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PHOENIX INTEGRATION

Model-Driven Innovation

The Role of Multi-domain Dynamic Models for Functional Verification in Model-based Systems Engineering (MBSE)

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NIST MBE Summit 2017, Gaithersburg, MD

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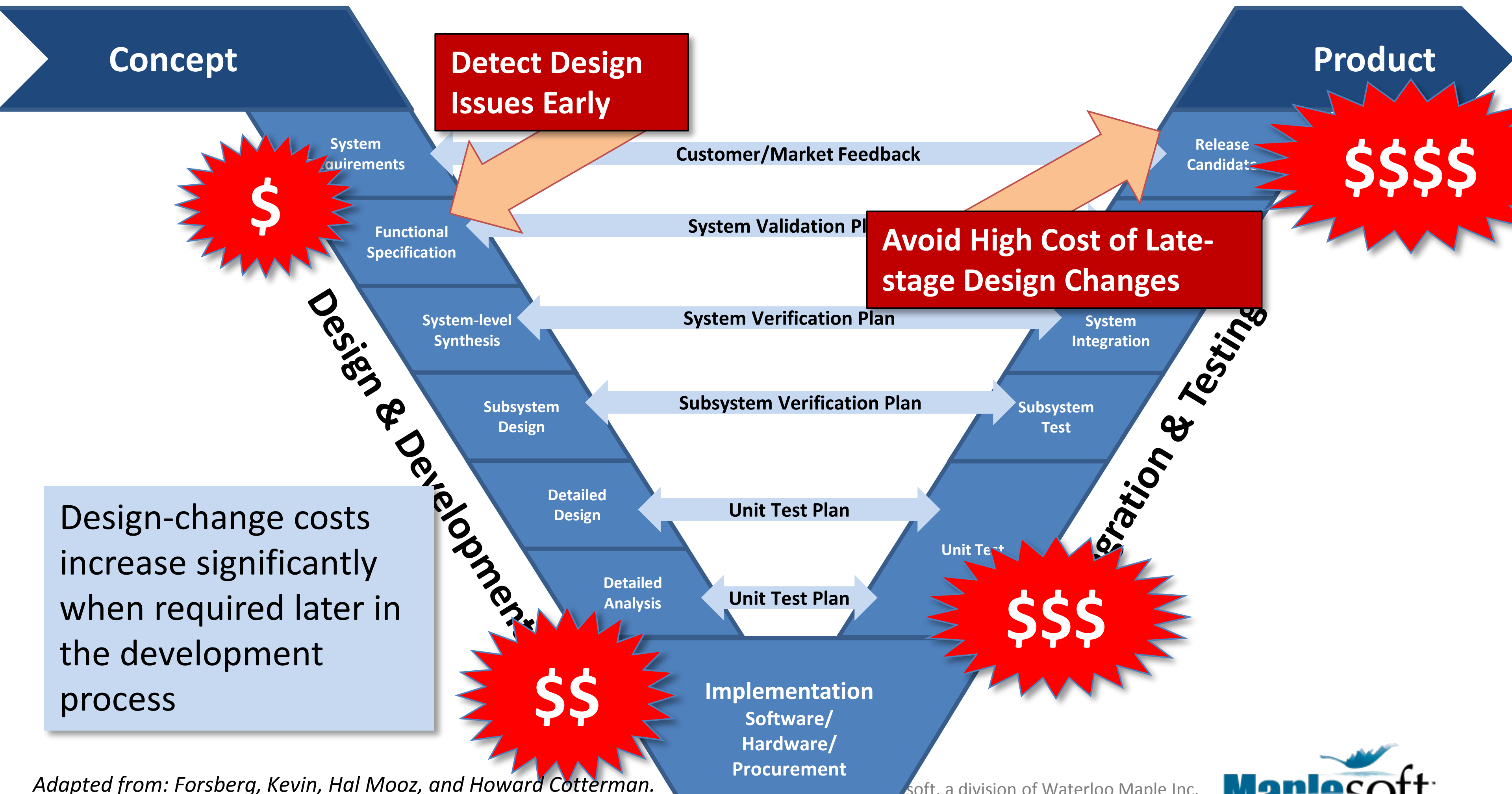
Systems Design & Development Process



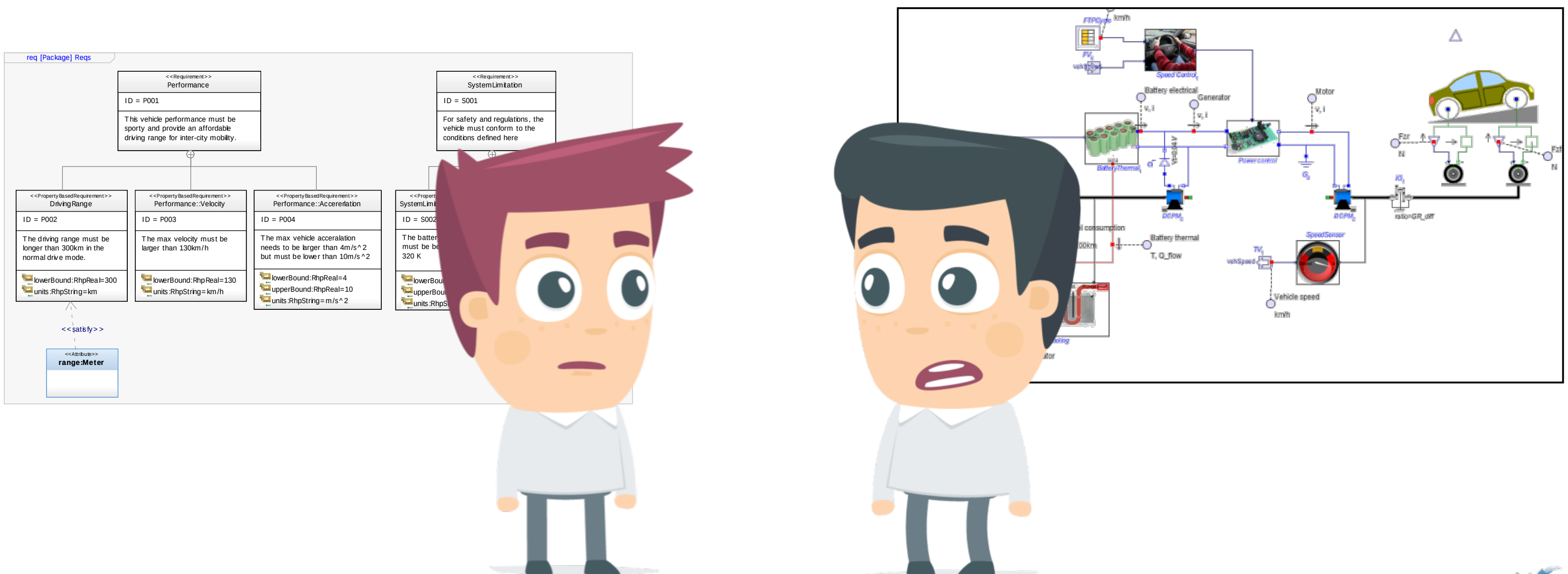
Design-change costs increase significantly when required later in the development process

Adapted from: Forsberg, Kevin, Hal Mooz, and Howard Cotterman. Visualizing Project Management. John Wiley & Sons. Hoboken, NJ. 2005.

Model-based Systems Engineering vs Model-based Engineering

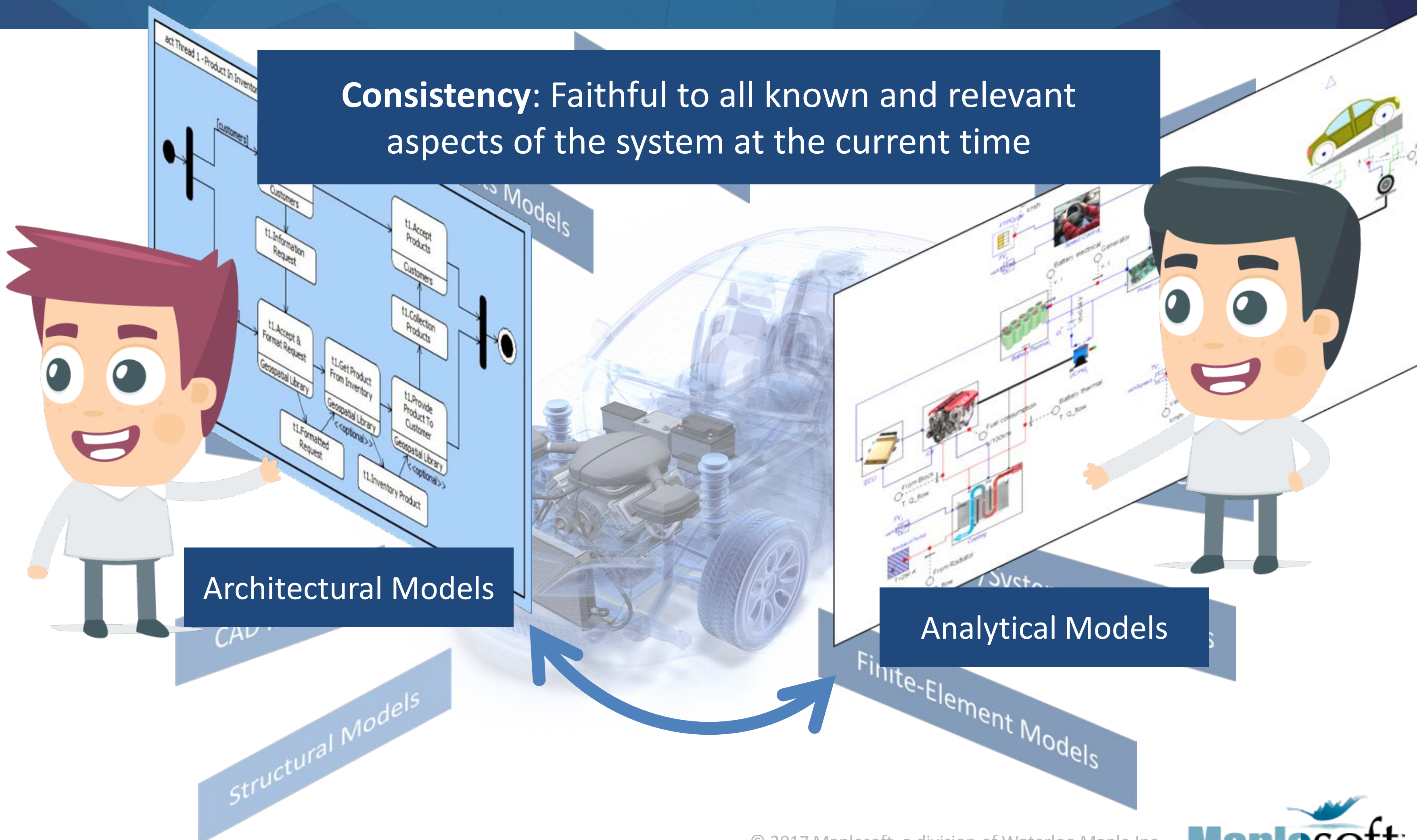
With apologies to George and Ira…

I say "system engineering", you say "systems engineering". …Let's call the whole thing off…



Model-based Systems Engineering vs Model-based Engineering

Consistency: Faithful to all known and relevant aspects of the system at the current time



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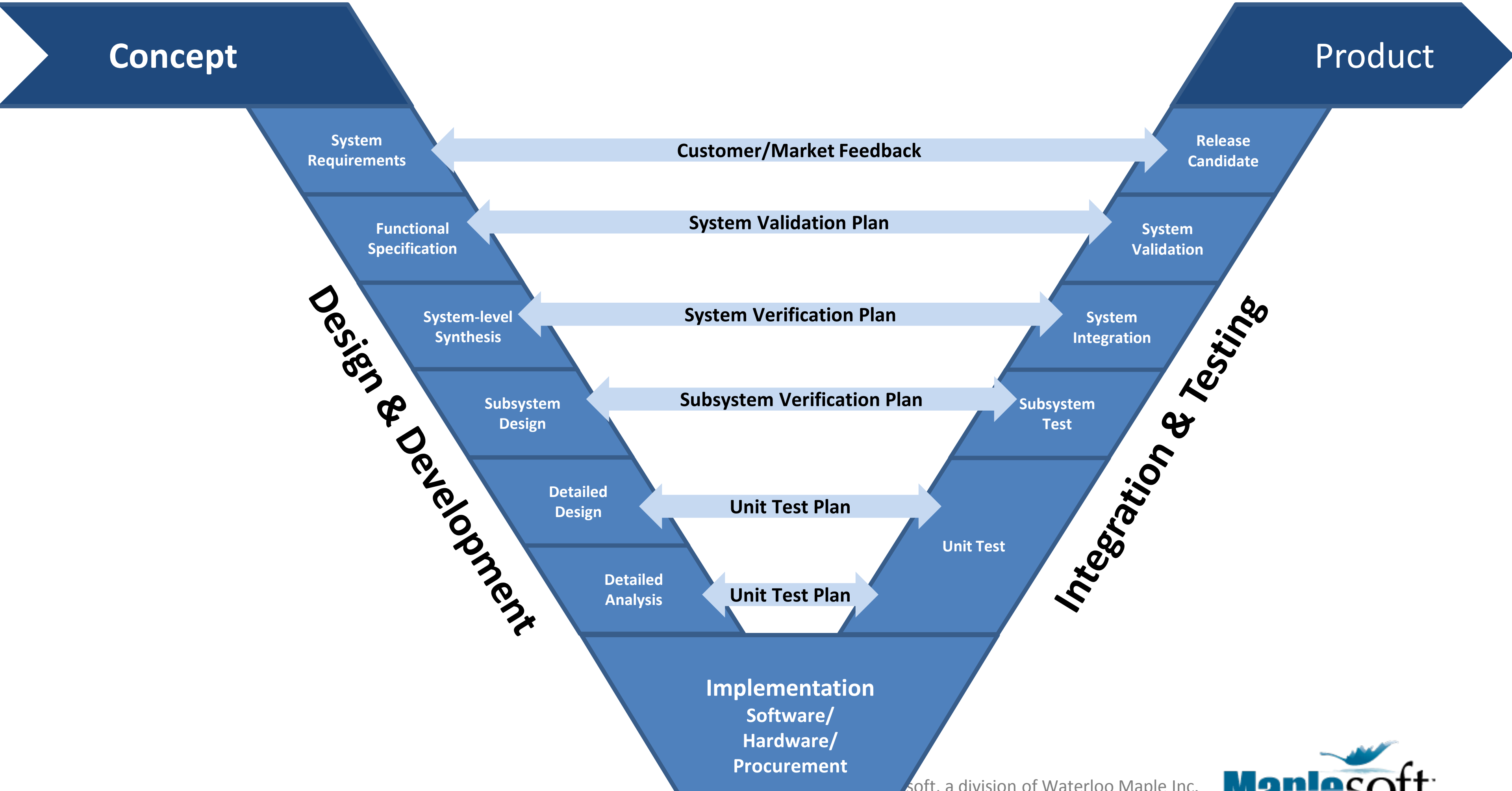
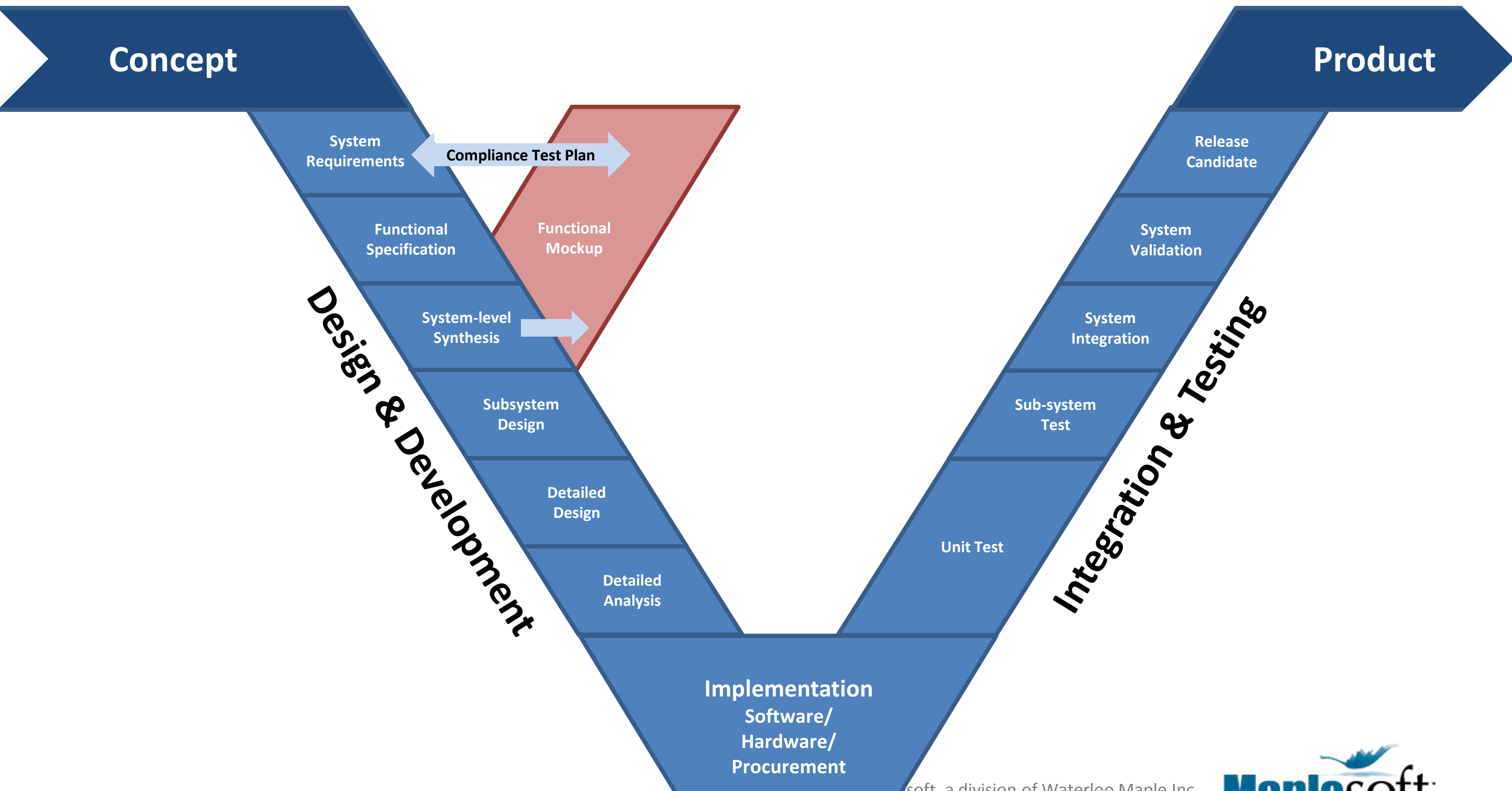
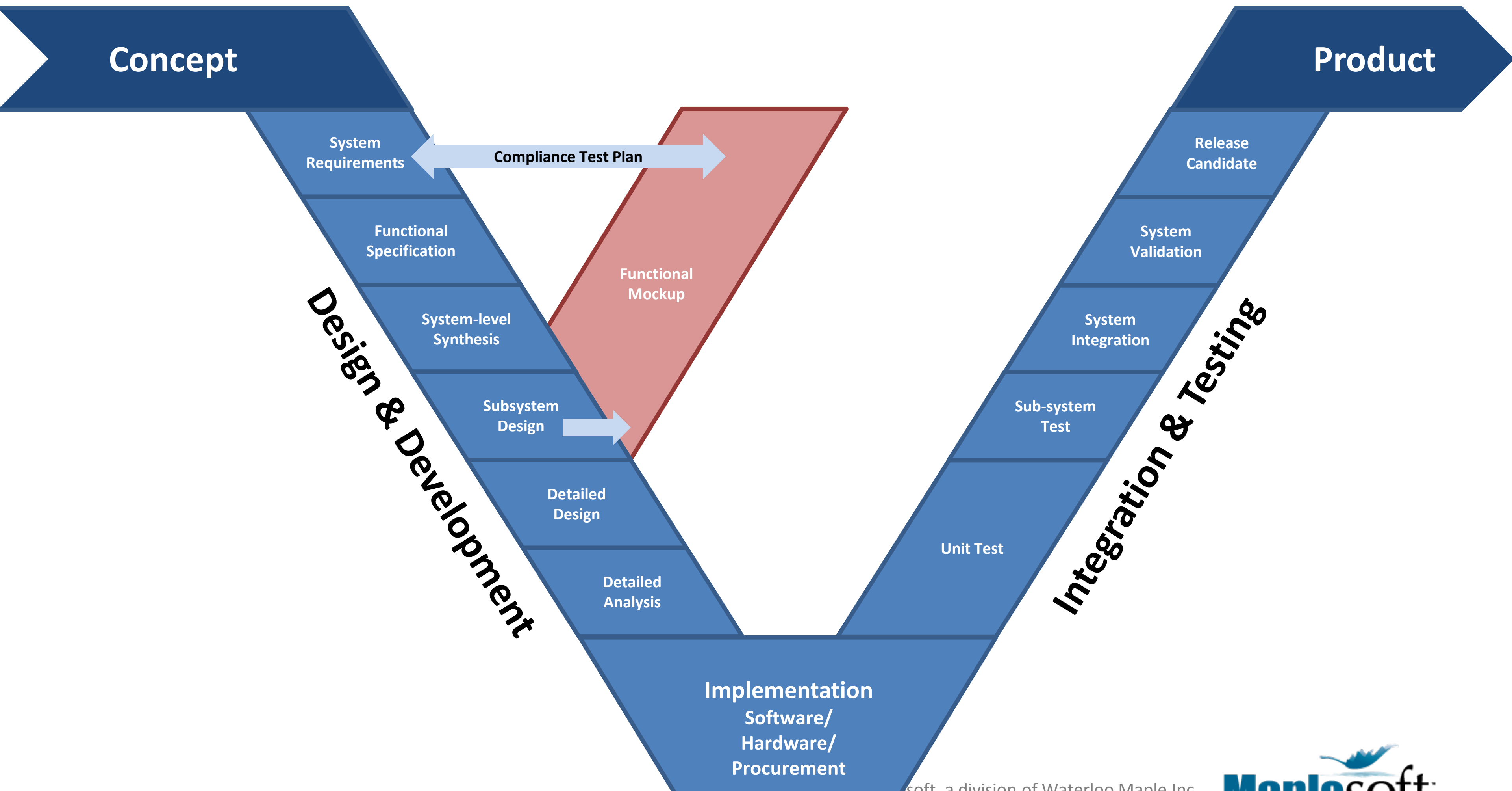
Systems Design & Development Process
Functional Verification



Systems Design & Development Process
Functional Verification



Systems Design & Development Process
Functional Verification



Systems Design & Development Process
Functional Verification

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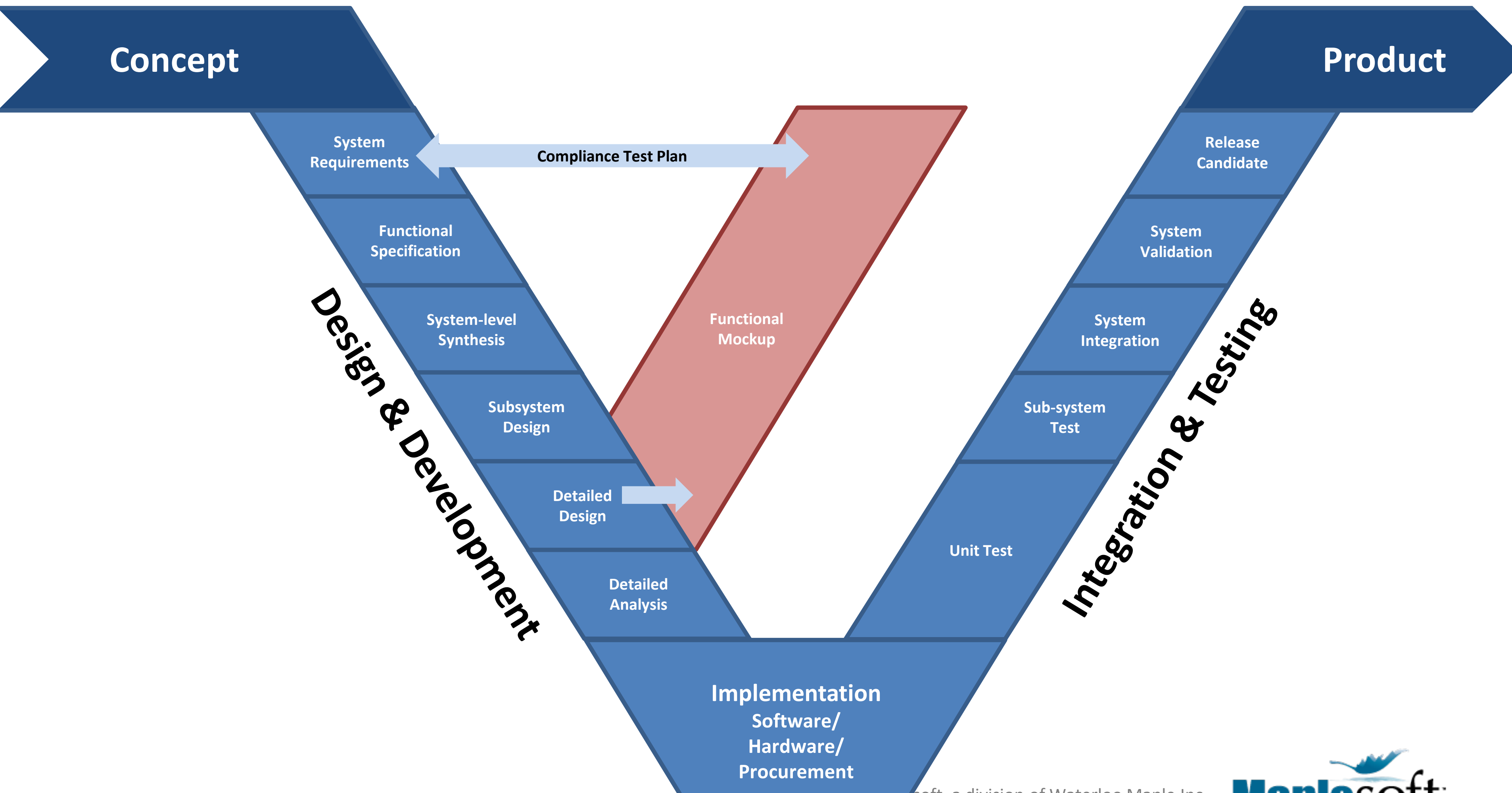

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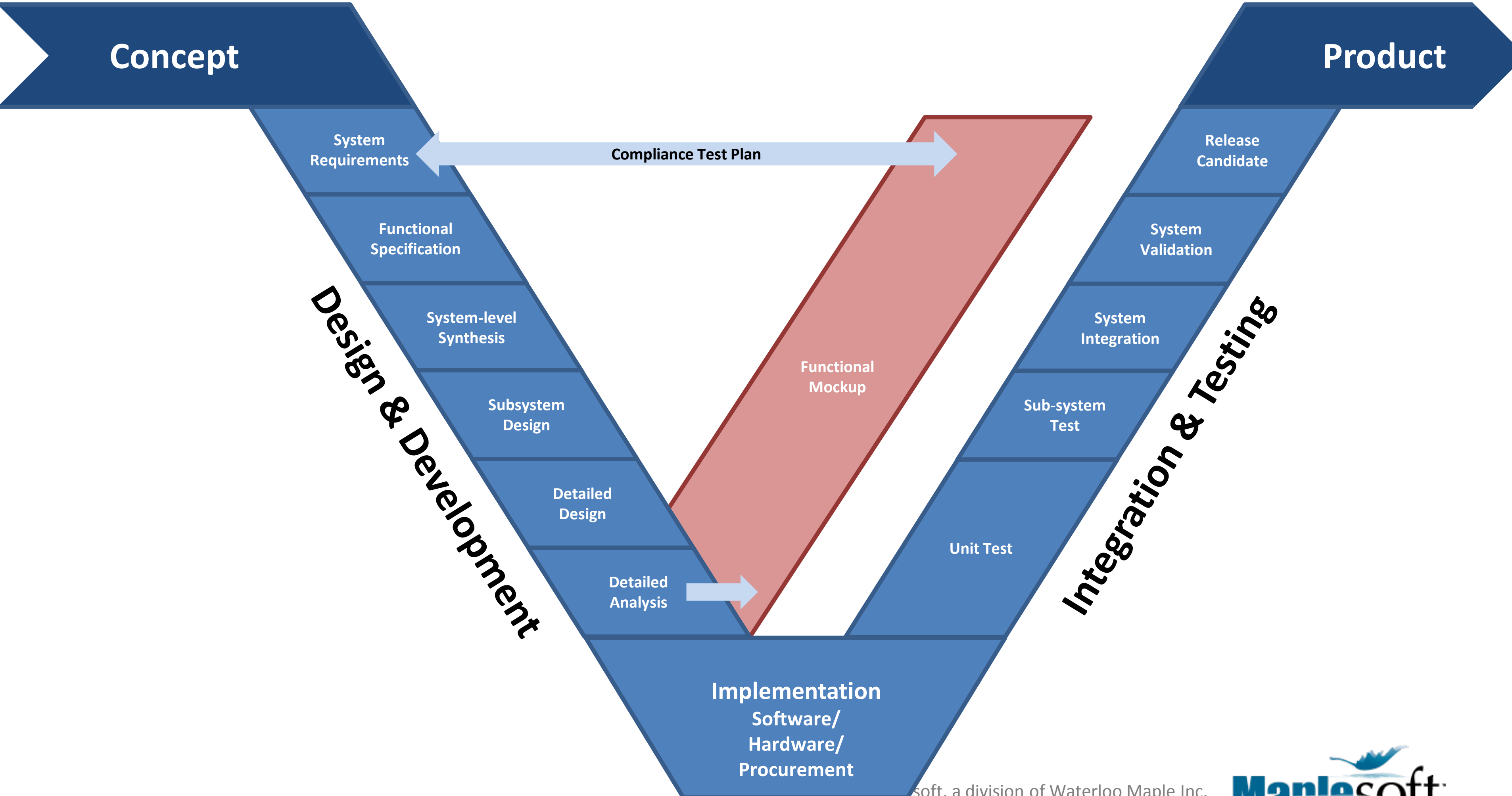
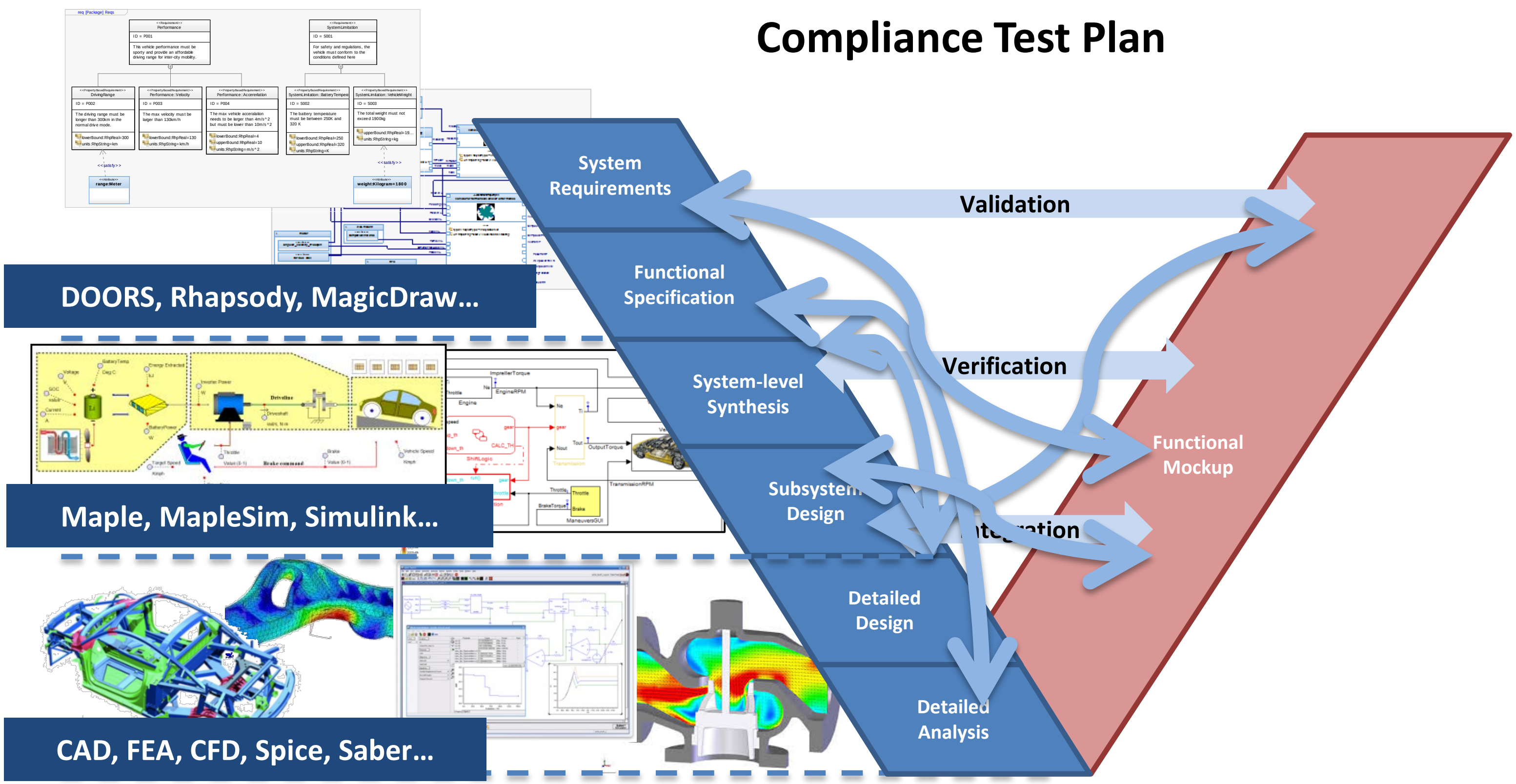
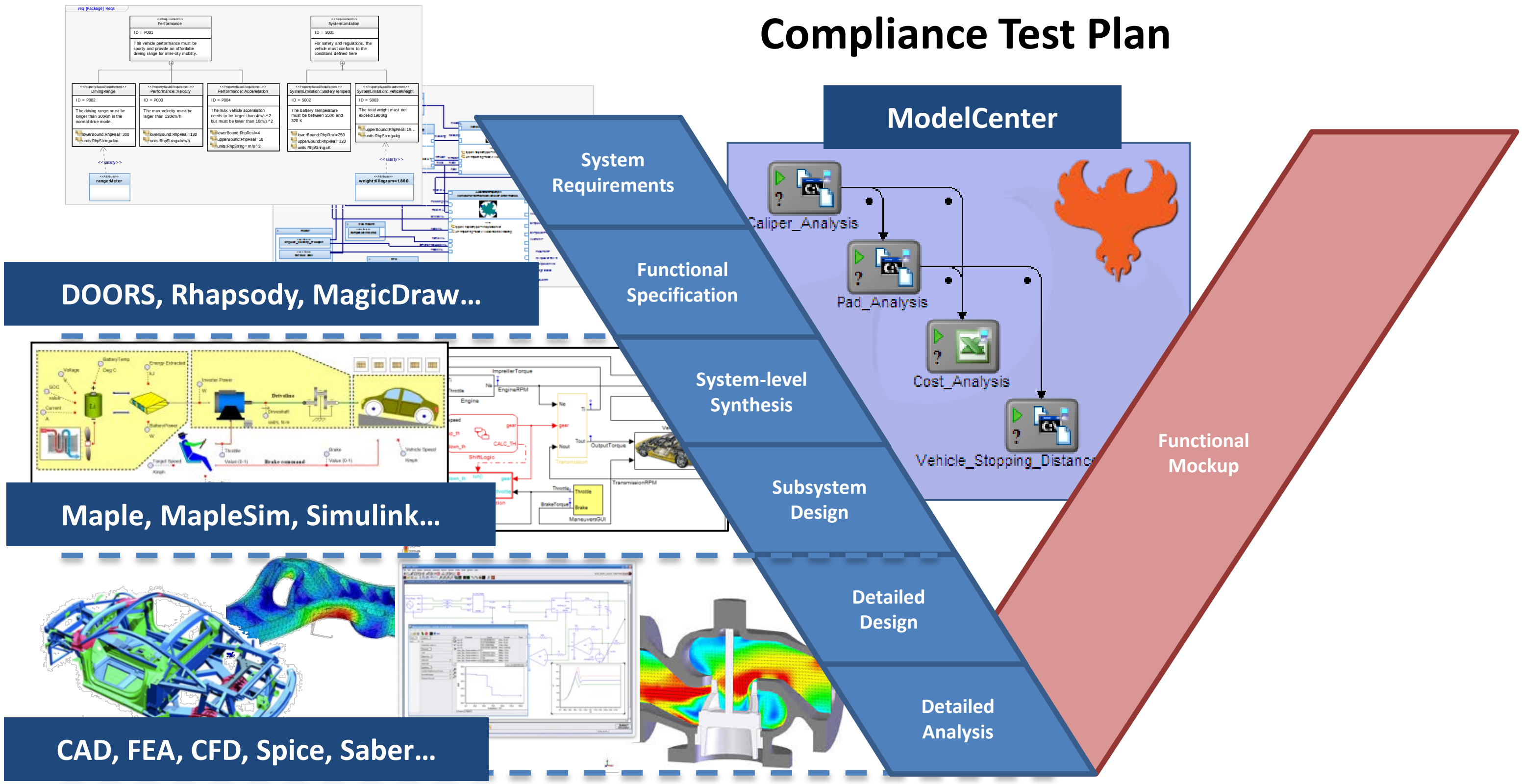
Systems Design & Development Process
Functional Verification



Systems Design & Development Process
Functional Verification



Systems Design & Development Process
Functional Verification



MapleSim

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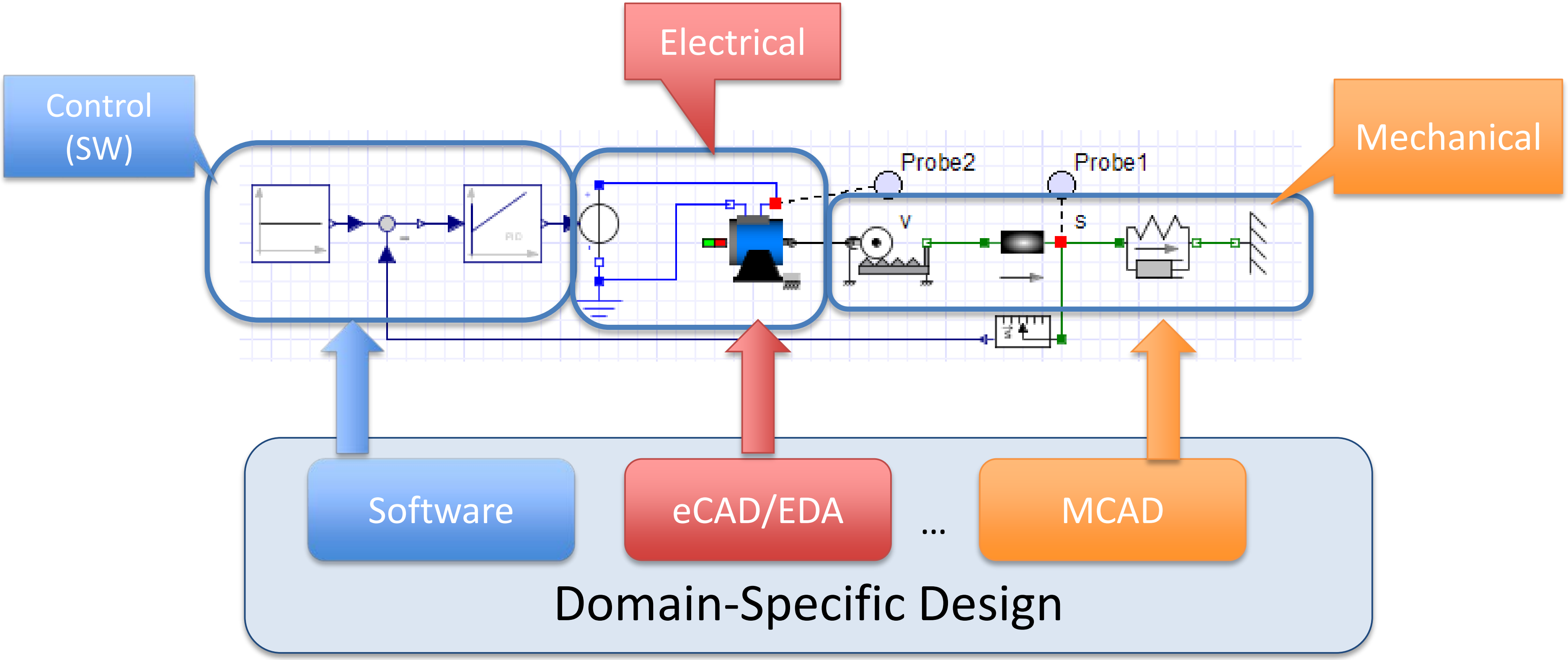
Multi-domain Systems Design



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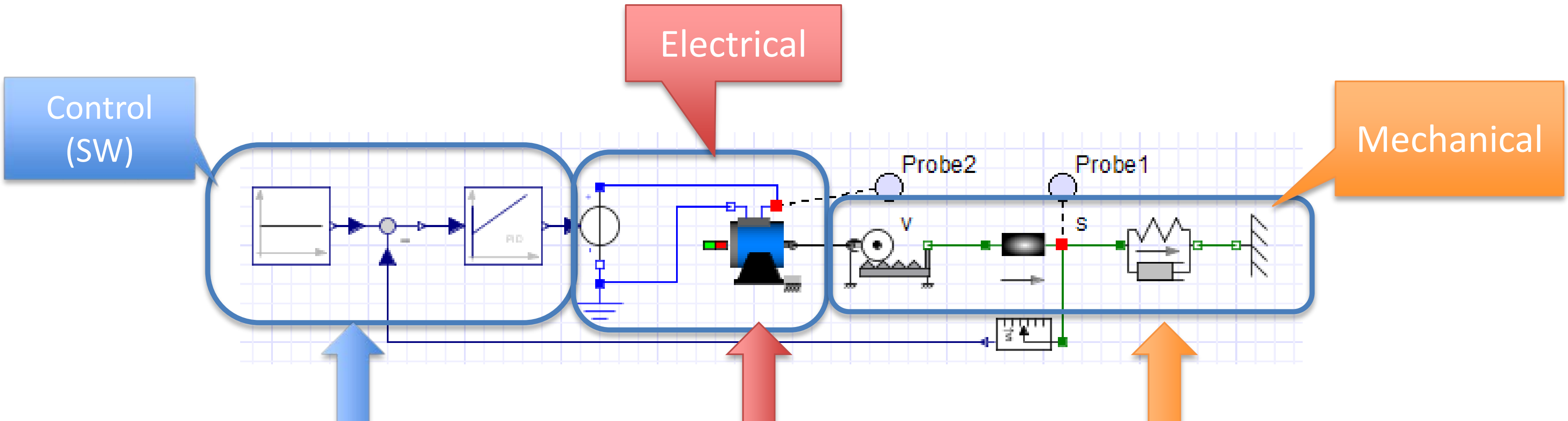
Modelica: Object-oriented Physical Modeling

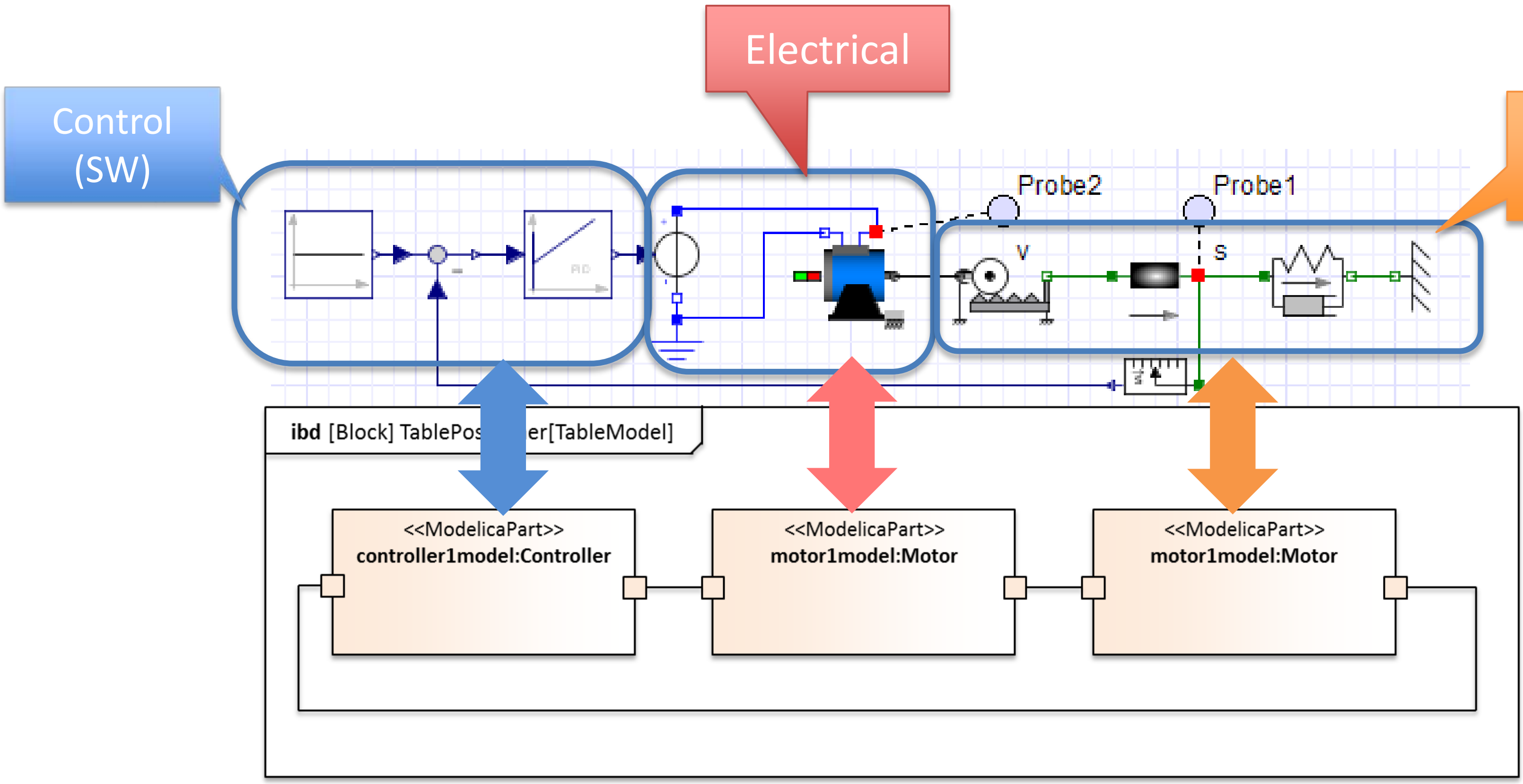



```
model Controller
   import Modelica.Constants.inf ;
   import Pi=Modelica.Constants.pi ;
   import Modelica.Constants.pi ;
   import Maplesoft.Constants.I ;

   public Maplesoft.SignalBlocks.Controllers.PID   PID1(sign
annotation (Placement (transformation (origin={190.0,60.0},ex
   public Maplesoft.SignalBlocks.Math.Operators.Feedback
   public Maplesoft.SignalBlocks.Sources.Real.Step   S1(heig
   public Modelica.Blocks.Interfaces.RealInput   u1 annotatio
   public Modelica.Blocks.Interfaces.RealOutput   y1 annotat
equation
   connect(F1.y, PID1.u) annotation(Line(points={{148.0,60
   connect(S1.y, F1.u1) annotation(Line(points={{92.0,60.0
   connect(PID1.y, y1) annotation(Line(points={{212.0,60.0
   connect(F1.u2, u1) annotation(Line(points={{130.0,44.0
   annotation(
         Diagram(coordinateSystem(preserveAspectRatio =true
         Icon(coordinateSystem(preserveAspectRatio =true,
   );
end Controller;
```

```
model Motor
   import Modelica.Constants.inf ;
   import Pi=Modelica.Constants.pi ;
   import Modelica.Constants.pi ;
   import Maplesoft.Constants.I ;

   public Maplesoft.Mechanics.Rotational.Common.Inertia   I4(J=1,
   public Maplesoft.Electrical.Analog.Sources.Voltage.SignalVoltag
   protected Modelica.Mechanics.Rotational.Interfaces.Flange_a
   public Maplesoft.Electrical.Analog.Passive.Resistors.Resistor
)));
   public Maplesoft.Electrical.Analog.Passive.Inductors.Inductor
   public Maplesoft.Electrical.Analog.Passive.Ground   G2 annotat
   public Maplesoft.Mechanics.Rotational.Sensors.AngleSensor
   public Maplesoft.Mechanics.Rotational.Sensors.RotationalSpeedSe
rotation=0)));
   public Maplesoft.Electrical.Analog.Passive.EMF   EMF2(useSuppo
   public Modelica.Blocks.Interfaces.RealInput   InputSource
   public Modelica.Mechanics.Rotational.Interfaces.Flange_b
   public Modelica.Blocks.Interfaces.RealOutput   PositionOutput
   public Modelica.Blocks.Interfaces.RealOutput   RO3 annotation
equation
   connect(R2.n, I7.p) annotation(Line(points={{128.0,268.0},
   connect(EMF2.n, G2.p) annotation(Line(points={{228.0,158.0
```

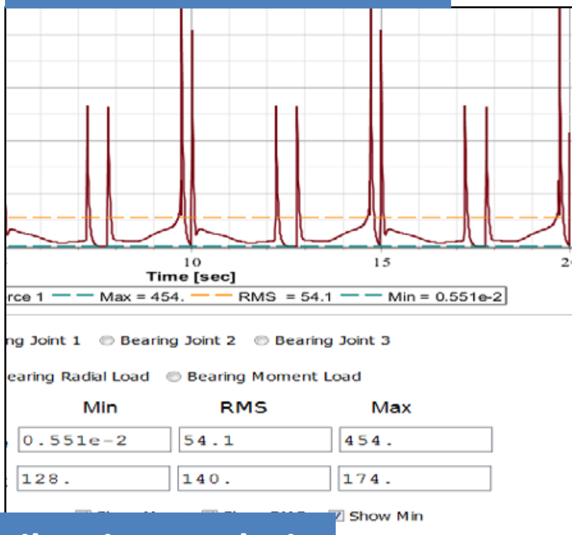
```
model Table
   import Modelica.Constants.inf ;
   import Pi=Modelica.Constants.pi ;
   import Modelica.Constants.pi ;
   import Maplesoft.Constants.I ;

   public Maplesoft.Mechanics.Rotational.Common.Inertia   I3(J=0.
   public Maplesoft.Mechanics.Translational.Common.Mass   SM2(m=2
   public Maplesoft.Mechanics.Rotational.BearingsGears.IdealGearR2T
   public Modelica.Mechanics.Rotational.Interfaces.Flange_a   a1
   public Modelica.Mechanics.Translational.Interfaces.Flange_b   b1
equation
   connect(IGRT2.flangeT, SM2.flange_a) annotation(Line(points=
   connect(I3.flange_b, IGRT2.flangeR) annotation(Line(points=
   connect(SM2.flange_b, b1) annotation(Line(points={{220.0,60.
   connect(I3.flange_a, a1) annotation(Line(points={{50.0,60.0},
   annotation(
         Diagram(coordinateSystem(preserveAspectRatio =true, exte
         Icon(coordinateSystem(preserveAspectRatio =true, extent
   );
end Table;
```

Functional Verification against formal requirements models

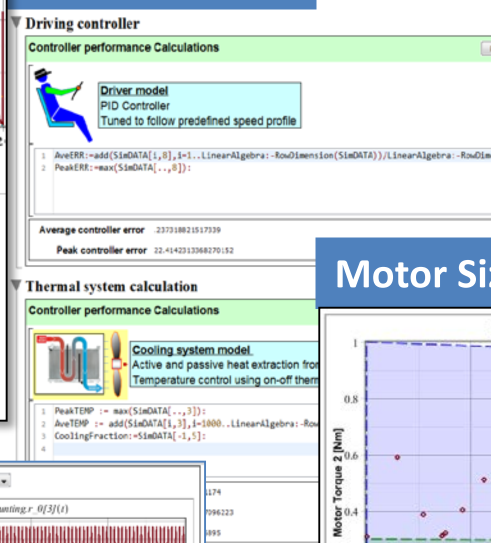


Symbolic Tools for Design-space Exploration

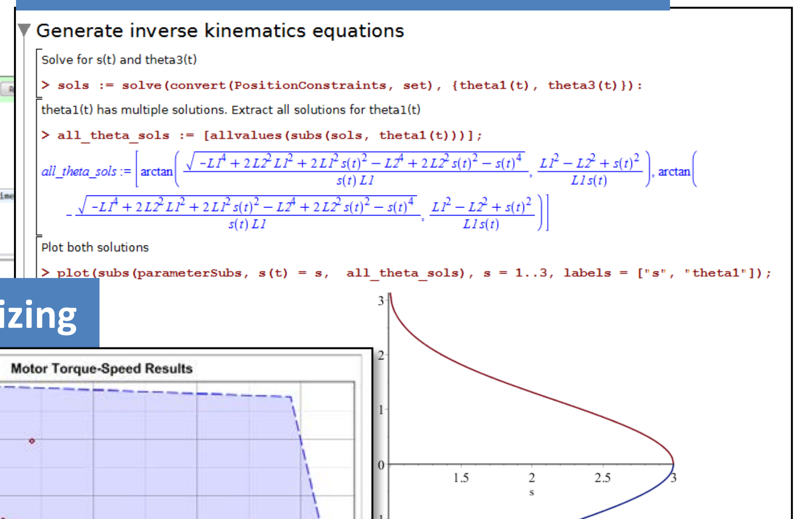
Dynamic Load Analysis



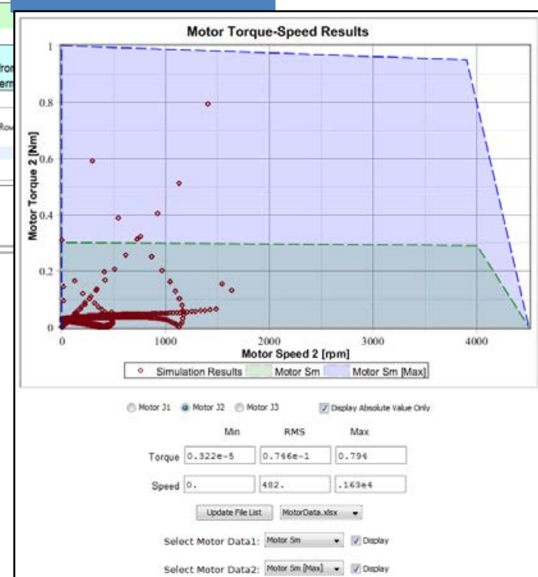
Post-Processing



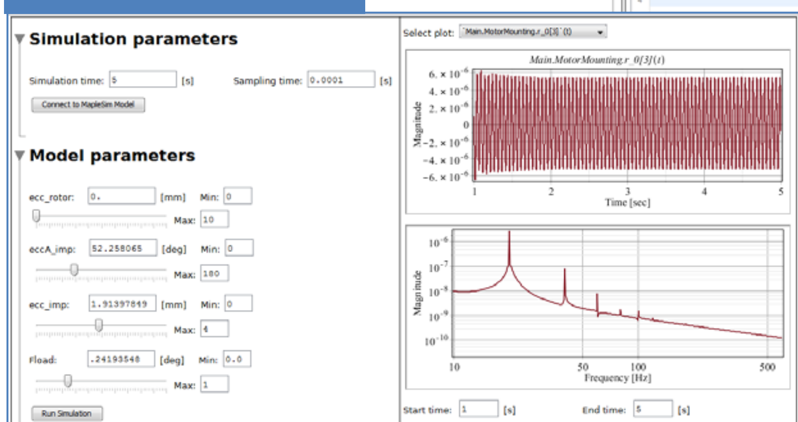
Inverse Kinematics and Dynamics



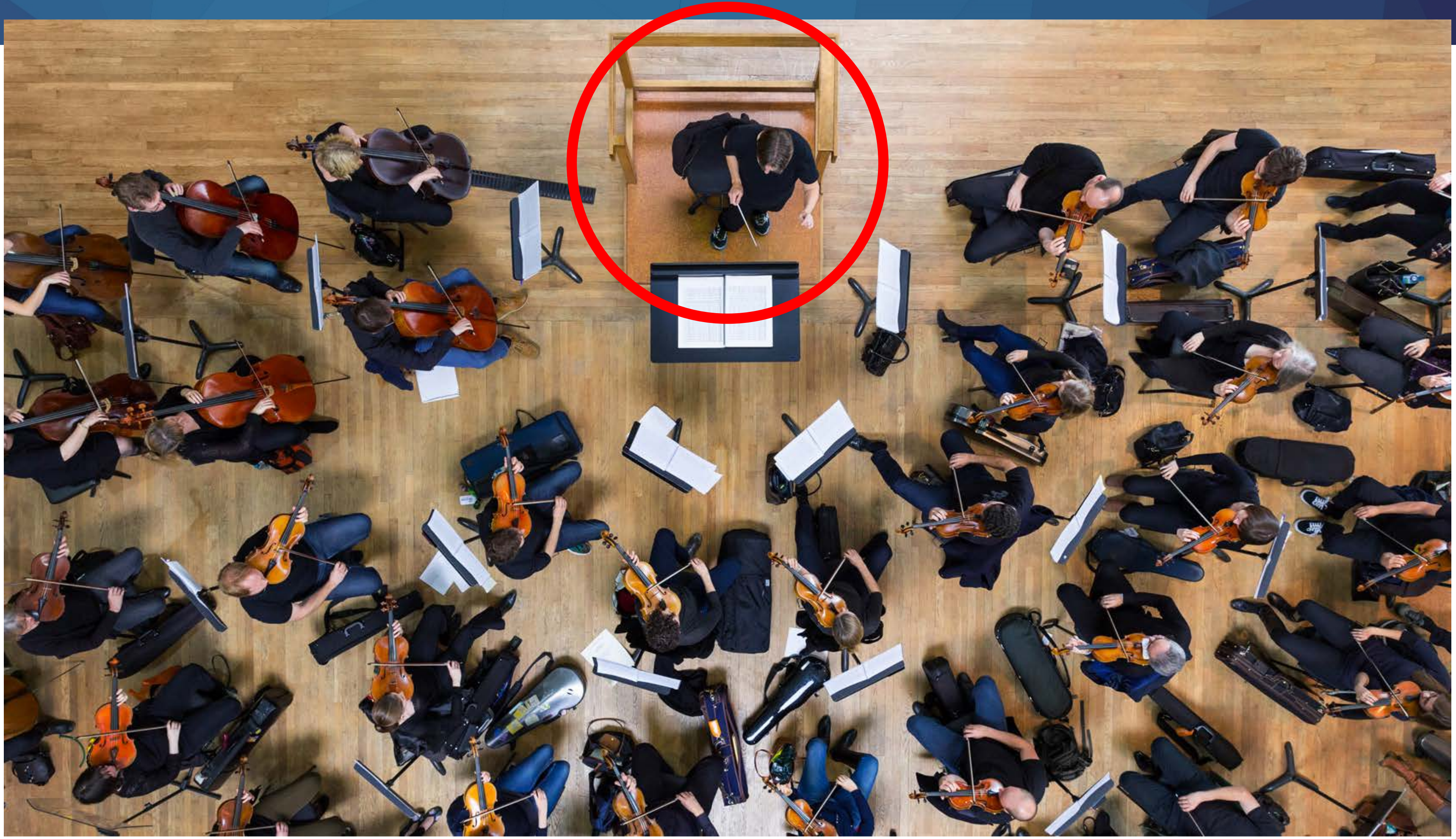
Motor Sizing



Vibration Analysis

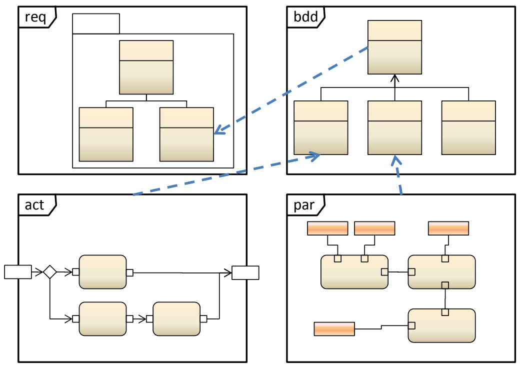


PHX ModelCenter

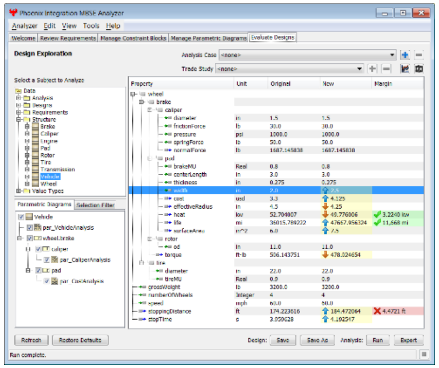


PHX Systems Engineering Integration Module

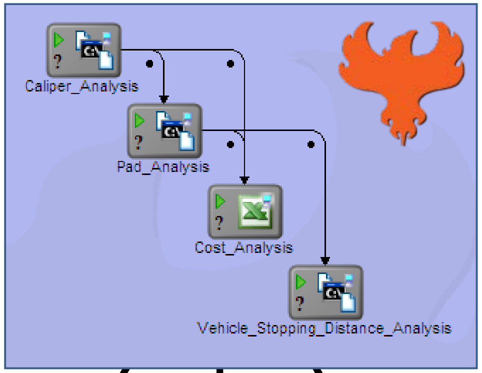
Systems Engineering: Architectural Model

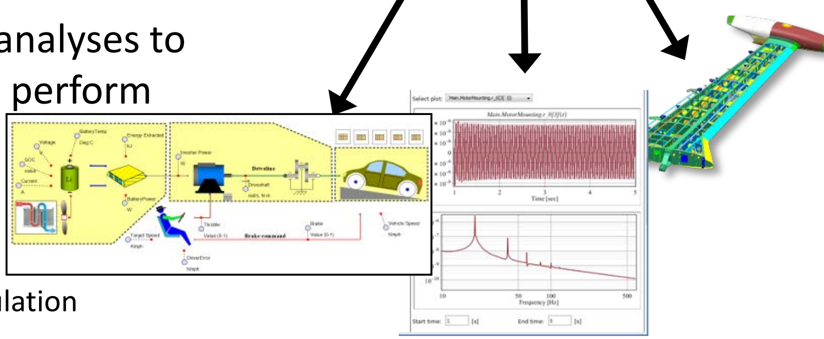


MBSE Analyzer



Domain Engineering: Executable Analysis Model

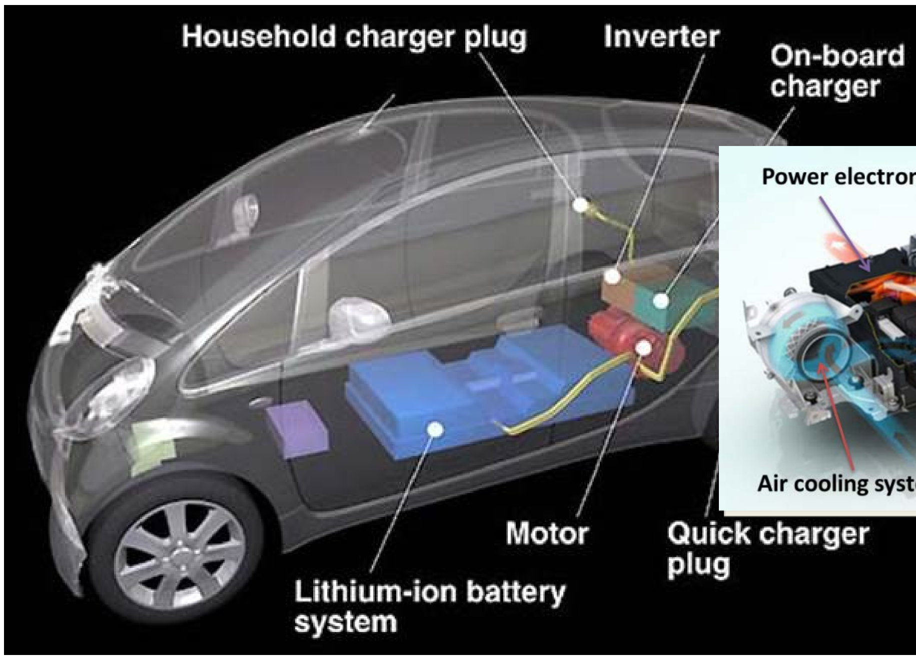


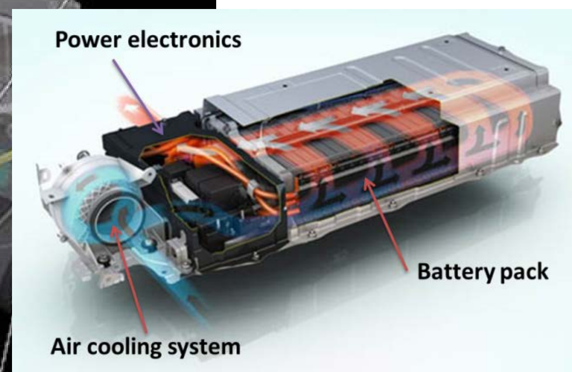


Engineering Analysis

- Connect systems architecture models with engineering analyses to calculate system performance, check requirements, and perform design trade-offs
- Capabilities
  - Execute SysML parametric diagrams to evaluate designs
  - Perform requirements compliance analysis using modeling and simulation
  - Perform design trade-off studies
  - Update SysML models with analysis results
  - Import engineering analyses into a SysML model

Electric Vehicle: Battery System Thermal Performance





Battery Power Electronics and Cooling

Stored Energy

- Battery Capacity
- State-of-Charge
- Affects driving range

Temperature Control

- Heat flow to/from battery
- Thermal effects on battery performance
- Active/passive cooling system

Electric Vehicle: Battery System Thermal Performance

Safety requirements

- Battery must operate in a safe temperature range
- Roll / pitch acceleration must be under a certain target
- Stopping distance should not be more than a specific target

Performance requirements

- Maximum acceleration / speed should be more than designated targets.
- Must be operable within a designated range

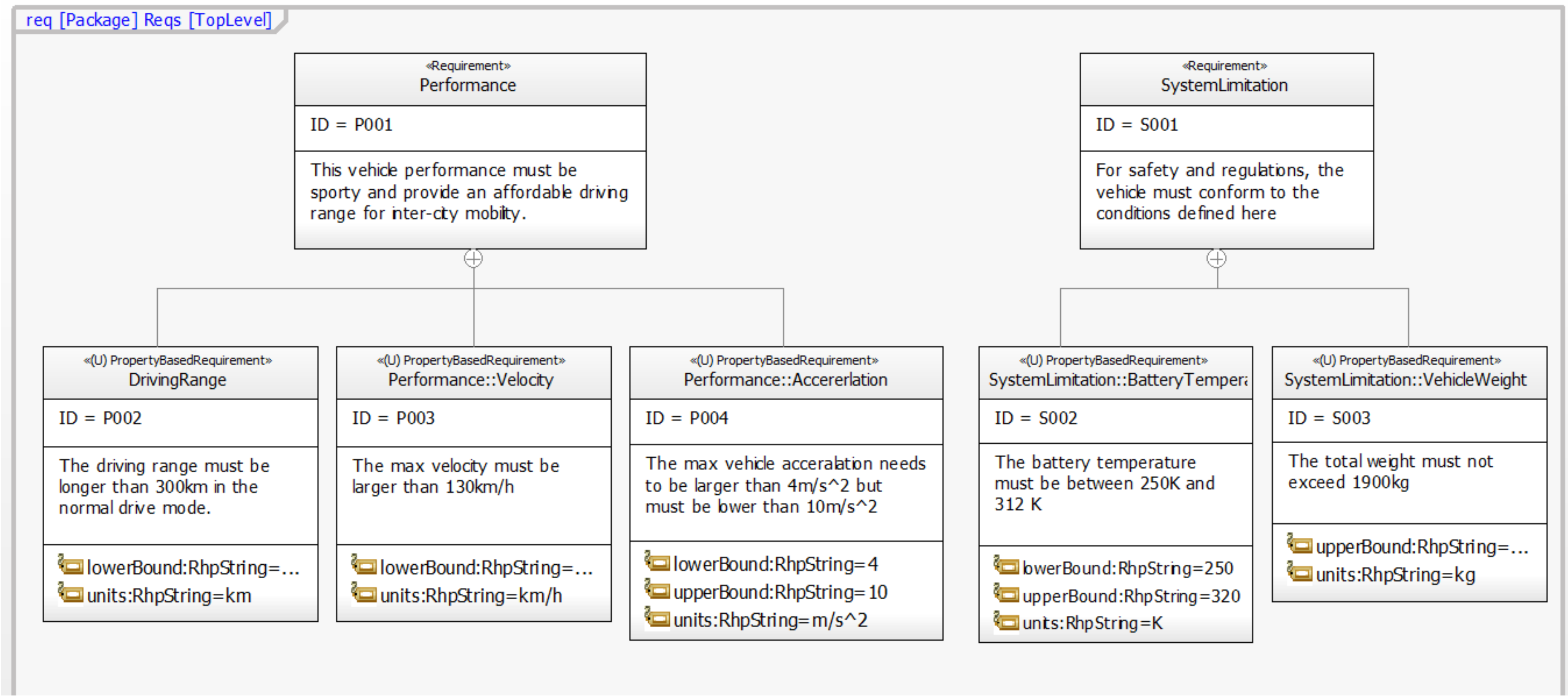
Battery requirements

- Battery mass, energy density
- Max/min operating temperature
- Max/min peak temperature
- Efficiency vs SOC characteristics
- State of Health characteristics

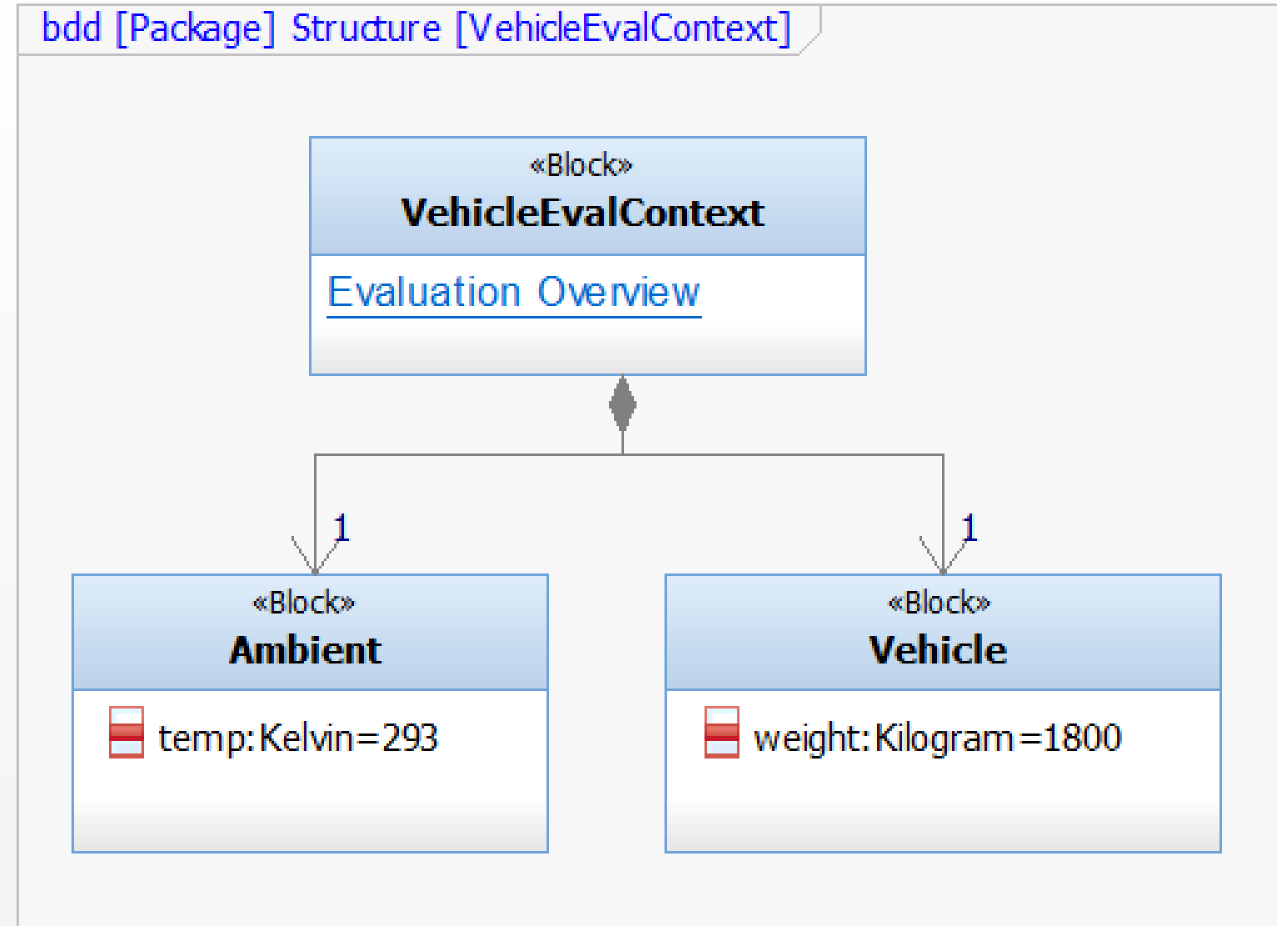
Cooling system requirements

- Heat transfer characteristics
- Maximum heat transfer rate
- Temperature control system
- Multi-component cooling
- Maximum weight of the system
- Critical temperature detection

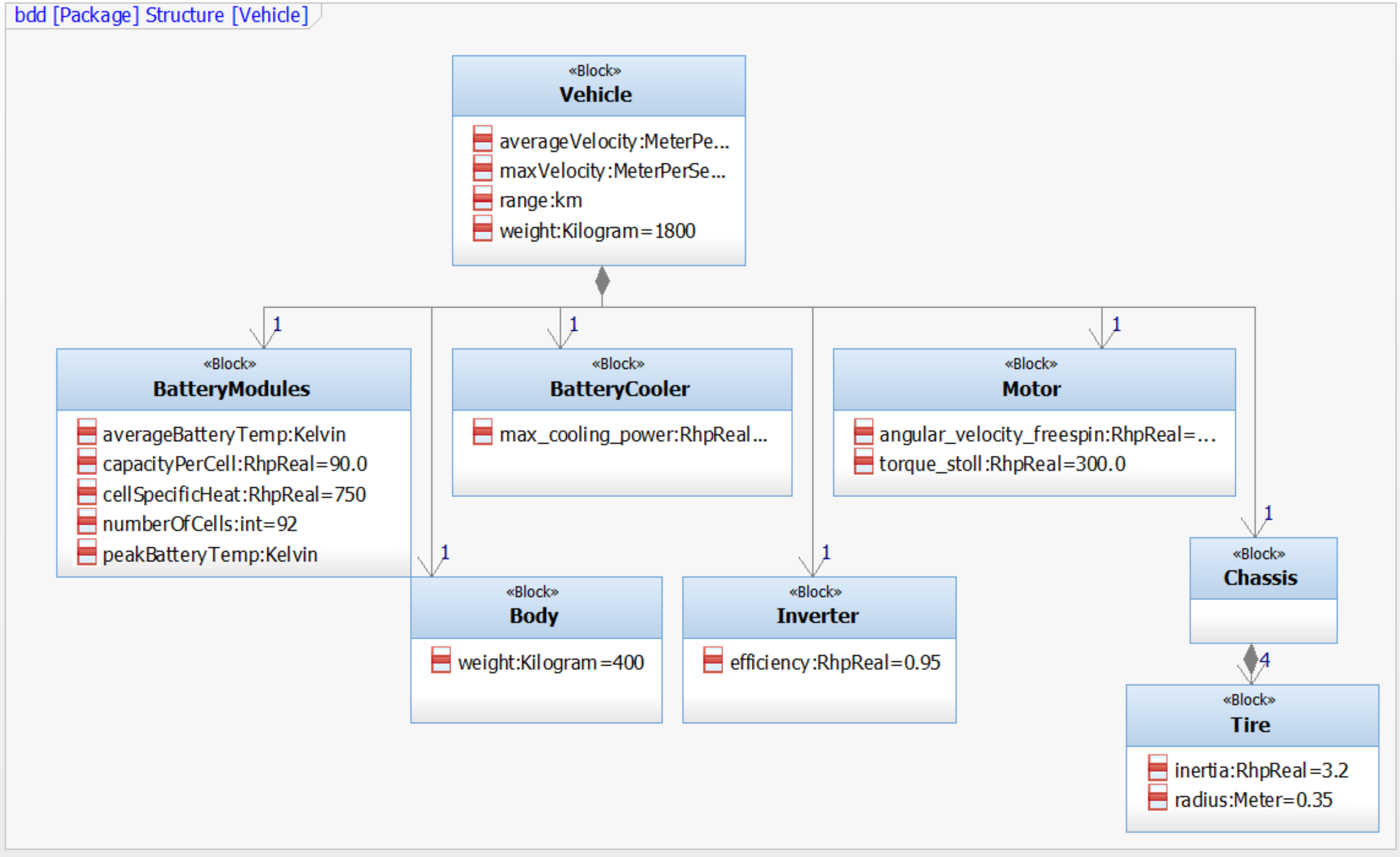
Architectural Model Requirement Diagram



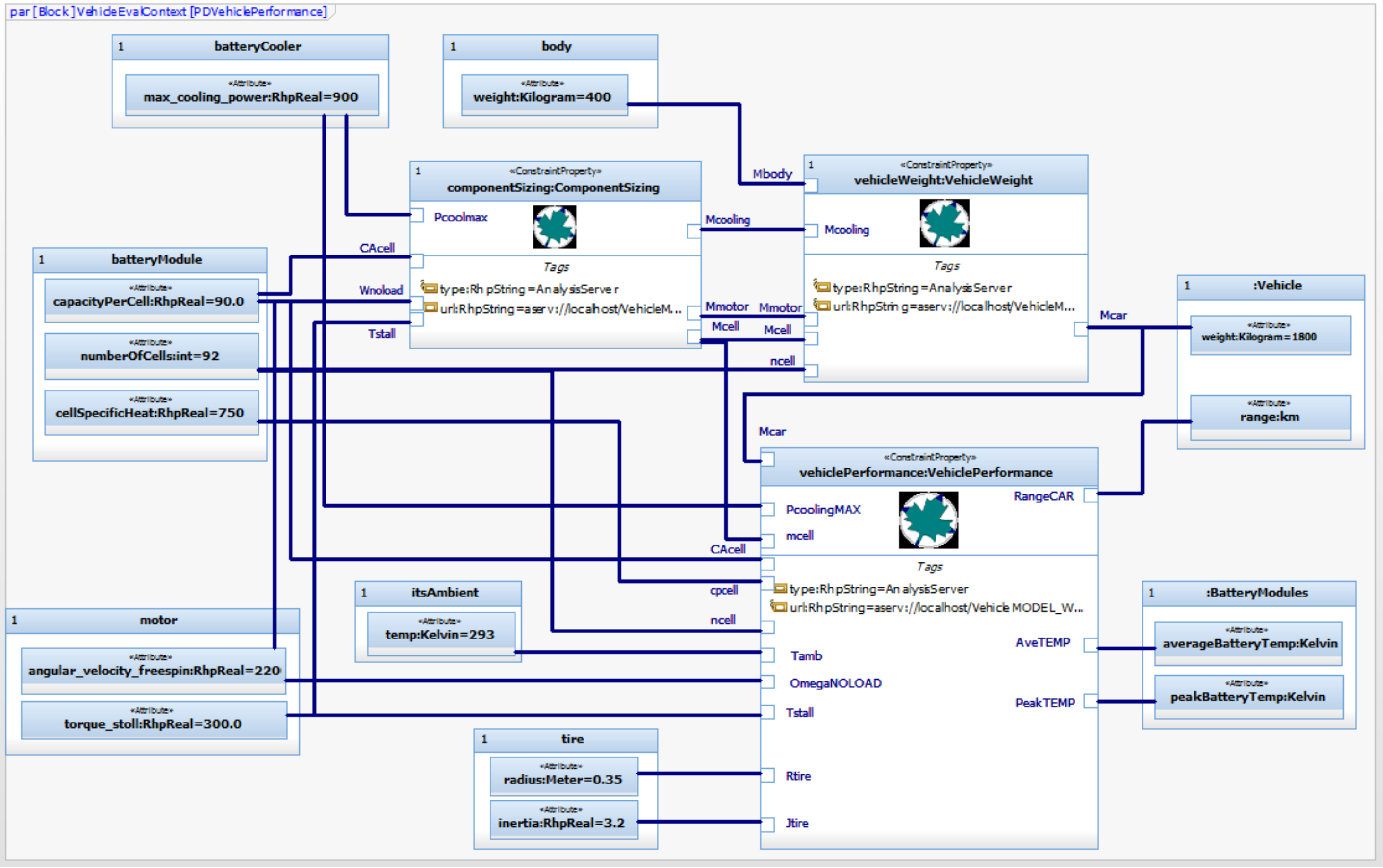
Block Definition Diagram (1)
Context Def.



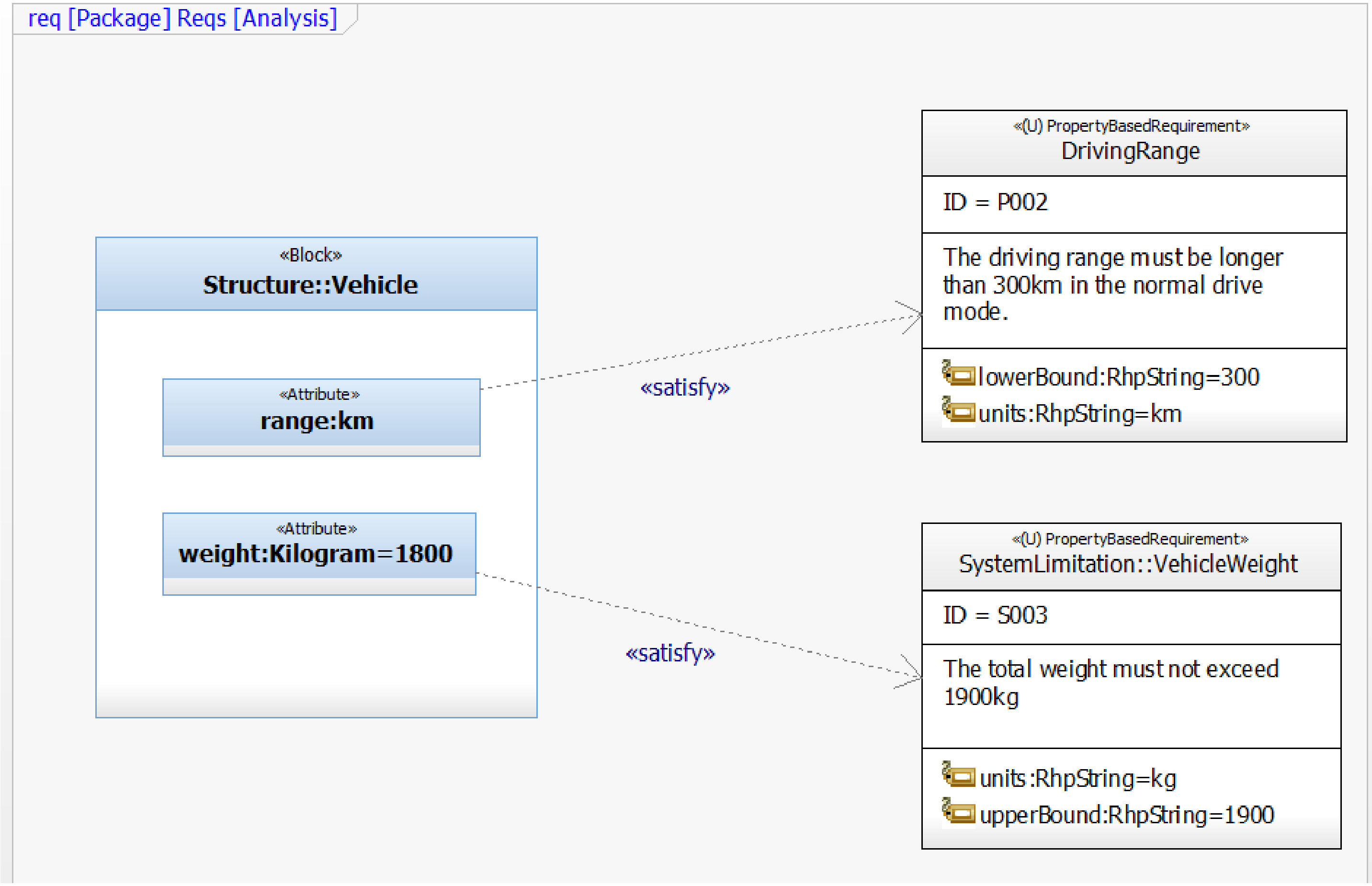
Block Definition Diagram (2)



Architectural Model Parametric Diagram



The Satisfy Relationship with Requirements



Analytical Model
Multi-domain System-level Dynamics

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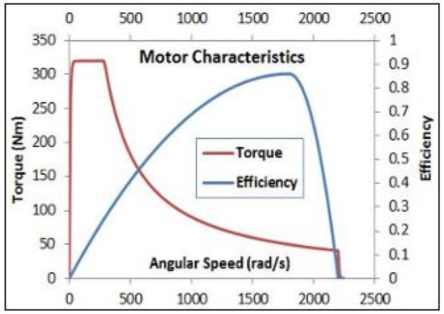
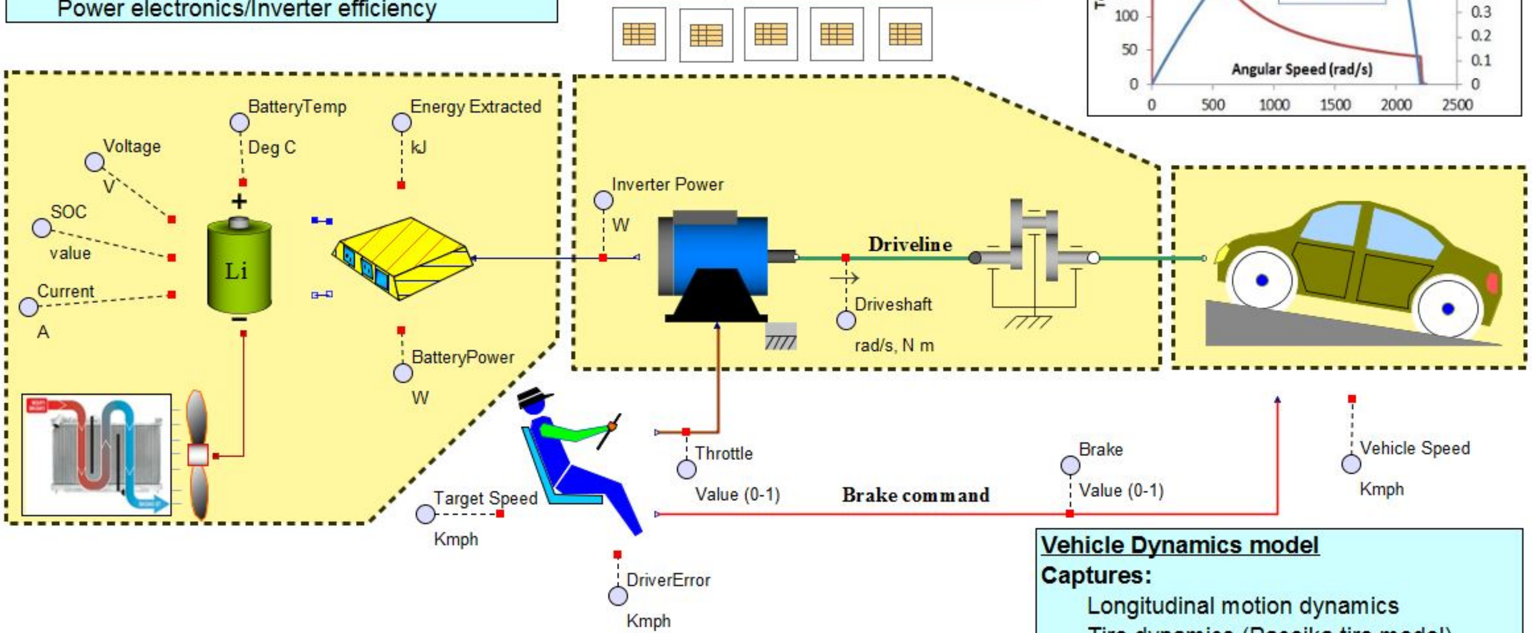
Li-ion Battery model
Graphite - Lithium Cobult Oxide electrodes
Captures:
- Thermal effects on the battery chemistry
- Temperature dependent internal resistance
- Degradation effects
- Power electronics/Inverter efficiency

DC motor
Model decribed by
- A torque - speed curve
- A Motor efficiency map
- Rated power and angular speed





Vehicle Dynamics model
Captures:
- Longitudinal motion dynamics
- Tire dynamics (Pacejka tire model)
- Fixed reduction gear from the motor
- Effects of aerodynamic drag forces
- Effects of tire sizing (radius and inertia)
- Effects of variable road grade

Cooling system model
Active and passive heat extraction from battery
Temperature control using on-off thermostat

Driver model
PID Controller
Tuned to follow predefined speed profile

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Normal Loading

25°C Ambient, Gentle Grades

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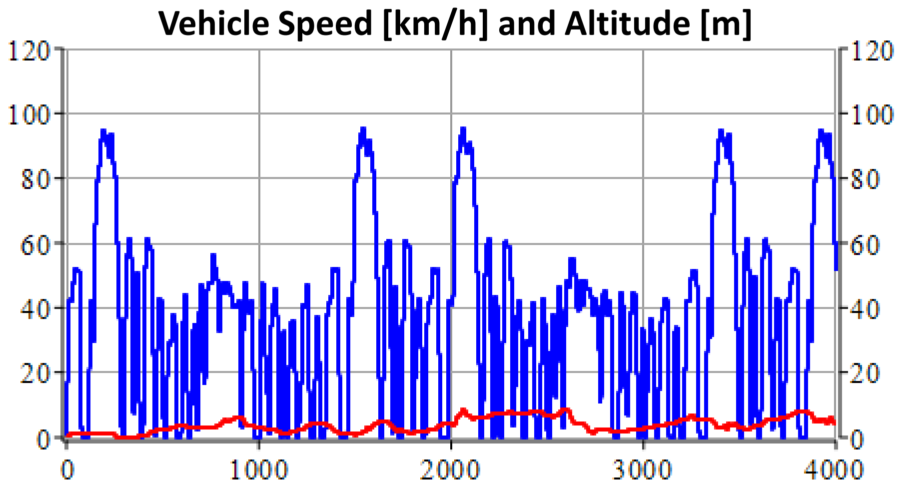
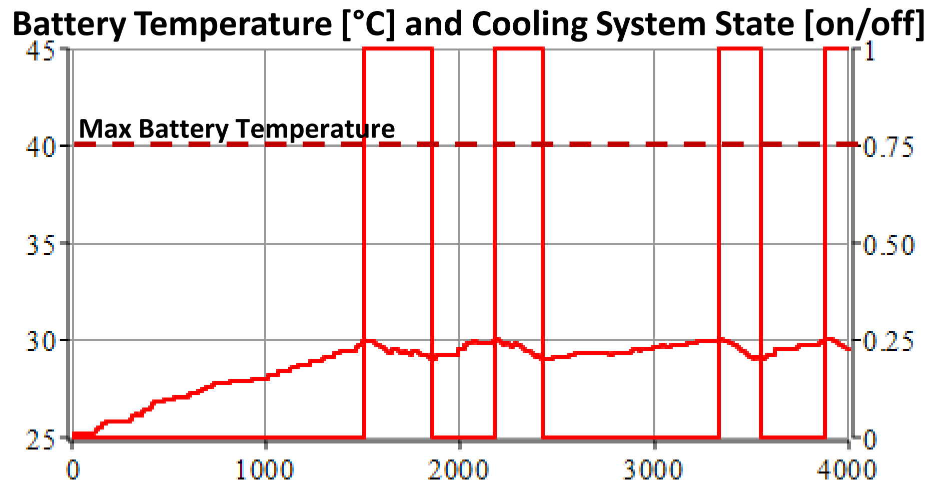
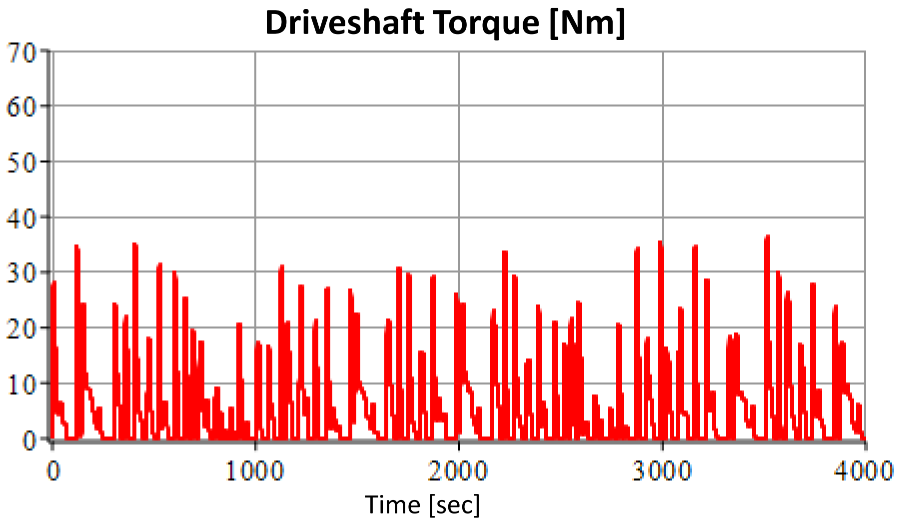
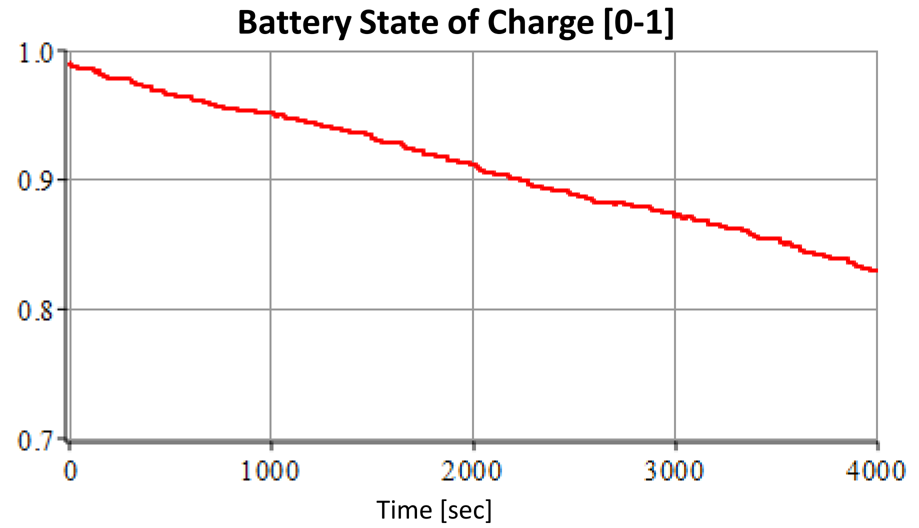


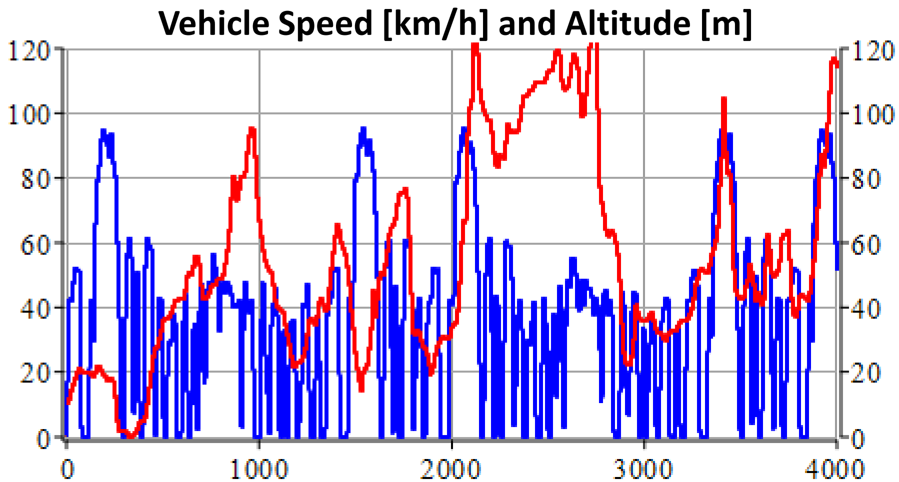


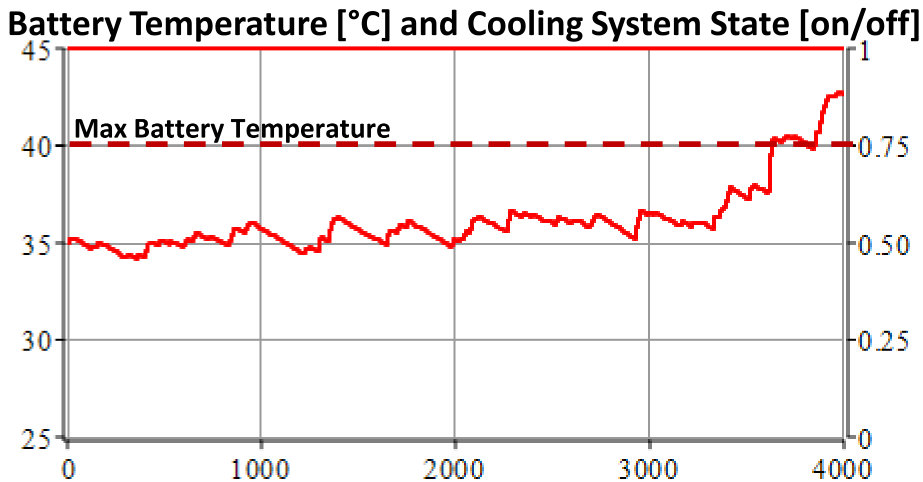


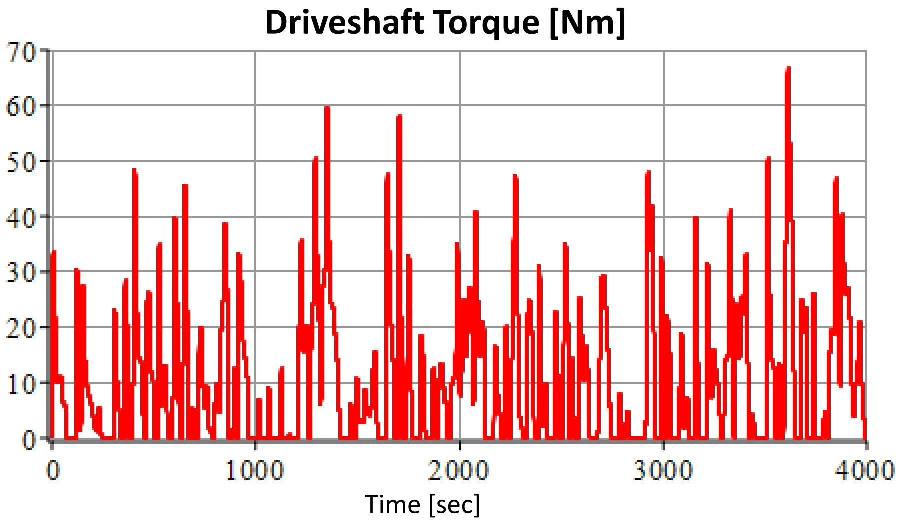


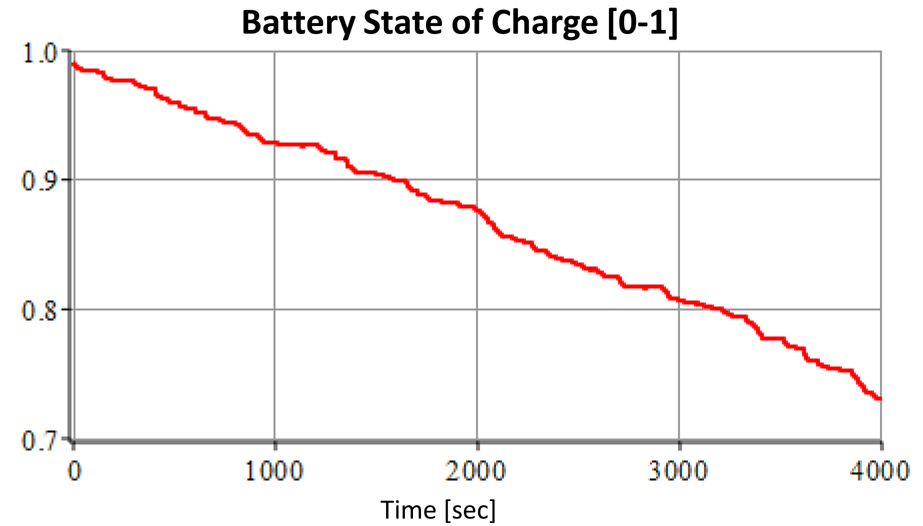
Extreme Loading

35°C Ambient, Steep Grades

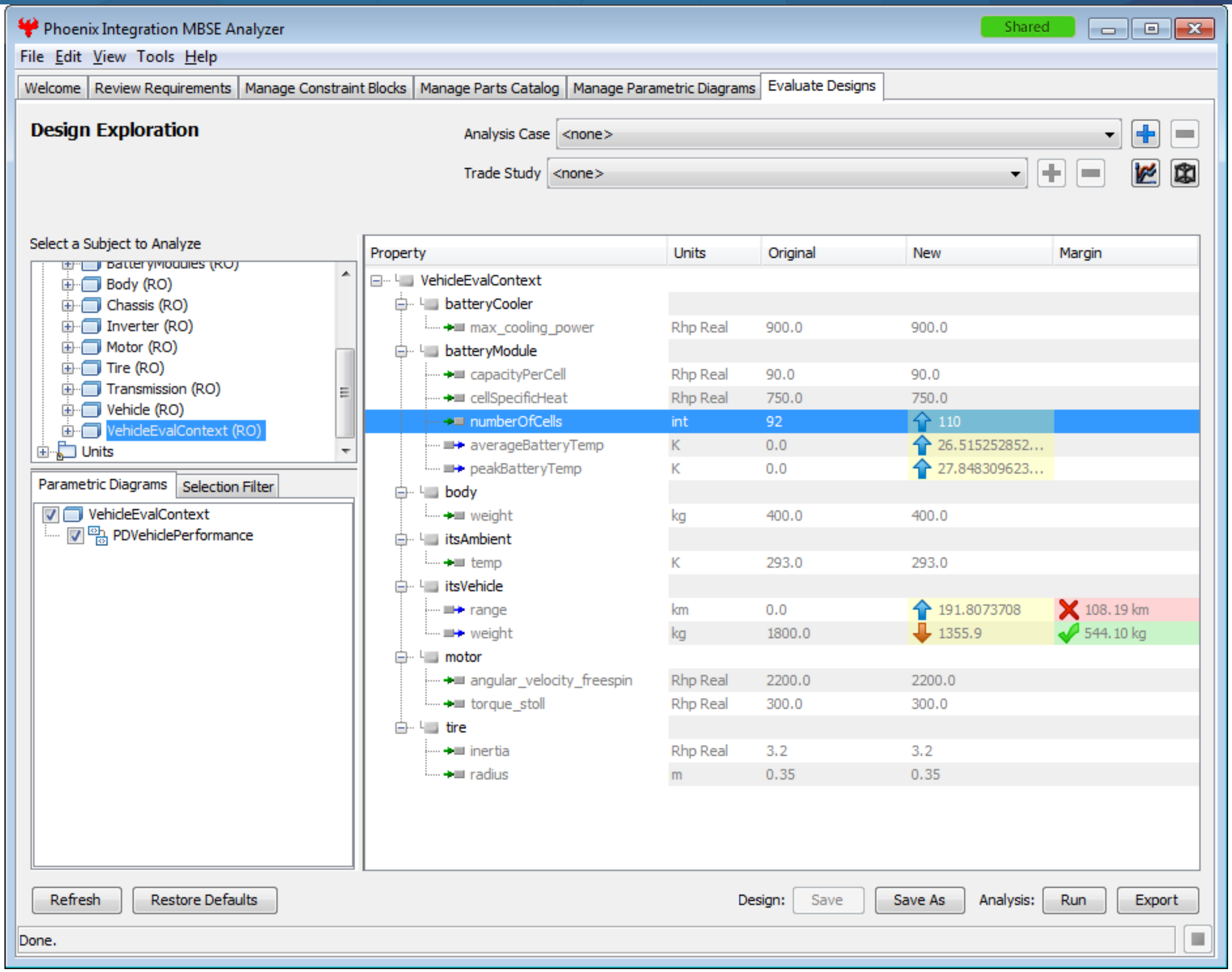




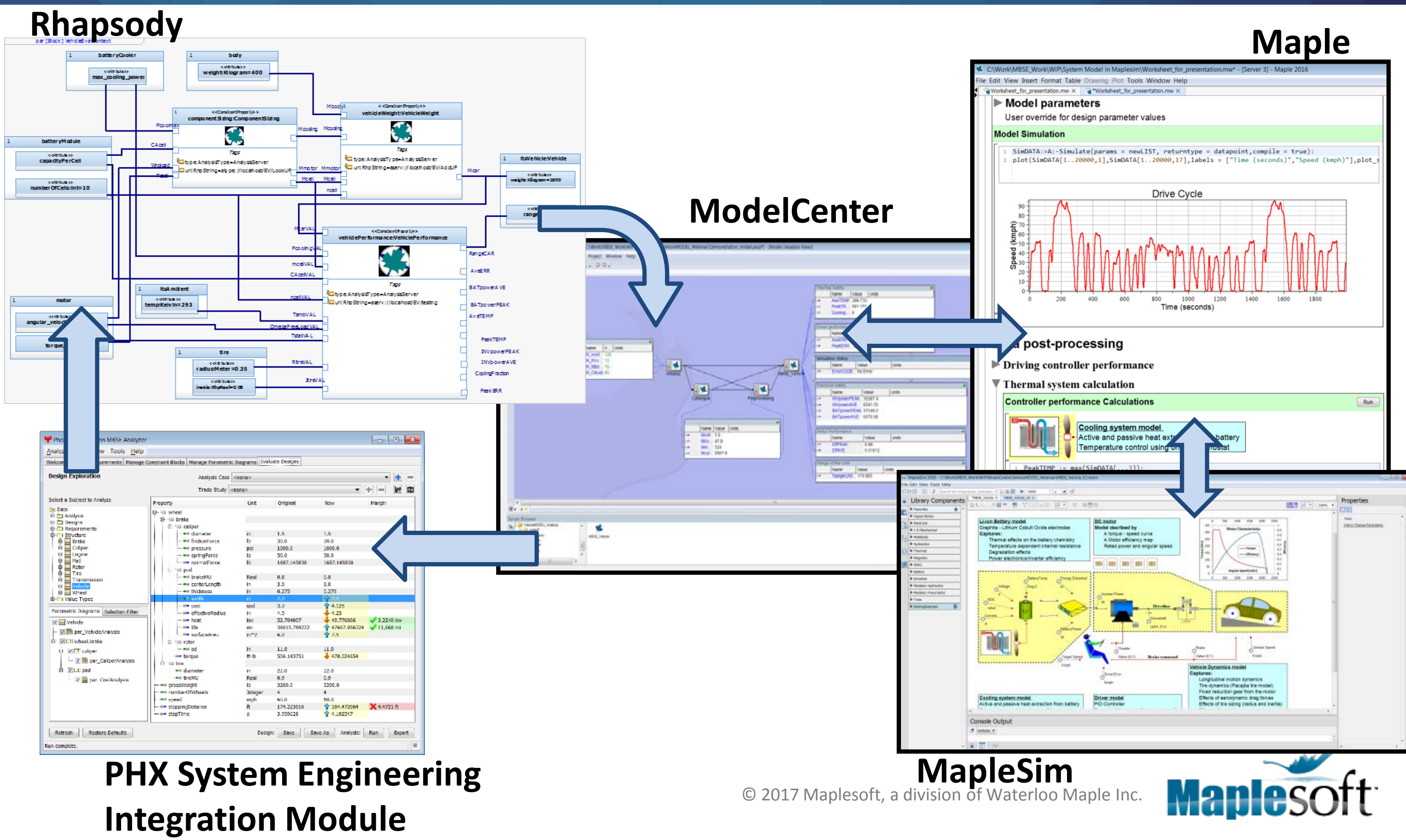




Requirements Compliance Testing



Requirements Compliance Testing



Summary

- MBSE: Process is being increasingly automated through architectural modeling tools
- MapleSim provide rapid functional verification of complex multidomain dynamic systems
- Maple provides powerful environment for data pre- and post-processing as well as managing executable requirements
- ModelCenter brings everything together for rapid requirements-compliance testing, trade-off studies, and impact analysis due to changes in design requirements
- **Convergence of tools helps realize the Systems Design (“V“) process**

Thank You

Questions?

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