



Maplesoft  
Engineering  
Solutions



# Model-Driven Innovation

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

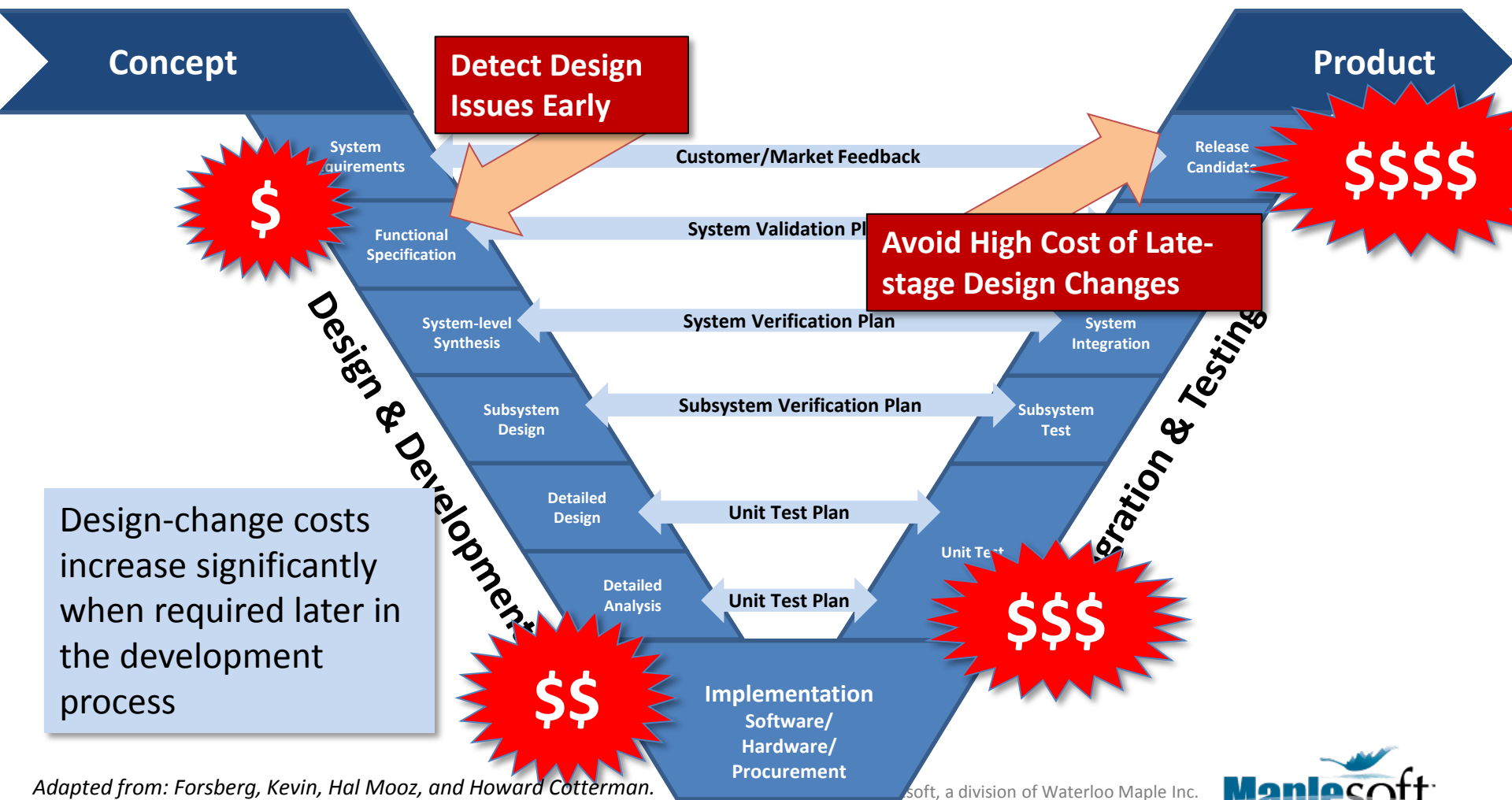
Paul Goossens, VP, Engineering Solutions, Maplesoft

Joydeep Banerjee, Application Engineer, Maplesoft

Andy Ko, Ph.D., Manager of Engineering Services, Phoenix Integration

NIST MBE Summit 2017, Gaithersburg, MD

# Systems Design & Development Process



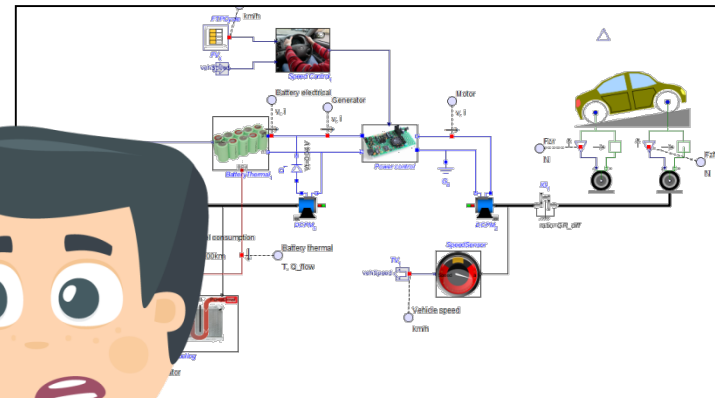
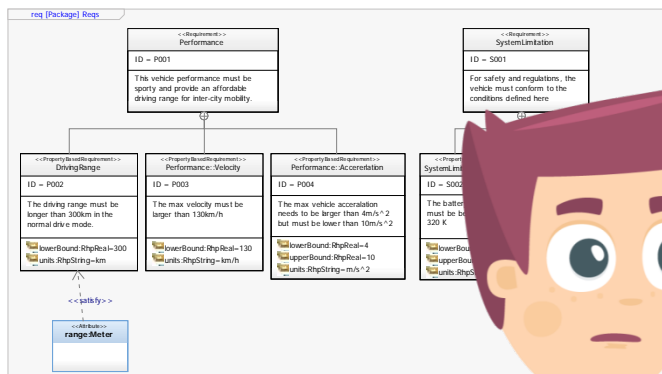
Design-change costs increase significantly when required later in the development process

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...*

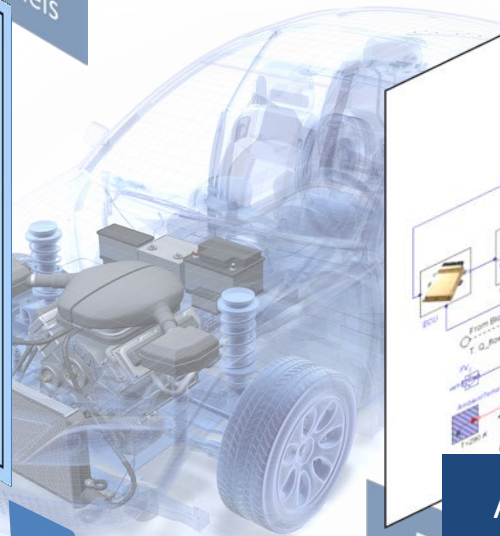


# Model-based Systems Engineering vs Model-based Engineering

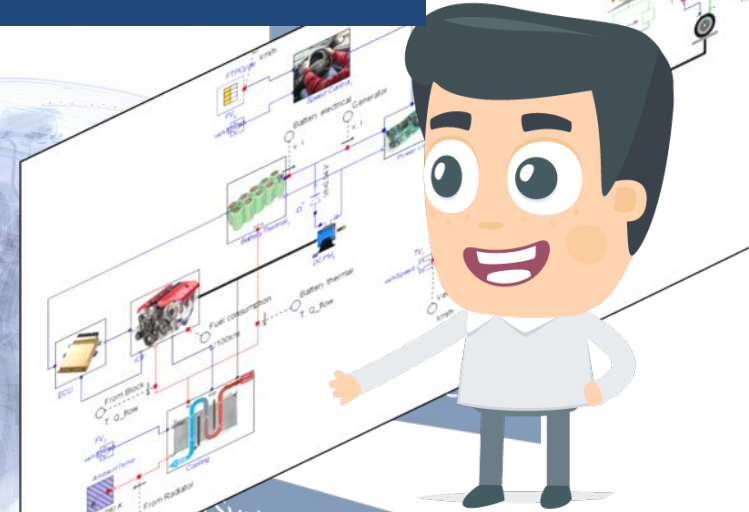
**Consistency:** Faithful to all known and relevant aspects of the system at the current time



Architectural Models



Structural Models



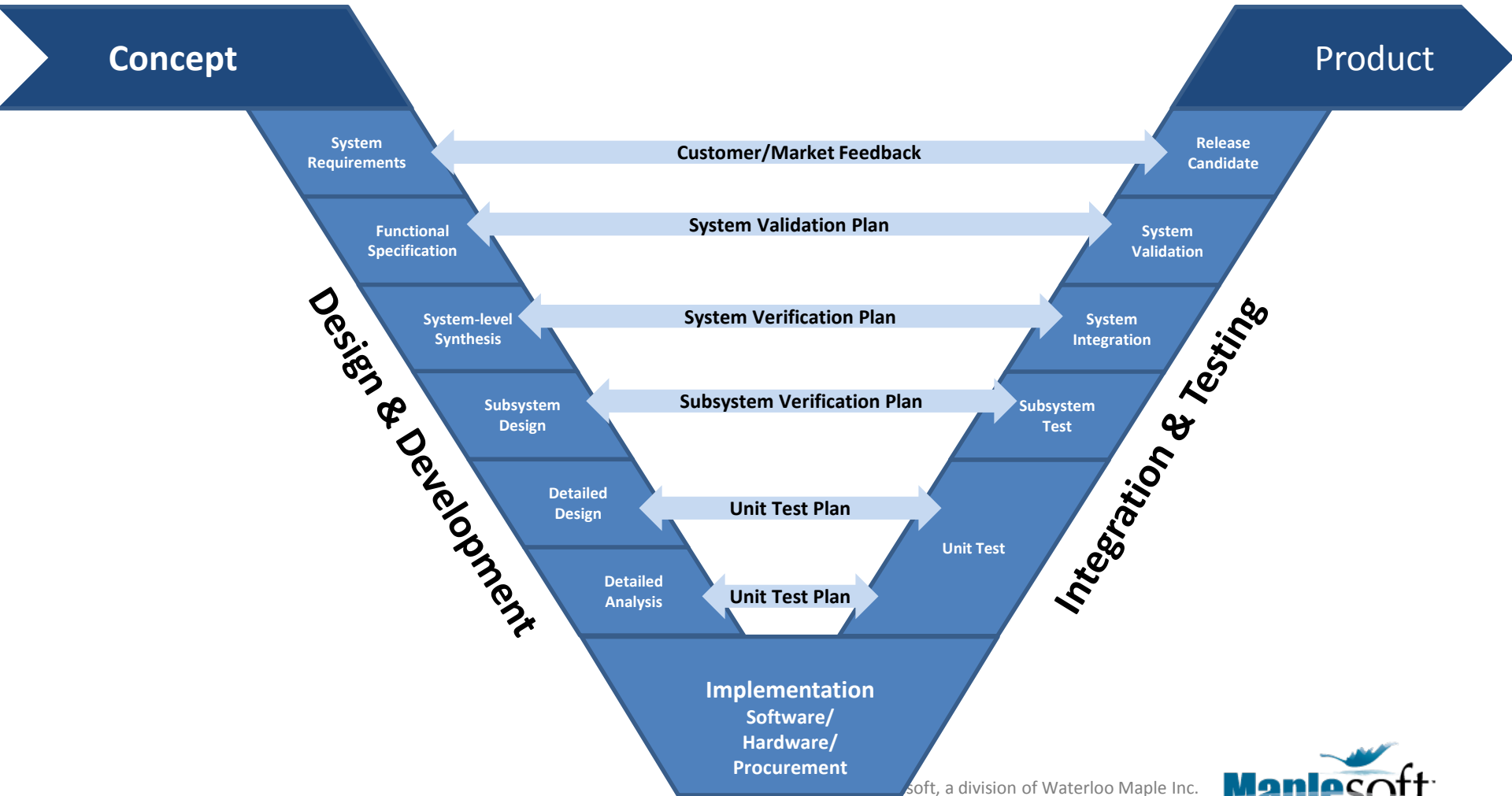
Analytical Models

Finite-Element Models



# Systems Design & Development Process

## Functional Verification

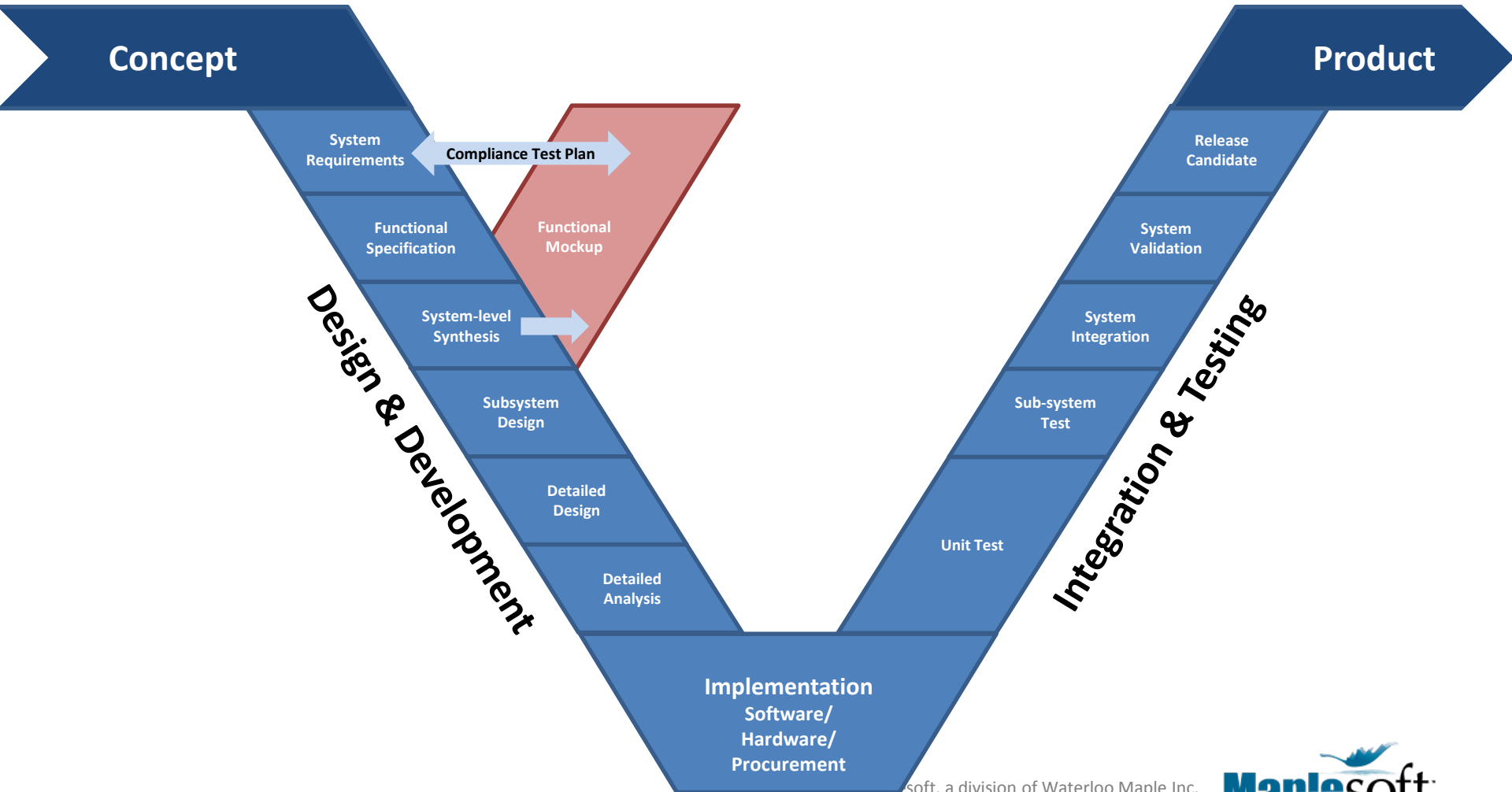






# Systems Design & Development Process

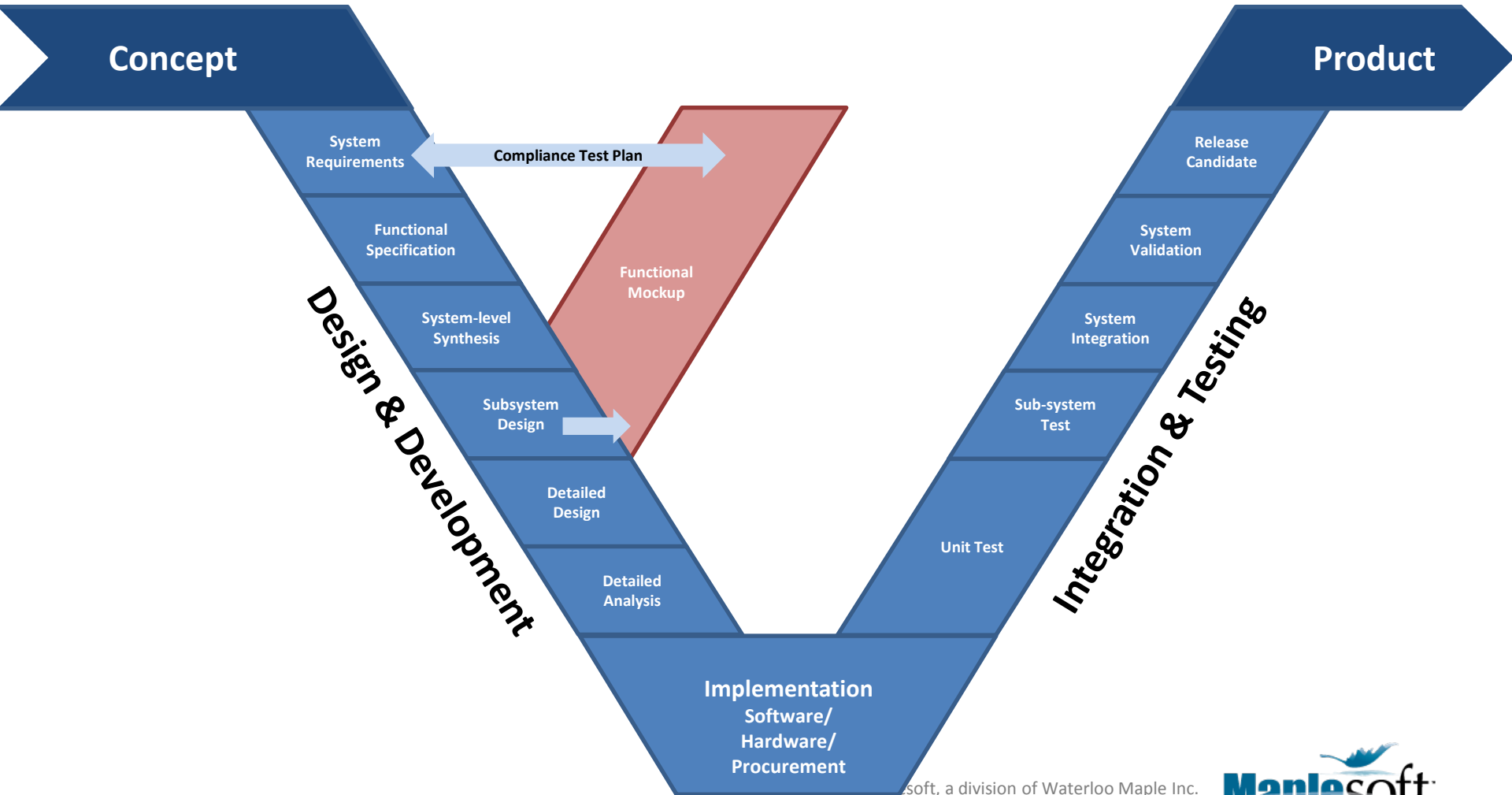
## Functional Verification





# Systems Design & Development Process

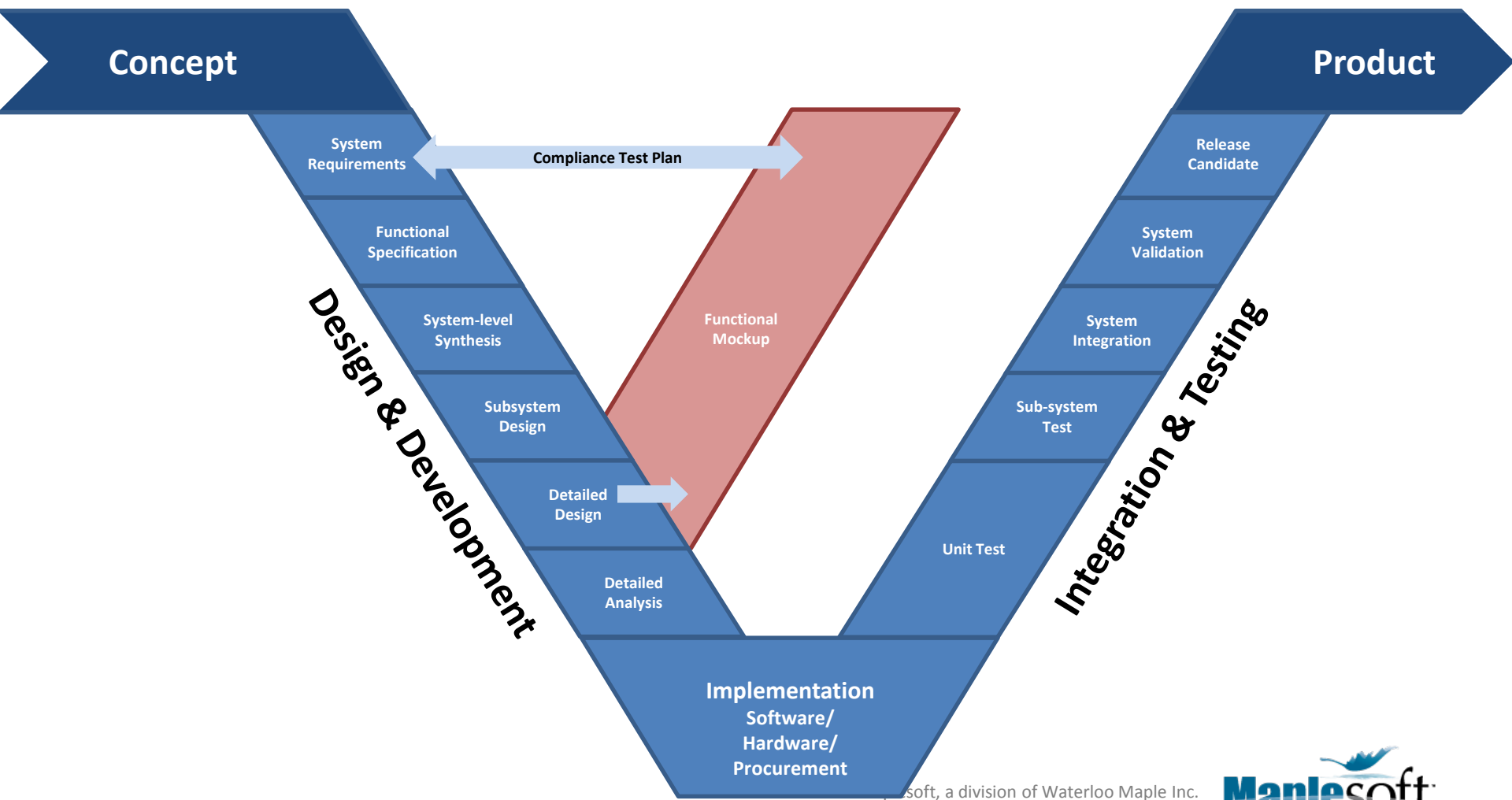
## Functional Verification





# Systems Design & Development Process

## Functional Verification

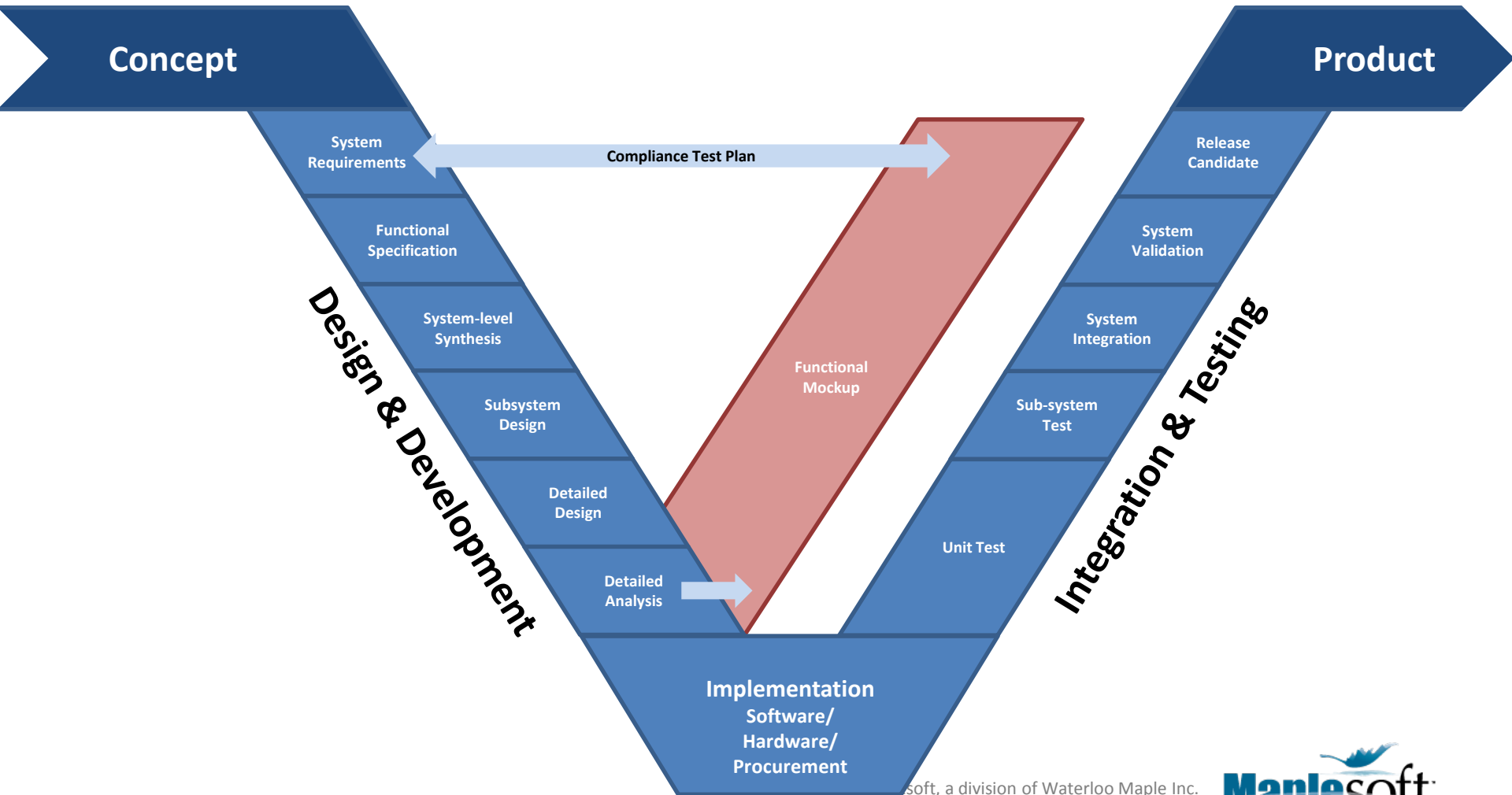






# Systems Design & Development Process

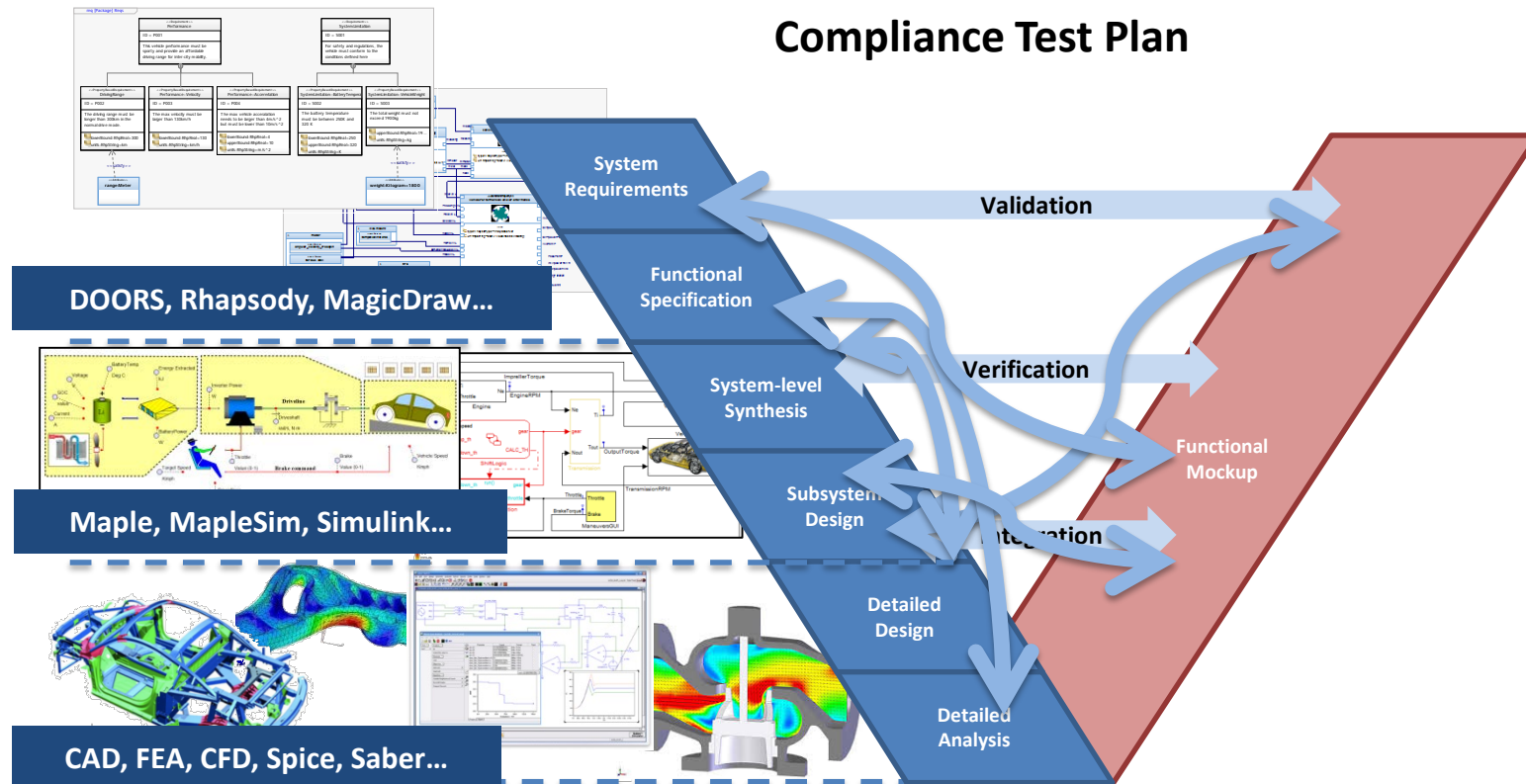
## Functional Verification



# Systems Design & Development Process

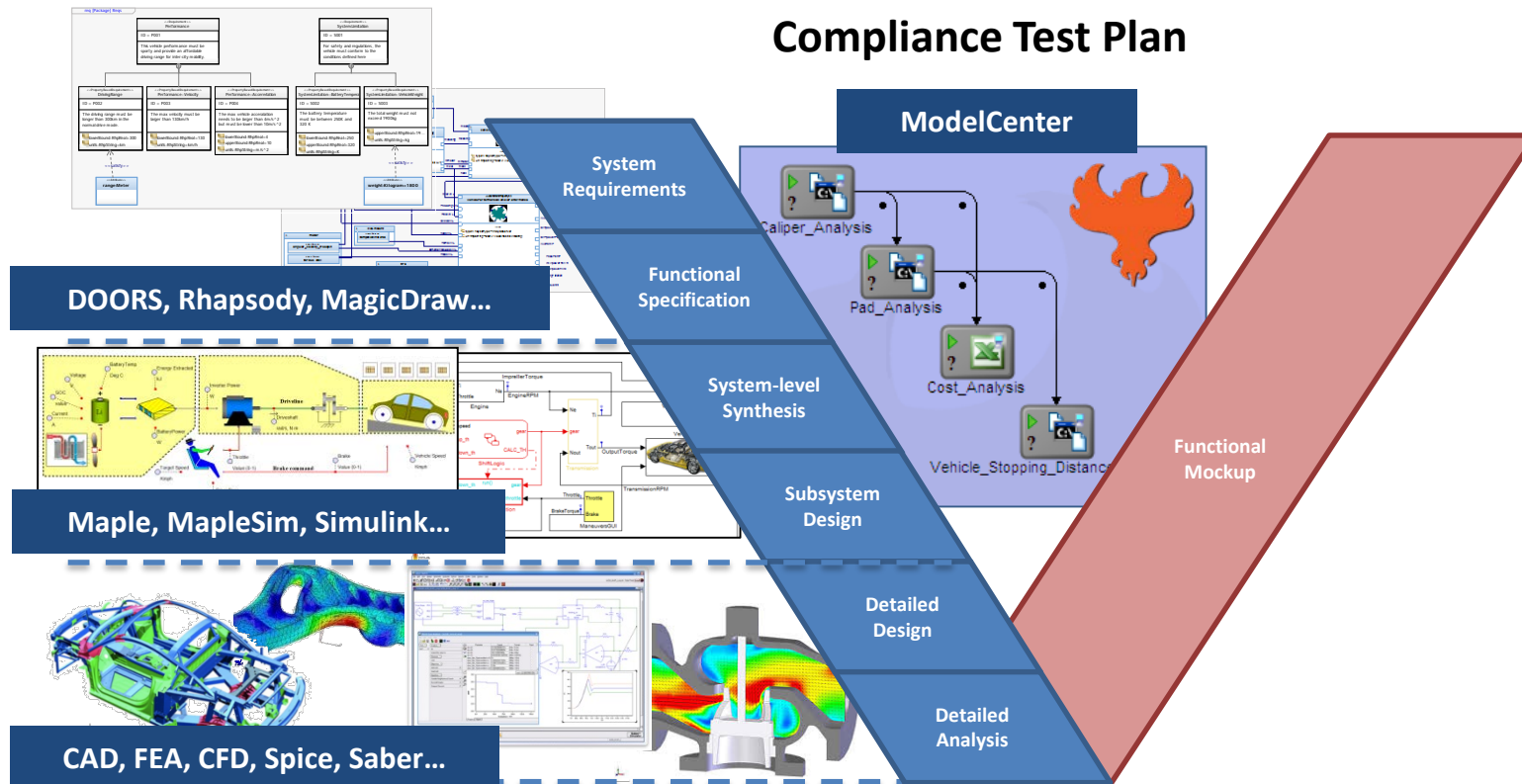
## Functional Verification

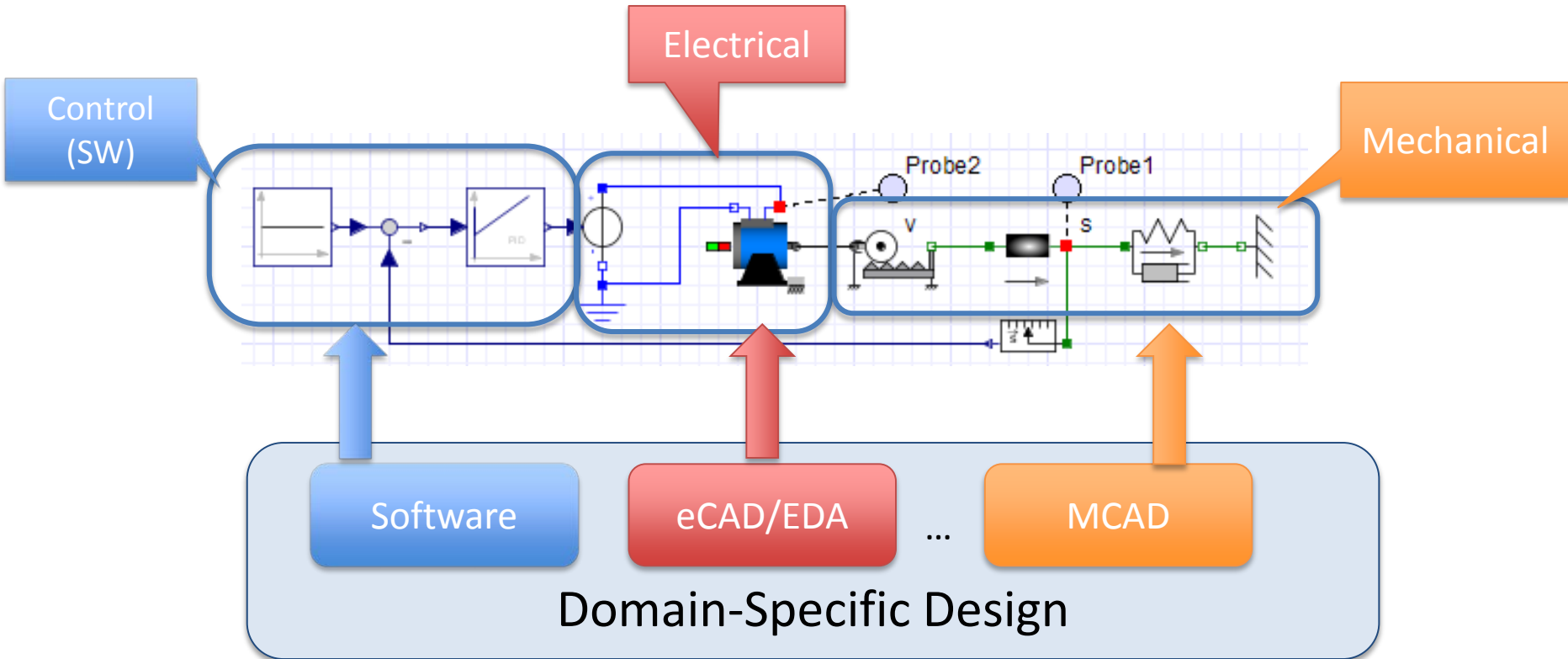
### Compliance Test Plan



# Systems Design & Development Process

## Functional Verification



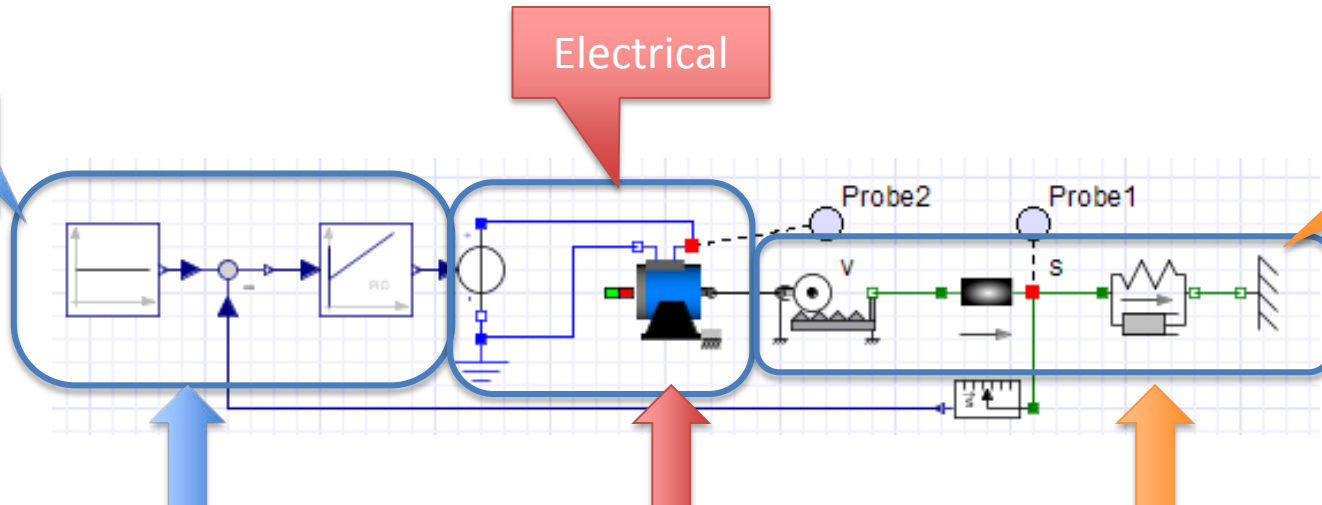


## Modelica: Object-oriented Physical Modeling

Control  
(SW)

Electrical

Mechanical



```

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(signal
annotation (Placement (transformation (origin={190.0,60.0}),ext
public Maplesoft.SignalBlocks.Math.Operators.Feedback F1
public Maplesoft.SignalBlocks.Sources.Real.Step S1(height
public Modelica.Blocks.Interfaces.RealInput u1 annotation
public Modelica.Blocks.Interfaces.RealOutput y1 annotation
equation
connect (F1.y, PID1.u) annotation (Line (points={{148.0,60.0},
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, ext
));
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.SignalVoltage
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 annotation
public Maplesoft.Mechanics.Rotational.Sensors.AngleSensor AS2
public Maplesoft.Mechanics.Rotational.Sensors.RotationalSpeedSen
rotation=0));
public Maplesoft.Electrical.Analog.Passive.EMF EMF2 (useSupport
public Modelica.Blocks.Interfaces.RealInput InputSource annot
public Modelica.Mechanics.Rotational.Interfaces.Flange_b F6
public Modelica.Blocks.Interfaces.RealOutput PositionOutput
public Modelica.Blocks.Interfaces.RealOutput R03 annotation (P
equation
connect (R2.n, I7.p) annotation (Line (points={{128.0,268.0},13
connect (EMF2.n, G2.p) annotation (Line (points={{228.0,158.0},
    
```

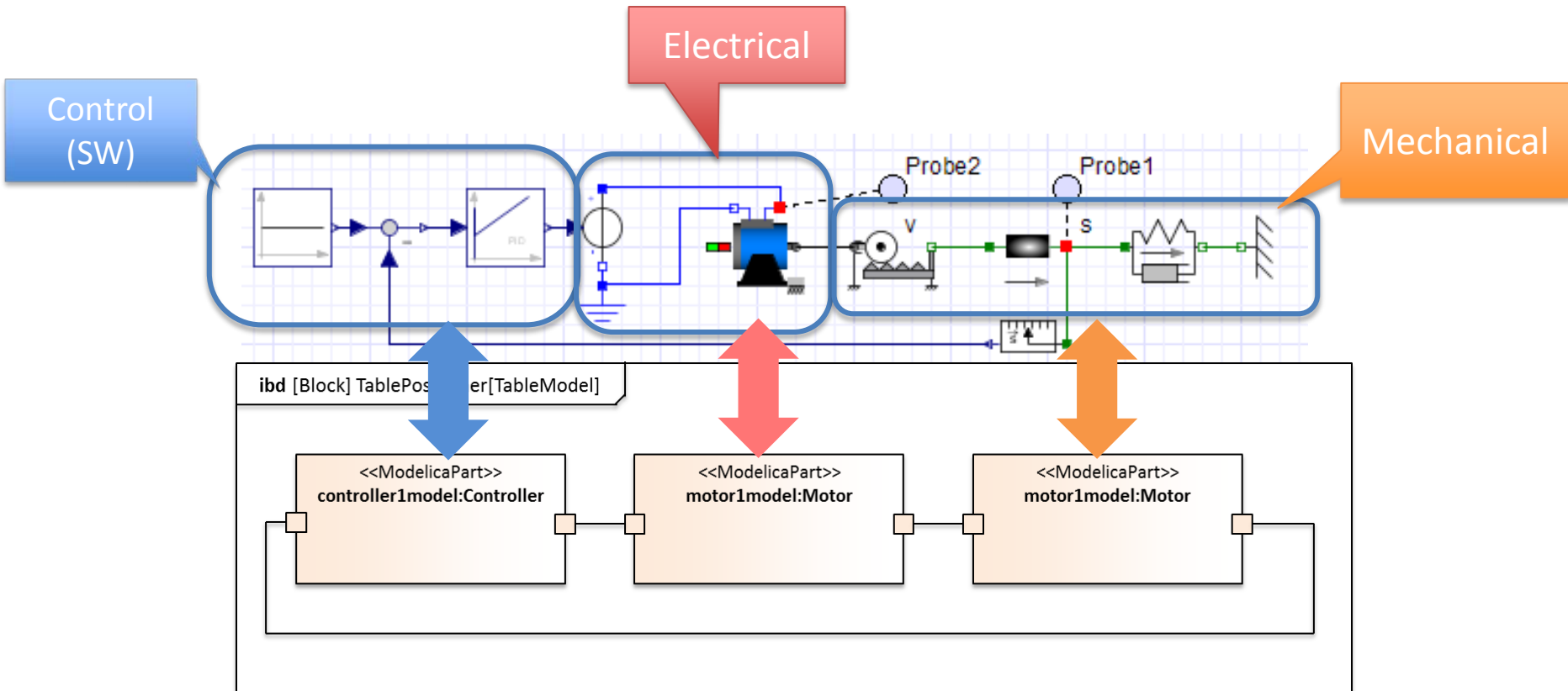
```

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=0.1,
public Maplesoft.Mechanics.Translational.Common.Mass SM2 (m=20
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={{220.0,60.0},
connect (I3.flange_a, a1) annotation (Line (points={{50.0,60.0},
annotation (
Diagram (coordinateSystem (preserveAspectRatio =true, exten
Icon (coordinateSystem (preserveAspectRatio =true, exten
));
end Table ;
    
```



# Functional Verification against formal requirements models

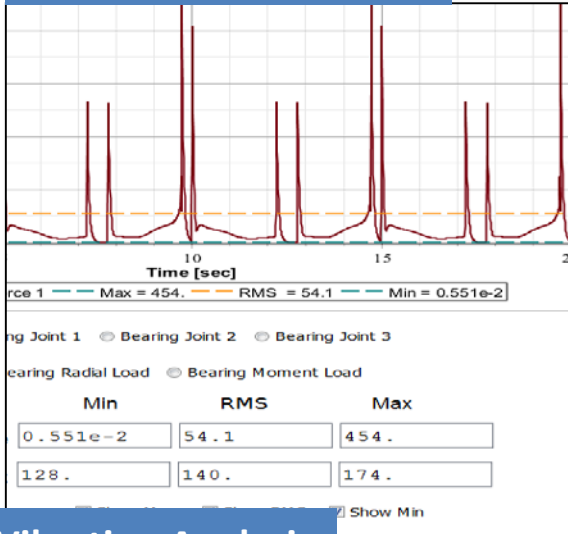




## Symbolic Tools for Design-space Exploration



### Dynamic Load Analysis



### Post-Processing

**Driving controller**

Controller performance Calculations

Driver model  
PID Controller  
Tuned to follow predefined speed profile

```

1 AveERR:=add(SinDATA[1..8],1-1..LinearAlgebra:-RowDimension(SinDATA))/LinearAlgebra:-RowDim
2 PeakERR:=max(SinDATA[1..8]);

```

Average controller error 237318821517339  
Peak controller error 22-4142313568270152

---

**Thermal system calculation**

Controller performance Calculations

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

```

1 PeakTEMP := max(SinDATA[1..3]);
2 AveTEMP := add(SinDATA[1..3],1-1000..LinearAlgebra:-Row
3 CoolingFraction:=SinDATA[1..5];
4

```

### Inverse Kinematics and Dynamics

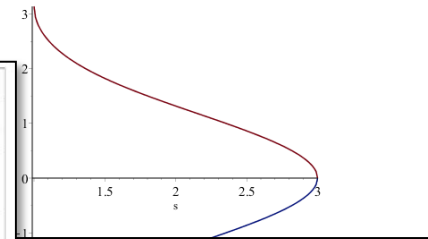
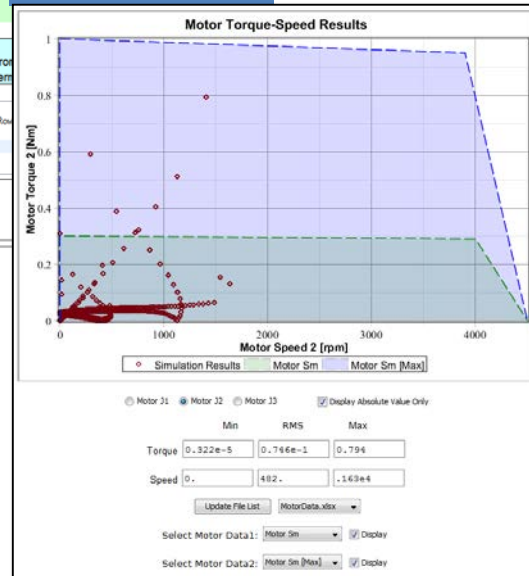
#### Generate inverse kinematics equations

```

Solve for s(t) and theta3(t)
> sols := solve(convert(PositionConstraints, set), {theta1(t), theta3(t)});
theta1(t) has multiple solutions. Extract all solutions for theta1(t)
> all_theta_sols := [allvalues(subs(sols, theta1(t)))];
all_theta_sols := [arctan( (sqrt(-L1^2 + 2LL^2L1^2 + 2LL^2s(t)^2 - L1^4 + 2LL^2s(t)^2 - s(t)^4) / (s(t)L1), (L1^2 - L2^2 + s(t)^2) / (L1s(t))), arctan(
sqrt(-L1^2 + 2LL^2L1^2 + 2LL^2s(t)^2 - L1^4 + 2LL^2s(t)^2 - s(t)^4) / (s(t)L1), (L1^2 - L2^2 + s(t)^2) / (L1s(t)) )];
Plot both solutions
> plot(subs(parameterSubs, s(t) = s, all_theta_sols), s = 1..3, labels = ["s", "theta1"]);

```

### Motor Sizing



### Vibration Analysis

**Simulation parameters**

Simulation time: 5 [s] Sampling time: 0.0001 [s]

**Model parameters**

ecc\_rotor: 0 [mm] Min: 0 Max: 10

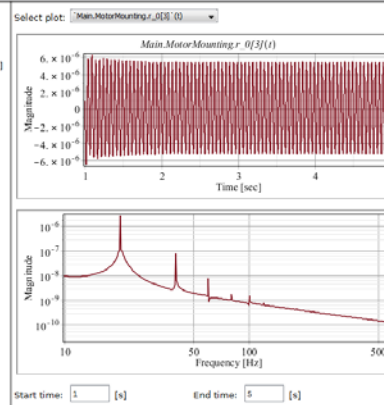
eccA\_imp: 52.258065 [deg] Min: 0 Max: 180

ecc\_imp: 1.91397819 [mm] Min: 0 Max: 6

Flload: -24193548 [deg] Min: 0.0 Max: 1

Run Simulation

Select plot: Main\_MotorMounting\_r\_0[3](t)



Main\_MotorMounting\_r\_0[3](t)

Magnitude

Time [sec]

Magnitude

Frequency [Hz]

Start time: 1 [s] End time: 5 [s]

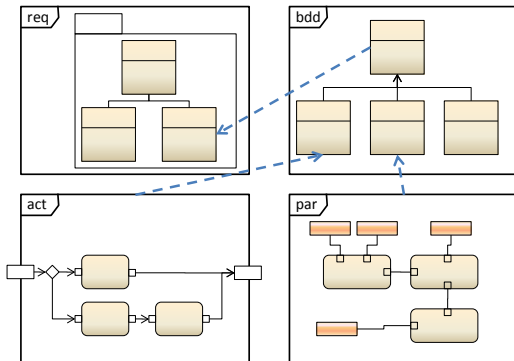
# PHX ModelCenter



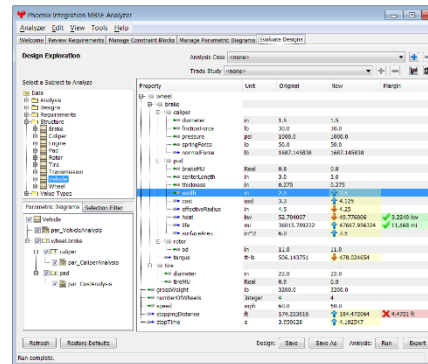


# PHX Systems Engineering Integration Module

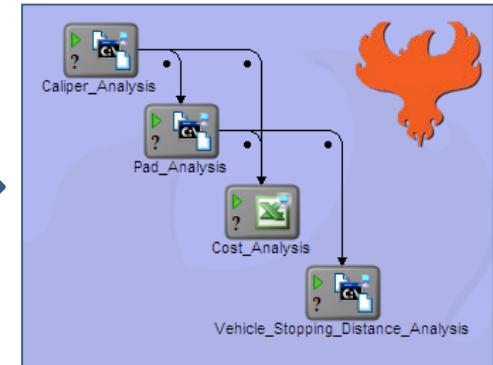
## Systems Engineering: Architectural Model



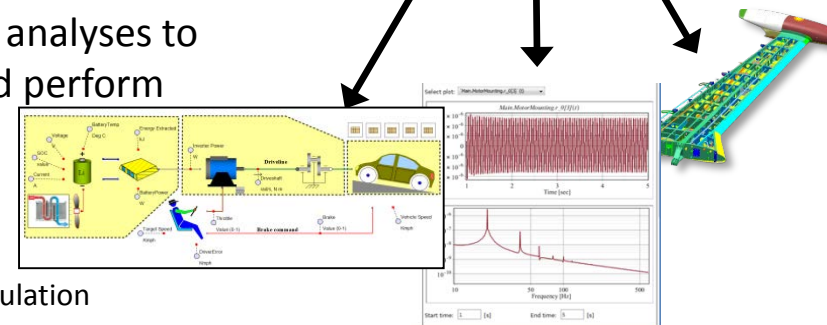
## MBSE Analyzer



## Domain Engineering: Executable Analysis Model

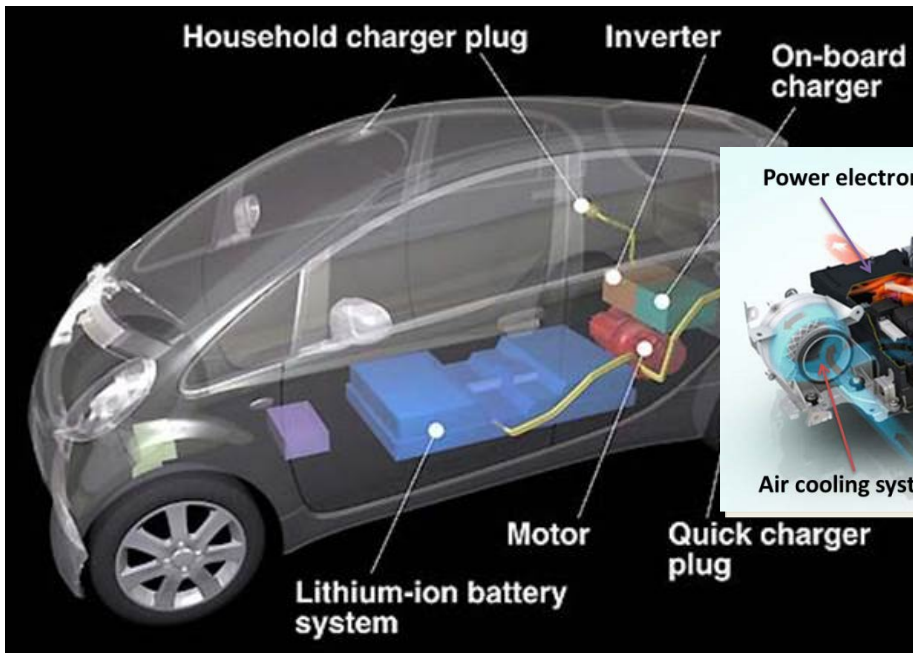


- Connect systems architecture models with engineering analyses to calculate system performance, check requirements, and perform design trade-offs
- Capabilities
  - Execute SysML parametric diagrams to evaluate designs
  - Perform requirements compliance analysis using modeling and simulation
  - Perform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

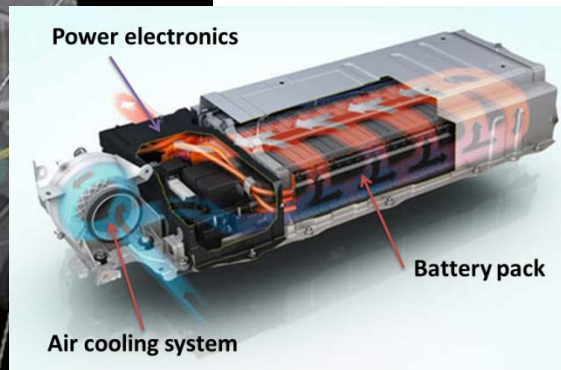


## Engineering Analysis

# 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

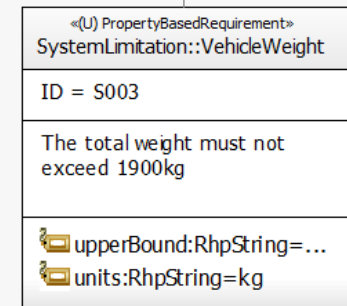
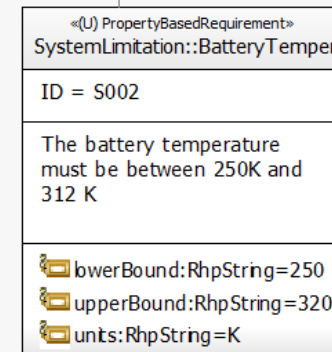
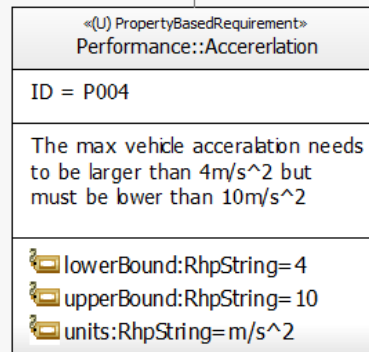
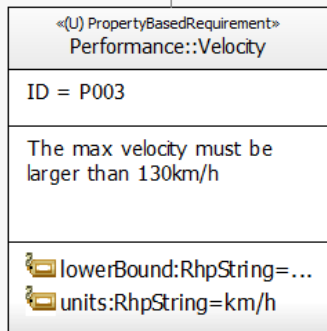
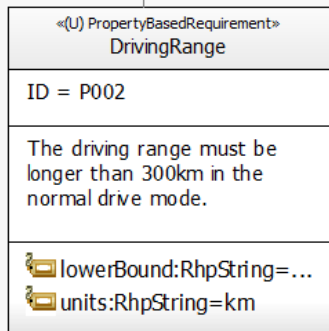
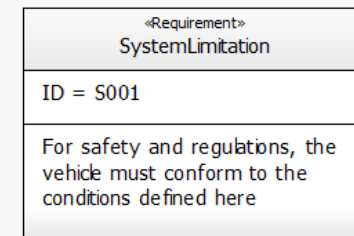
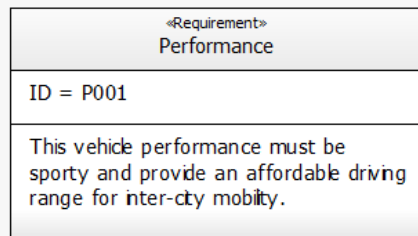


- Heat transfer characteristics
- Maximum heat transfer rate
- Temperature control system
- Multi-component cooling
- Maximum weight of the system
- Critical temperature detection

# Architectural Model Requirement Diagram

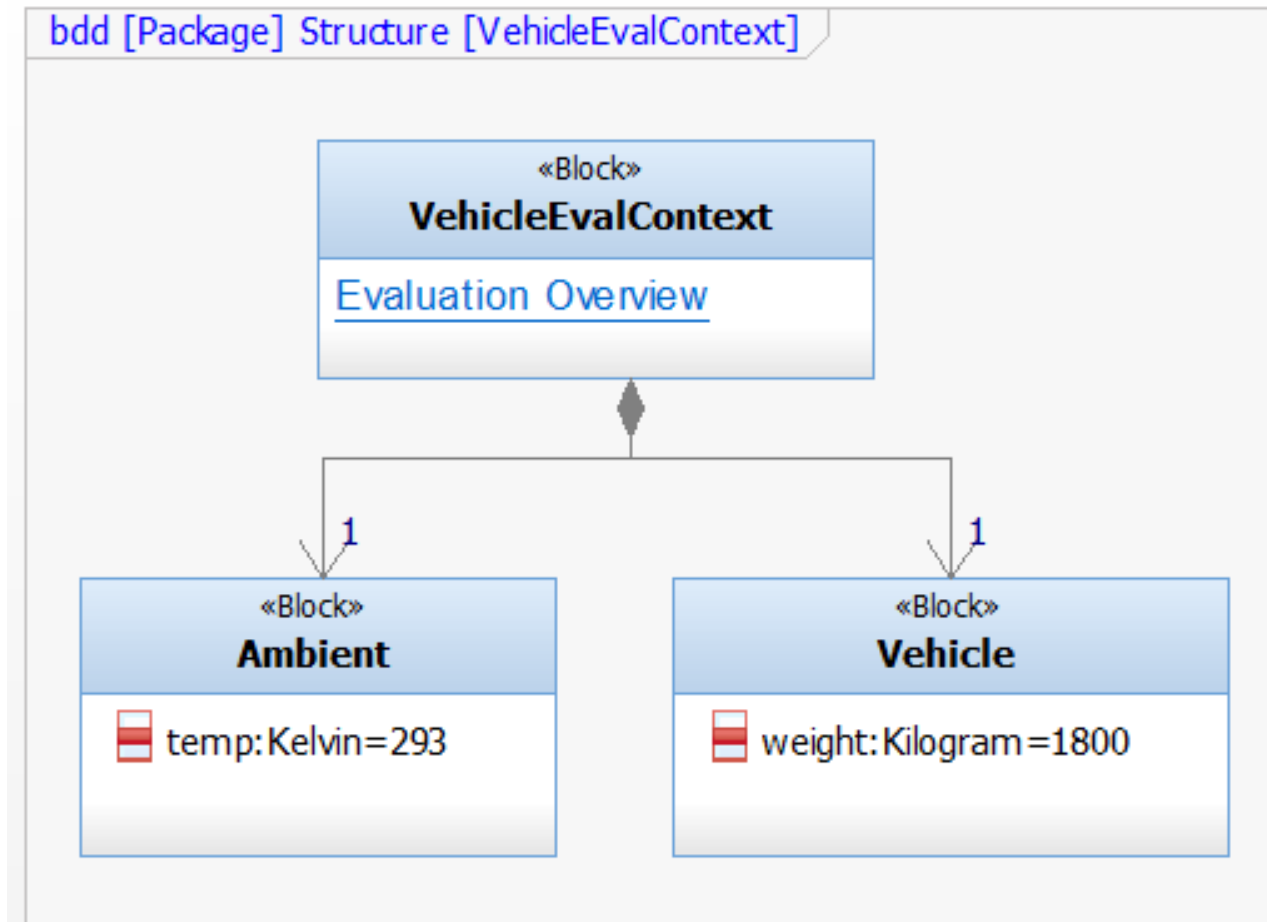


req [Package] Reqs [TopLevel]





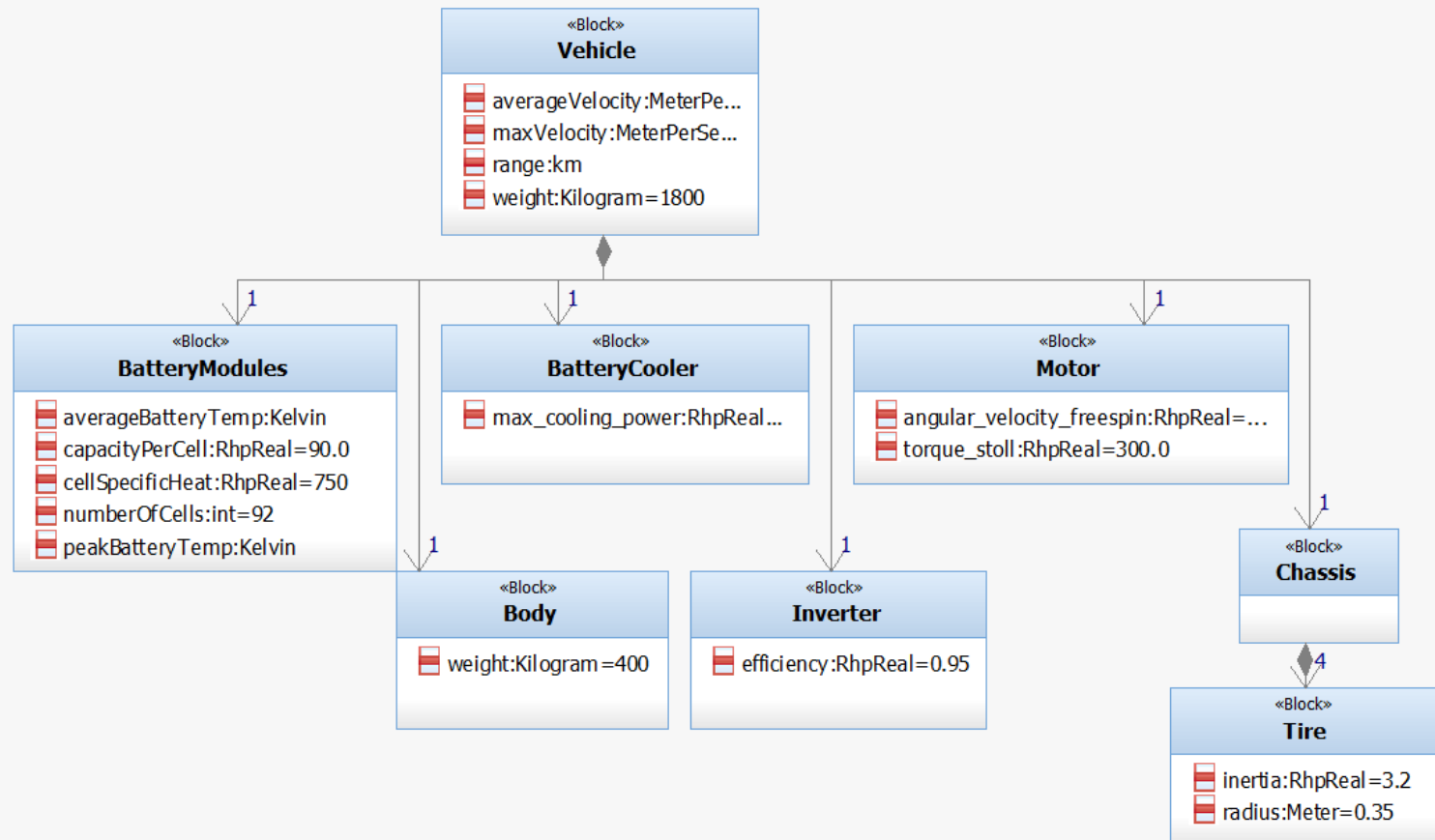
# Block Definition Diagram (1) Context Def.



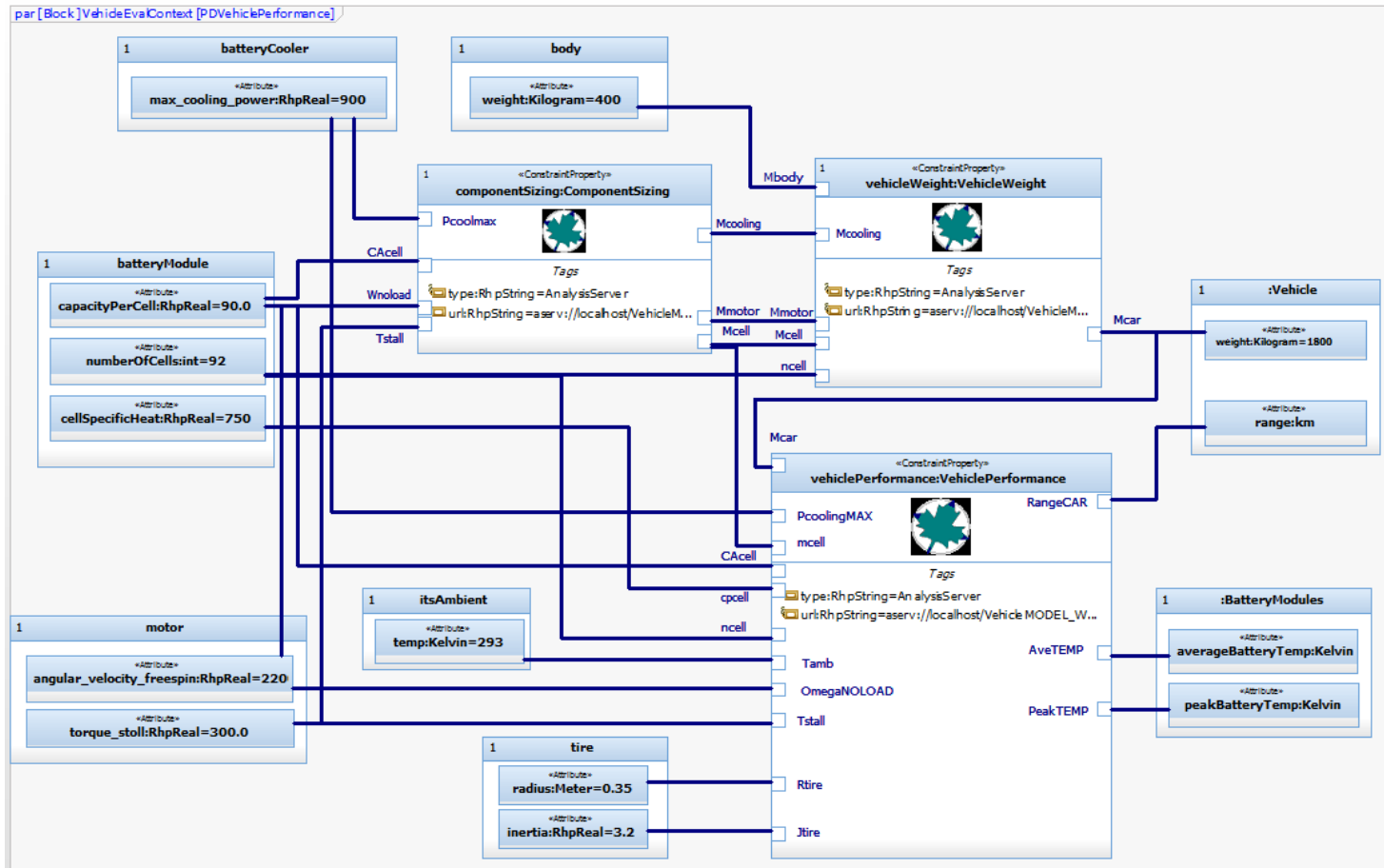
# Block Definition Diagram (2)



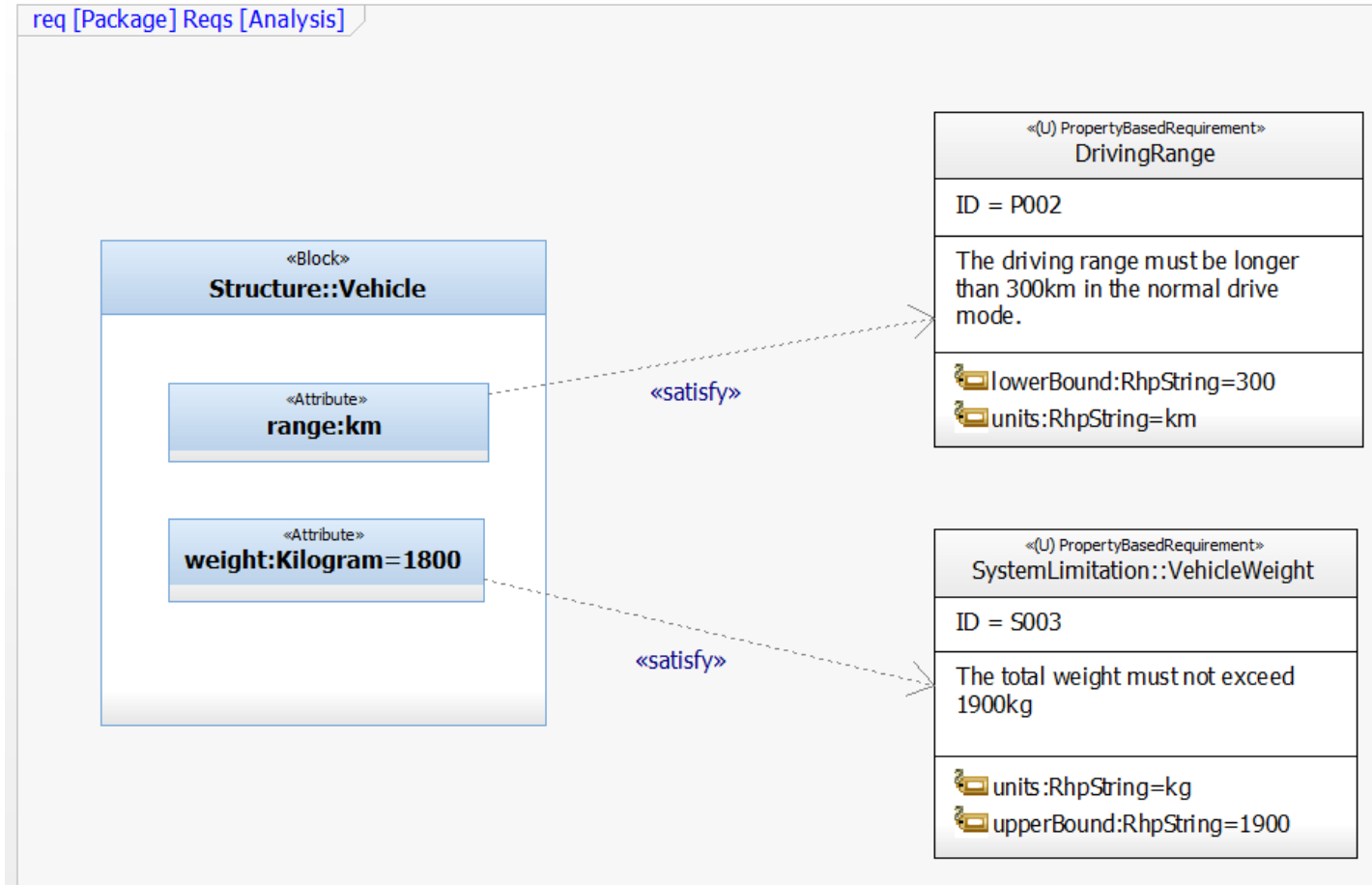
bdd [Package] Structure [Vehicle]



# Architectural Model Parametric Diagram



# The Satisfy Relationship with Requirements



# Analytical Model Multi-domain System-level Dynamics



## Li-ion Battery model

Graphite - Lithium Cobalt Oxide electrodes

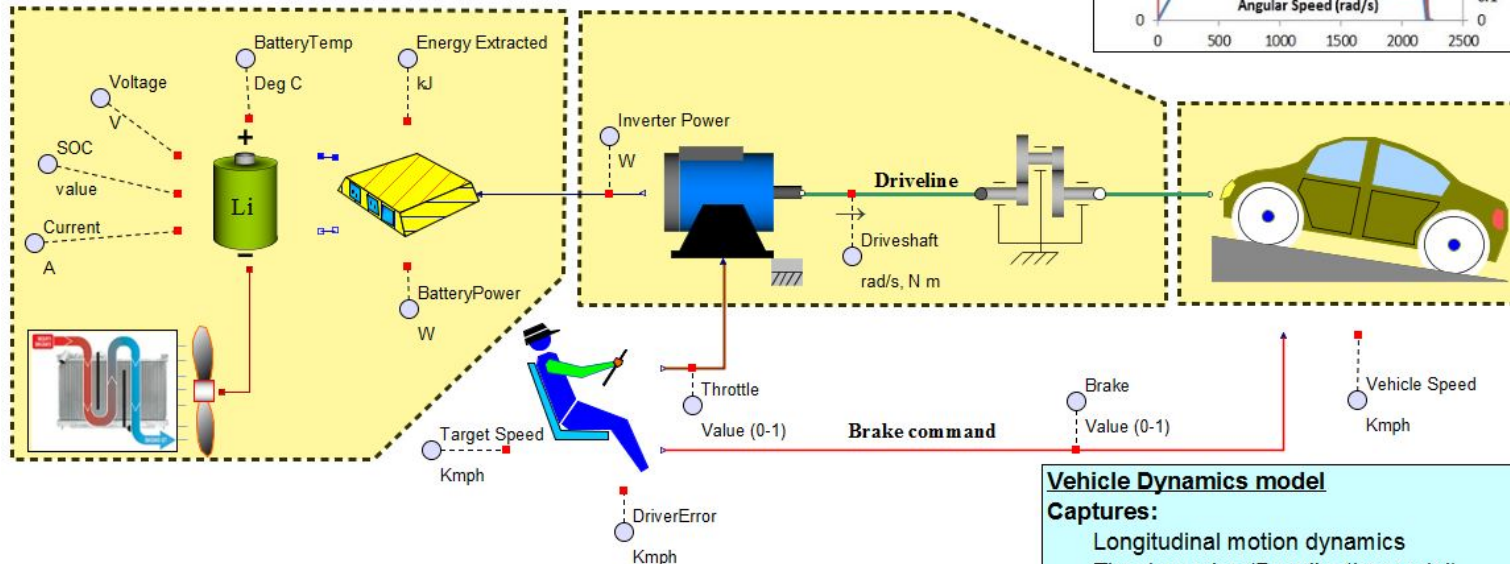
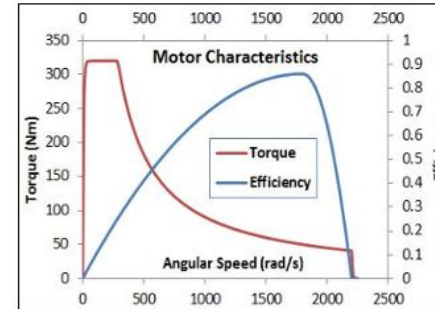
### Captures:

- Thermal effects on the battery chemistry
- Temperature dependent internal resistance
- Degradation effects
- Power electronics/Inverter efficiency

## DC motor

### Model described by

- A torque - speed curve
- A Motor efficiency map
- Rated power and angular speed



## 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

## Vehicle Dynamics model

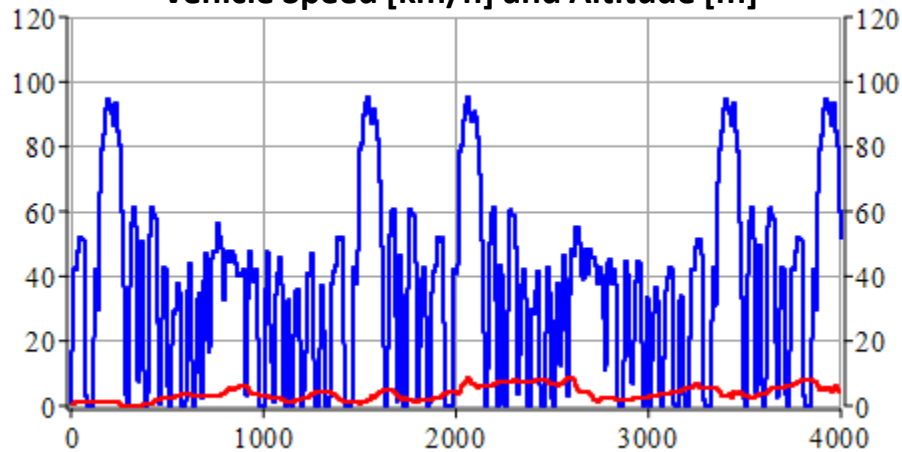
### Captures:

- 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

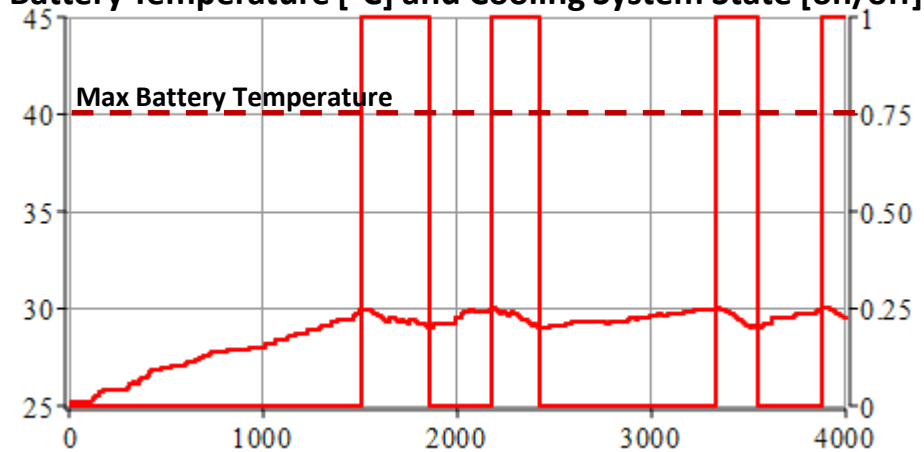
# Normal Loading

## 25°C Ambient, Gentle Grades

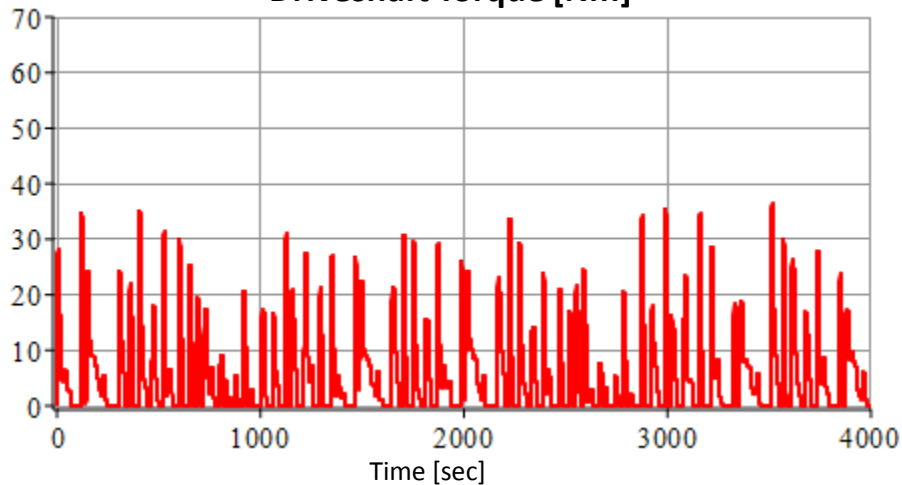
Vehicle Speed [km/h] and Altitude [m]



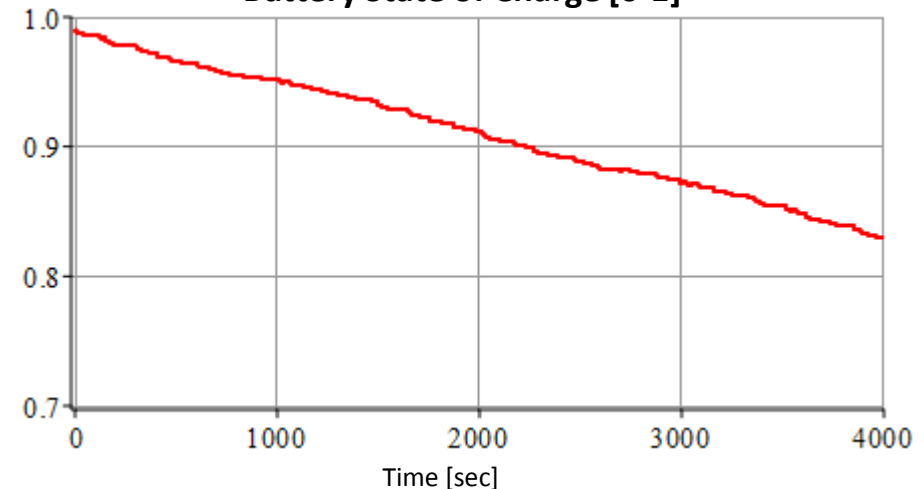
Battery Temperature [°C] and Cooling System State [on/off]



Driveshaft Torque [Nm]



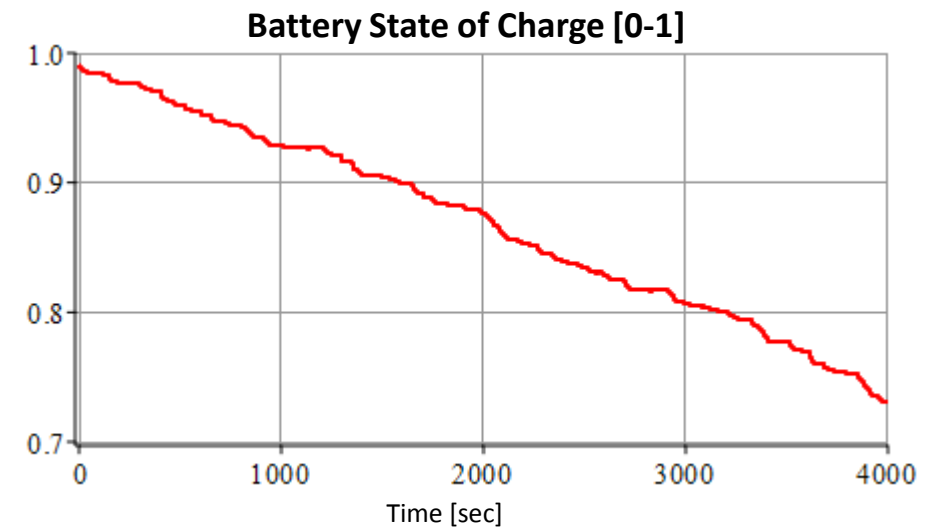
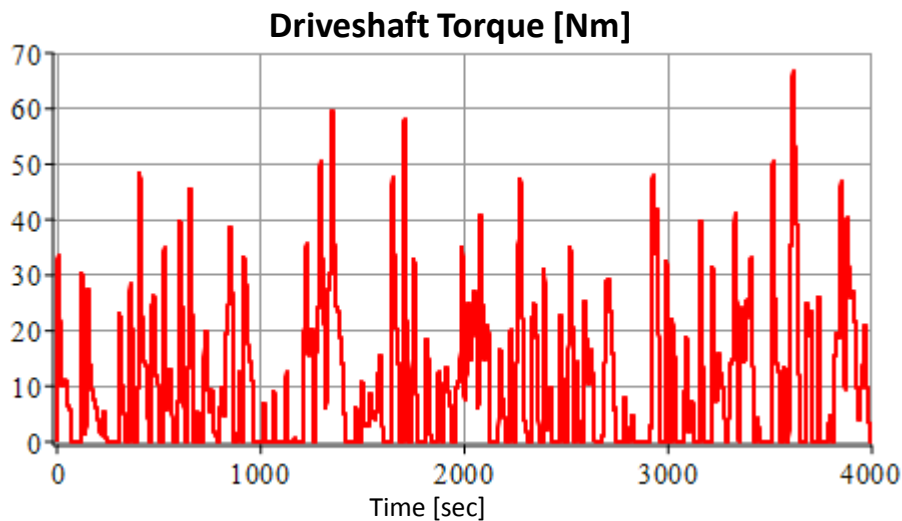
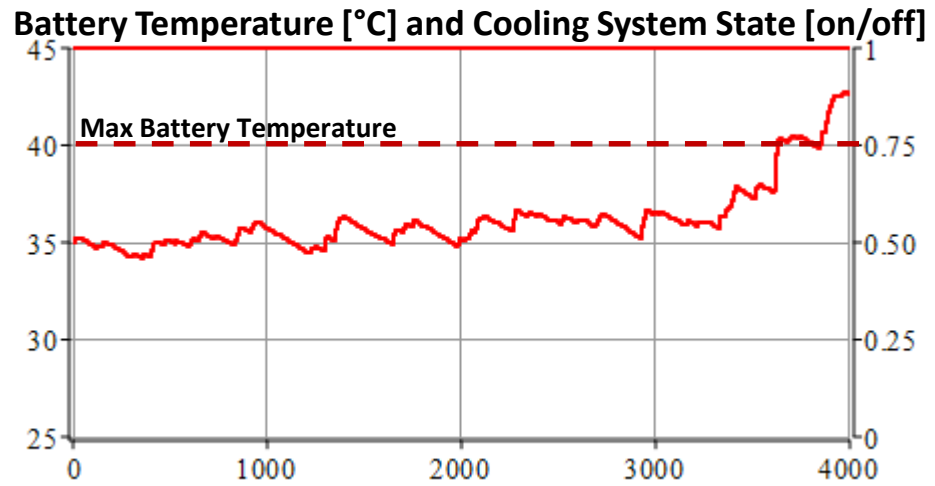
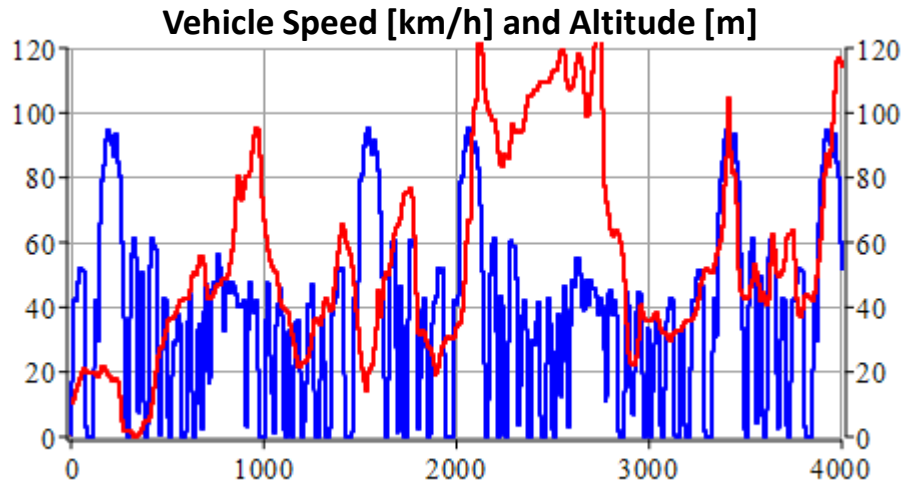
Battery State of Charge [0-1]





# Extreme Loading

## 35°C Ambient, Steep Grades



# Requirements Compliance Testing



Phoenix Integration MBSE Analyzer Shared

File Edit View Tools Help

Welcome | Review Requirements | Manage Constraint Blocks | Manage Parts Catalog | Manage Parametric Diagrams | Evaluate Designs

**Design Exploration**

Analysis Case: <none> + -

Trade Study: <none> + - ↻ 🔍

Select a Subject to Analyze

- [-] batteryModules (RO)
- [-] Body (RO)
- [-] Chassis (RO)
- [-] Inverter (RO)
- [-] Motor (RO)
- [-] Tire (RO)
- [-] Transmission (RO)
- [-] Vehicle (RO)
- [-] VehicleEvalContext (RO)
- [-] Units

Parametric Diagrams | Selection Filter

- VehicleEvalContext
- PDVehiclePerformance

Property	Units	Original	New	Margin
[-] VehicleEvalContext				
[-] batteryCooler				
max_cooling_power	Rhp Real	900.0	900.0	
[-] batteryModule				
capacityPerCell	Rhp Real	90.0	90.0	
cellSpecificHeat	Rhp Real	750.0	750.0	
numberOfCells	int	92	110	
averageBatteryTemp	K	0.0	26.515252852...	
peakBatteryTemp	K	0.0	27.848309623...	
[-] body				
weight	kg	400.0	400.0	
[-] itsAmbient				
temp	K	293.0	293.0	
[-] itsVehicle				
range	km	0.0	191.8073708	✗ 108.19 km
weight	kg	1800.0	1355.9	✓ 544.10 kg
[-] motor				
angular_velocity_freespin	Rhp Real	2200.0	2200.0	
torque_stoll	Rhp Real	300.0	300.0	
[-] tire				
inertia	Rhp Real	3.2	3.2	
radius	m	0.35	0.35	

Refresh | Restore Defaults

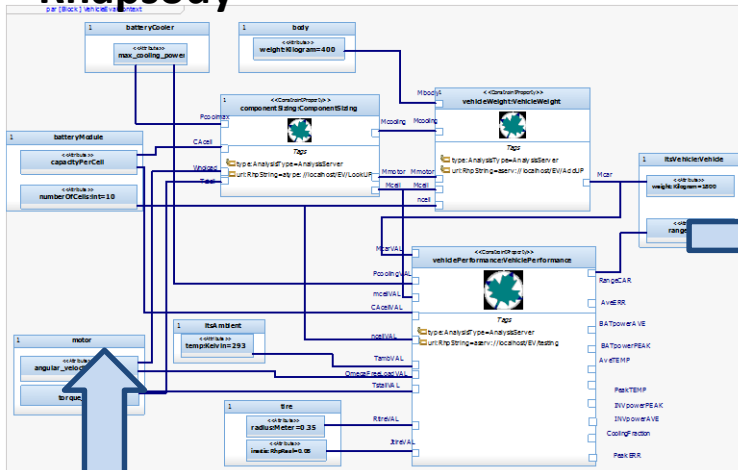
Design: Save | Save As | Analysis: Run | Export

Done.

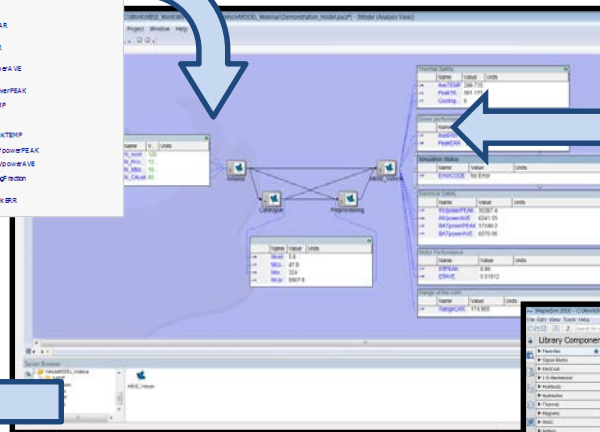
# Requirements Compliance Testing



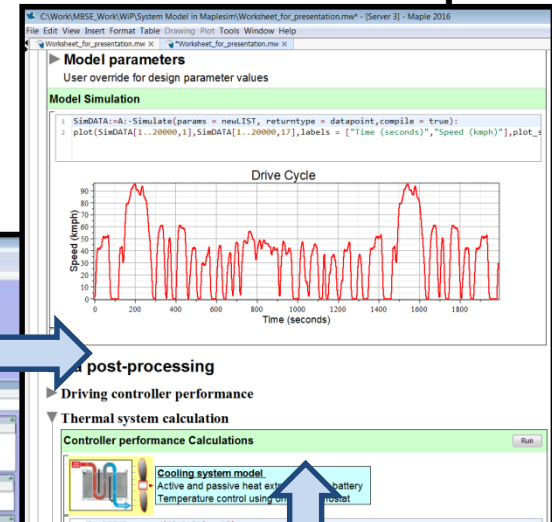
Rhapsody



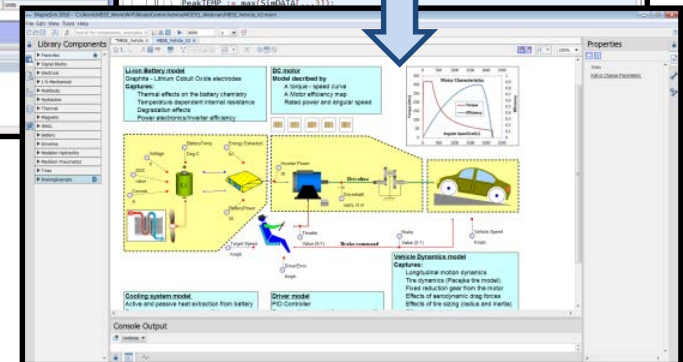
ModelCenter



Maple



Property	Unit	Original	New	Margin
radius	m	0.3	0.3	
radiusInner	m	0.25	0.25	
radiusOuter	m	0.35	0.35	
width	m	1.5	1.5	
height	m	20.0	20.0	
springForce	N	50.0	50.0	
springStiffness	N/m	1.667143838	1.667143838	
springDamping	Ns/m	0.0	0.0	
springLength	m	2.0	2.0	
springMass	kg	0.25	0.25	
springRadius	m	0.75	0.75	
springStiffness	N/m	4.235	4.235	
springDamping	Ns/m	0.0	0.0	
springLength	m	32.709627	32.709627	3.2210 km
springMass	kg	3.665179622	3.665179622	3.1468 km
springRadius	m	0.0	0.0	7.5
springStiffness	N/m	11.0	11.0	
springDamping	Ns/m	506.143751	476.024154	
springLength	m	22.0	22.0	
springMass	kg	0.0	0.0	
springRadius	m	3200.0	3200.0	
springStiffness	N/m	4.0	4.0	
springDamping	Ns/m	0.0	0.0	
springLength	m	174.223256	184.472294	4.4722 km
springMass	kg	3.00028	3.42027	



PHX System Engineering  
Integration Module

MapleSim

# 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**



Maplesoft  
Engineering  
Solutions

# Thank You

# Questions?

