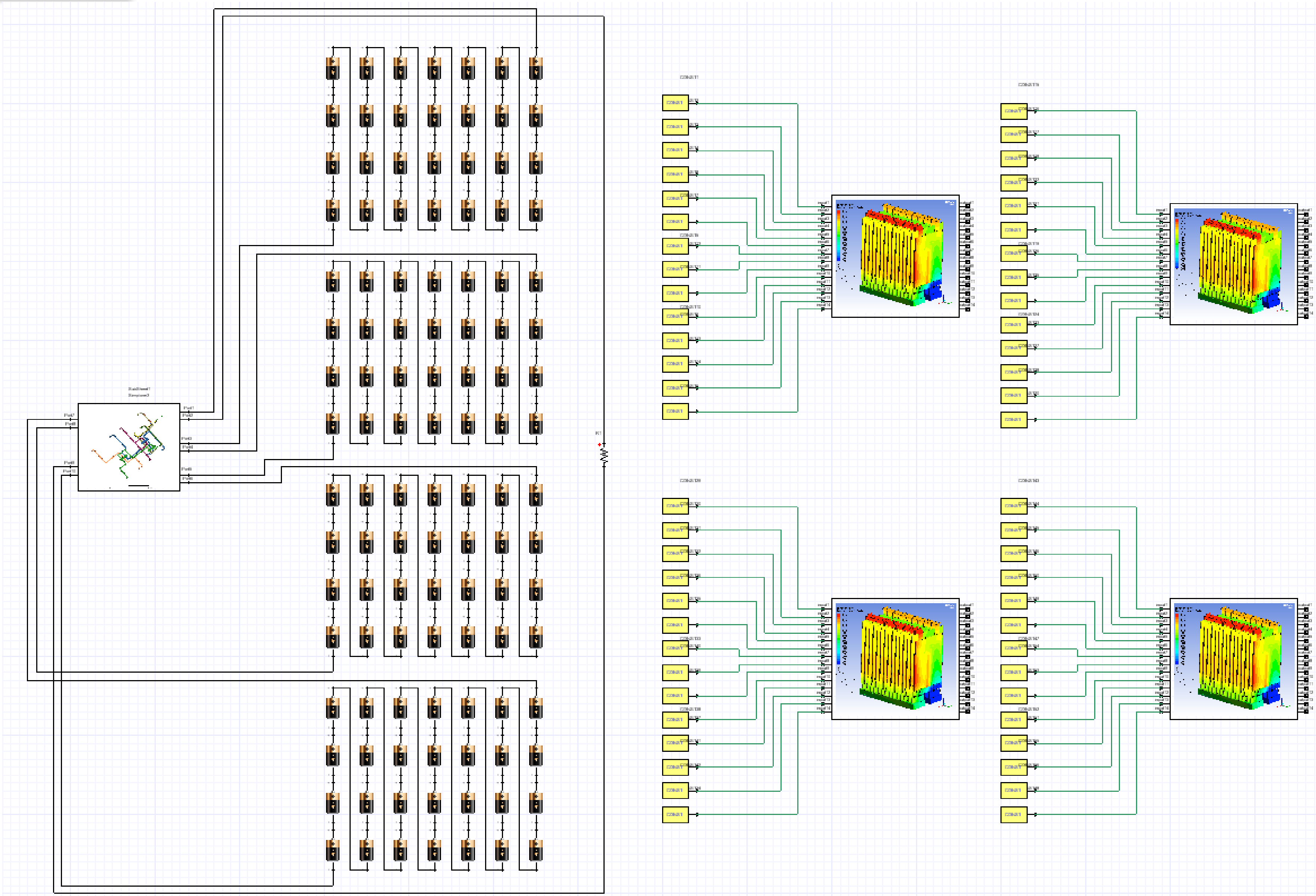




Average Cell Temperature




Battery Voltage as a Function of Time

# Full Battery Simulation



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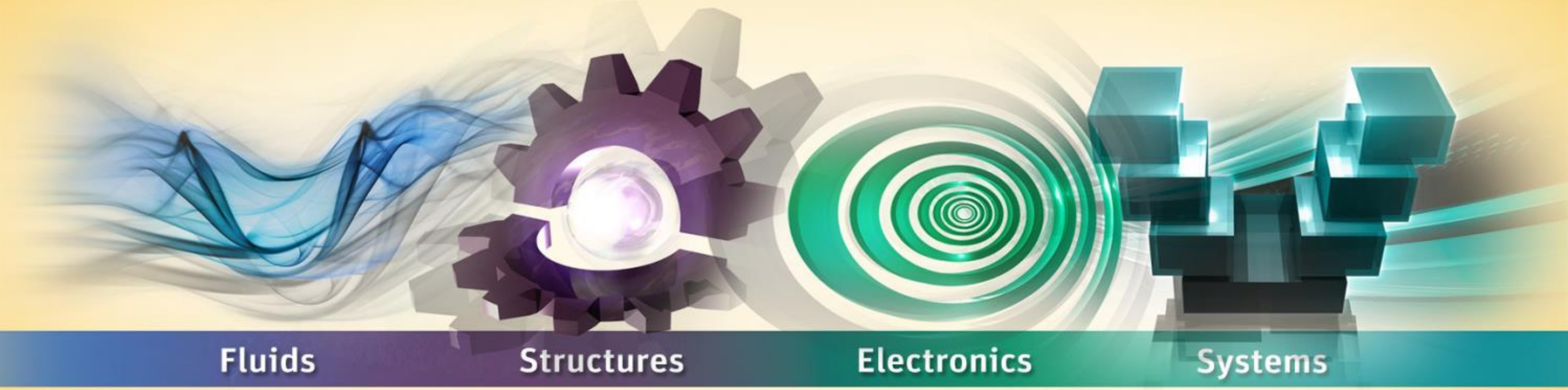
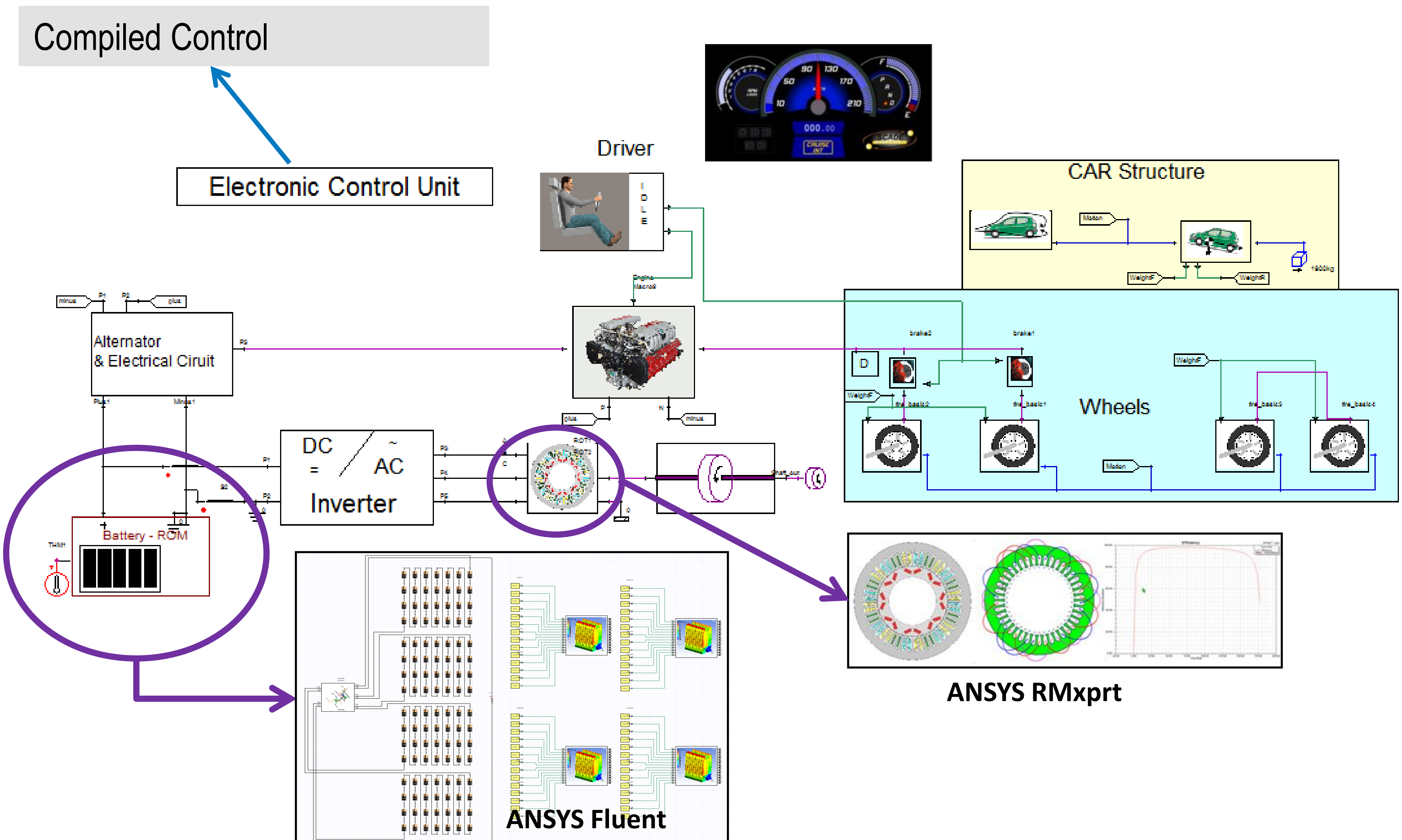
# Full system simulation



# Hybrid Electric Vehicle (HEV) Example

## *System Modeling with ROM Models*



# Summary

**Control software modeling is achieved by using a formally defined deterministic notation**

**Embedded software implementation is performed by using a ISO 26262 qualified toolchain**

**Multi-disciplinary simulation (electrical, mechanical, fluid, software):**

- Through appropriate languages (VHDL/AMS, Modelica, SCADE)
- In an appropriate environment (Simplorer)
- Via appropriate interfaces (FMI, 2D & 3D ROMs)

**Multi-order simulation is performed via coupling with 3D co-simulation and reduced order models (ROM)**

**Multi-physics & software model performances can be optimized via batch simulation campaigns**