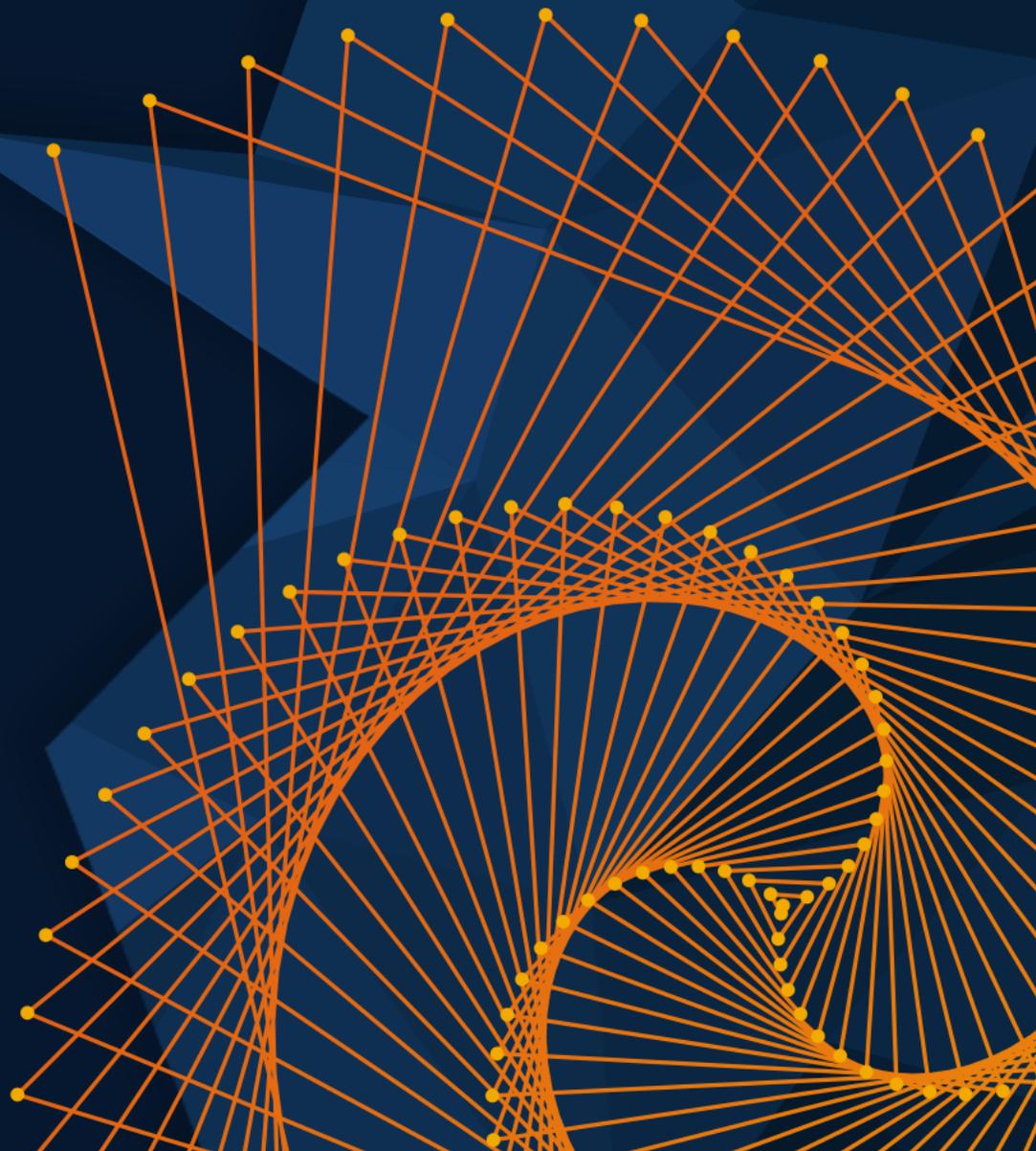


MATLAB EXPO

5月28日, 2024 | 北京

MathWorks 整车热管理系统设计仿真 解决方案

王梦佳, MathWorks



Agenda

- 基于模型设计在热管理系统开发中的运用
- 根据工程目的及建模需求的仿真 workflow 讨论
- 持续集成测试及数据驱动降阶技术加速热管理开发

基于模型设计在热管理系统开发中的运用

电动汽车热管理系统设计面临的挑战



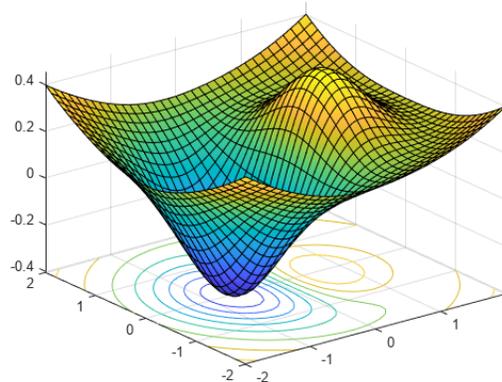
安全性



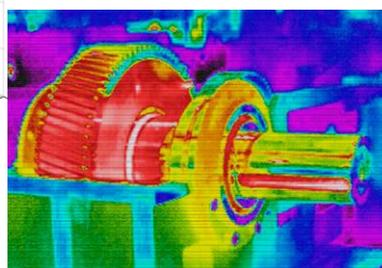
舒适性



热管理

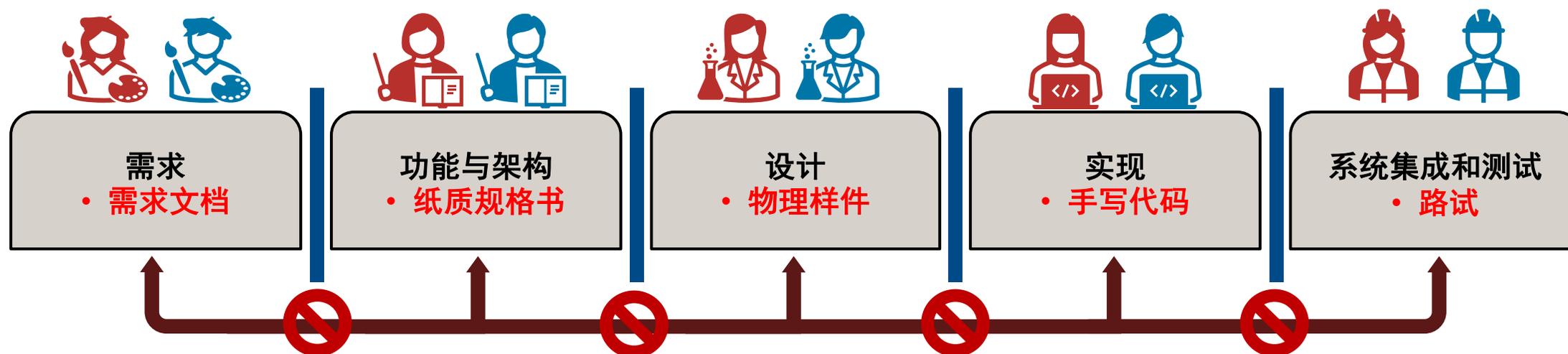


效率

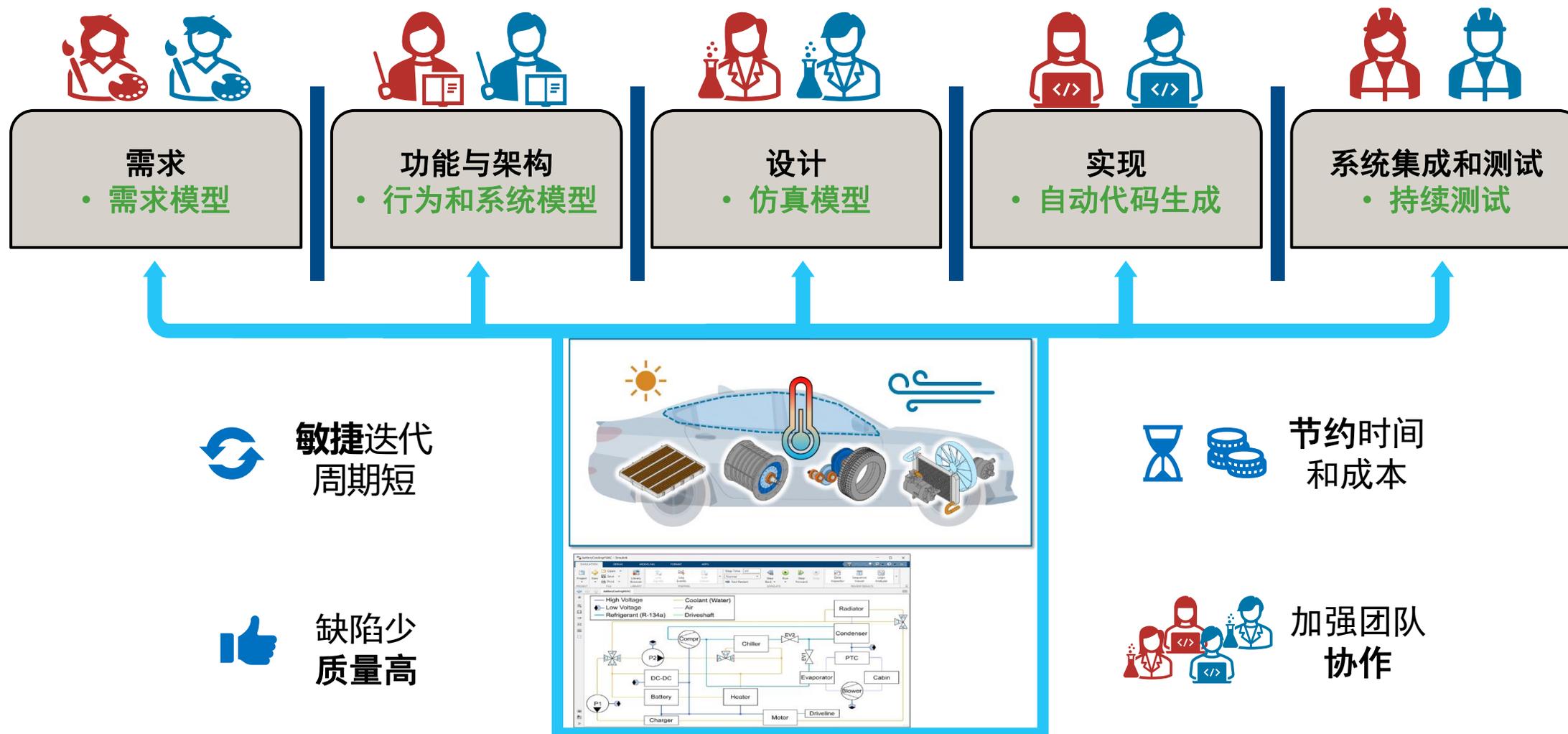


成本





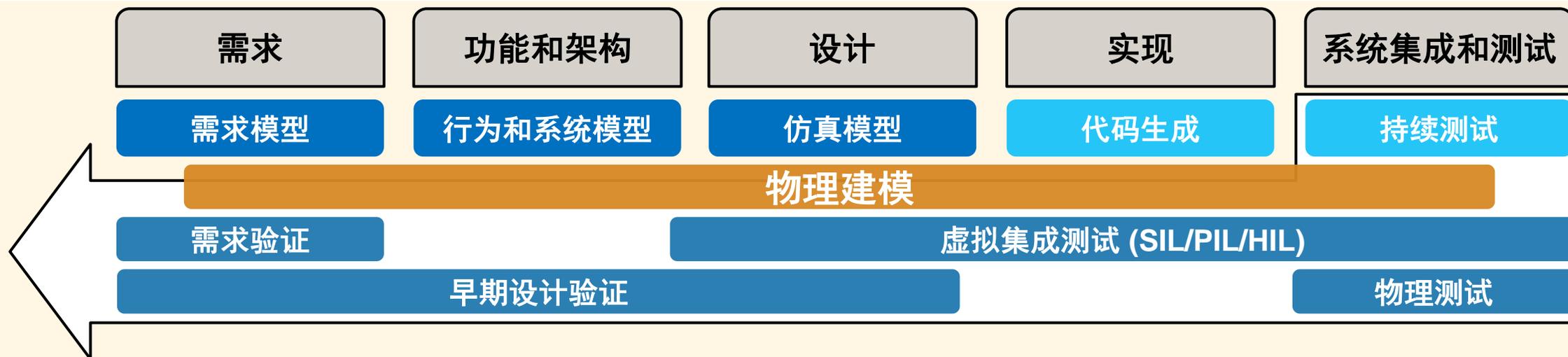
利用基于模型的设计，使虚拟模型成为开发过程的核心



在需求和系统架构与组件设计和测试之间建立一个可追溯的**数字线索**

基于模型设计在热管理系统开发中的运用

工作流程



应用场景



我该如何建模制冷系统？



我刚刚得到了一些车辆和实验室的数据，现在我想对系统进行建模。



但是等一下，简单的模型不会是正确的。



你为什么要建立这个模型，你将如何使用它？



嗯...让我们来谈谈基于模型设计的工作流程，也许可以从一些简单的模型开始。

“All models are wrong, but some are useful.”

- George Box, British statistician

根据工程目的及建模需求的仿真 workflow 讨论

Simscape产品线

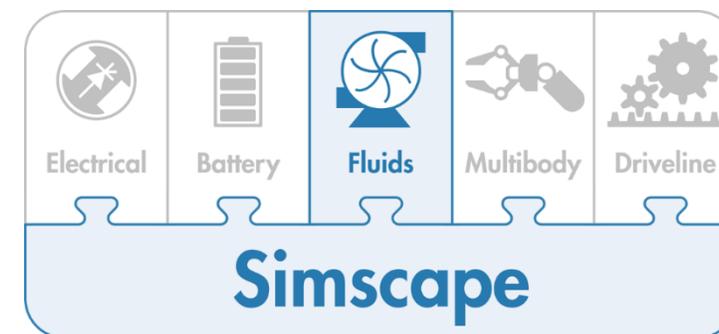
颜色与物理域

Simscape Line Styles Legend

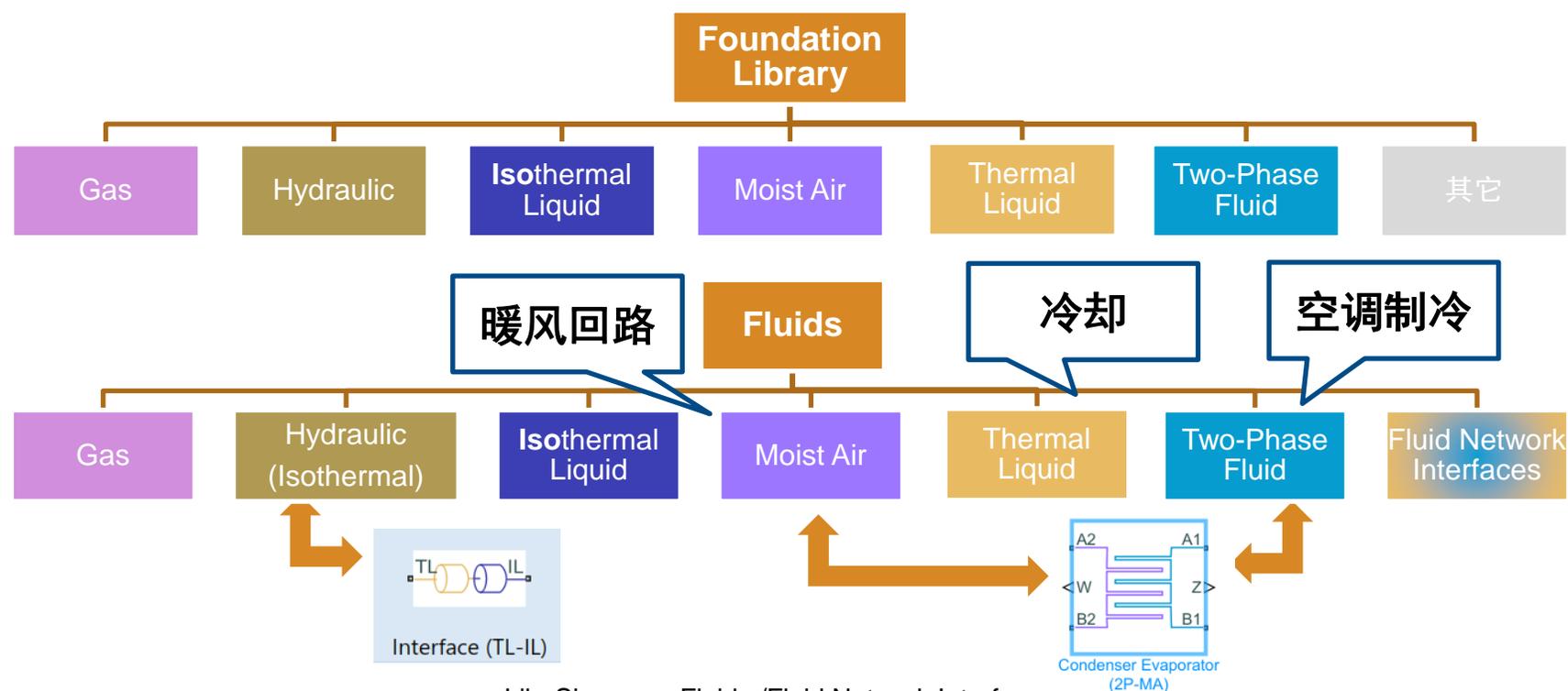
Color	Name
	Electrical Domain
	Gas Domain
	Hydraulic Domain
	Magnetic Domain
	Mechanical Rotational Domain
	Mechanical Translational Domain
	Moist Air Domain
	Moist Air Source Domain
	Thermal Domain
	Thermal Liquid Domain
	Two-Phase Fluid Domain
	Physical Signals
	Three-Phase Electrical Domain
	3-D Mechanical (Belt-Cable)
	3-D Mechanical (Frame)
	3-D Mechanical (Geometry)



Simscape 流体仿真工具箱说明



- 不同颜色物理域模块不能直接互连(除非使用转换接口模块)
- 相比于 Foundation Library 同名物理域模块库, **Fluids** 提供更丰富的模块
- 相比于 Gas, Moist Air 模型额外考虑水蒸气和第三组分气体(比如二氧化碳)
- 相比于 Hydraulic, Isothermal Liquid 是修改(升级)了底层平衡方程的等价模块库
- 相比于 Isothermal Liquid, thermal Liquid 考虑在仿真过程中的温度变化



Lib: Simscape Fluids /Fluid Network Interfaces

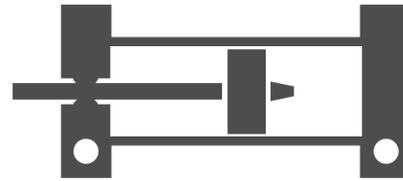
Simscape Fluids 模块库



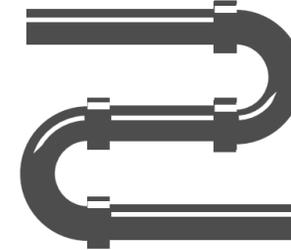
Pumps



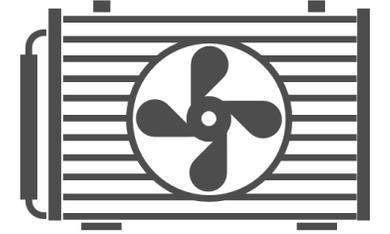
Valves



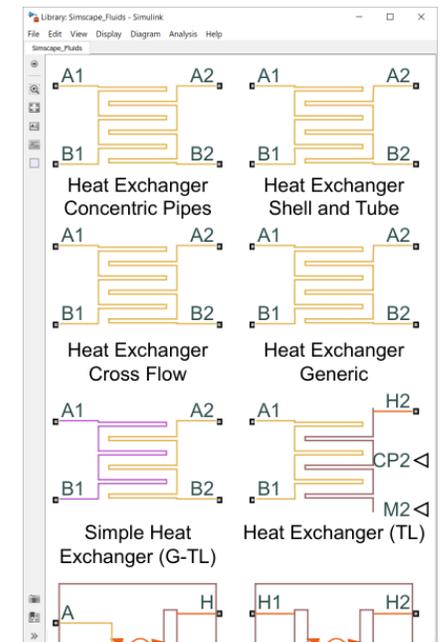
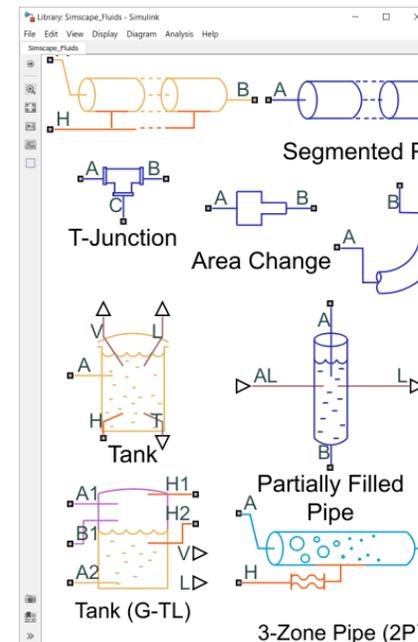
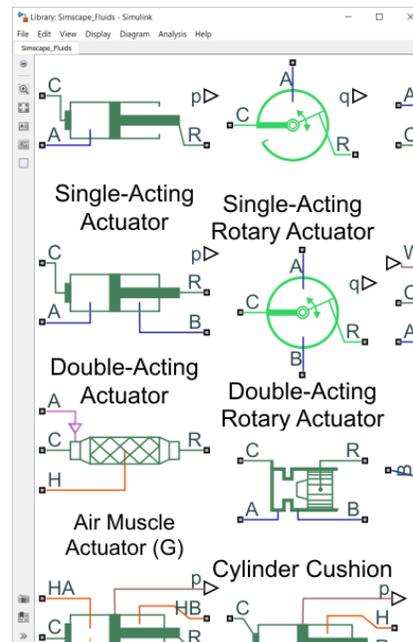
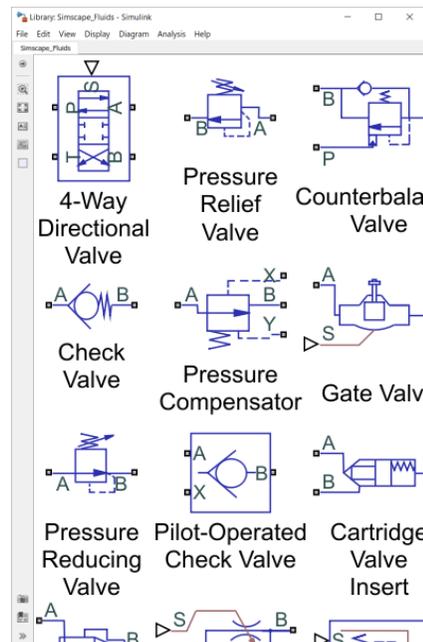
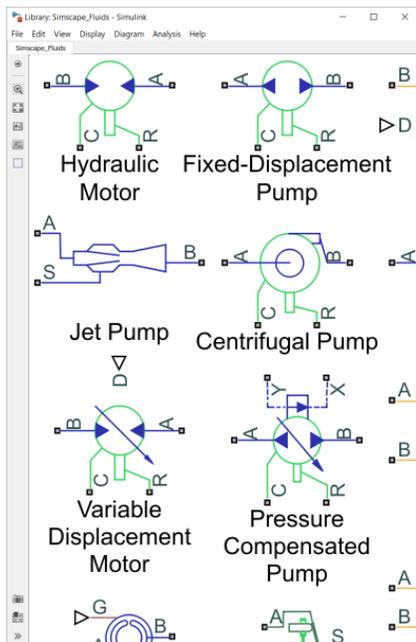
Actuators



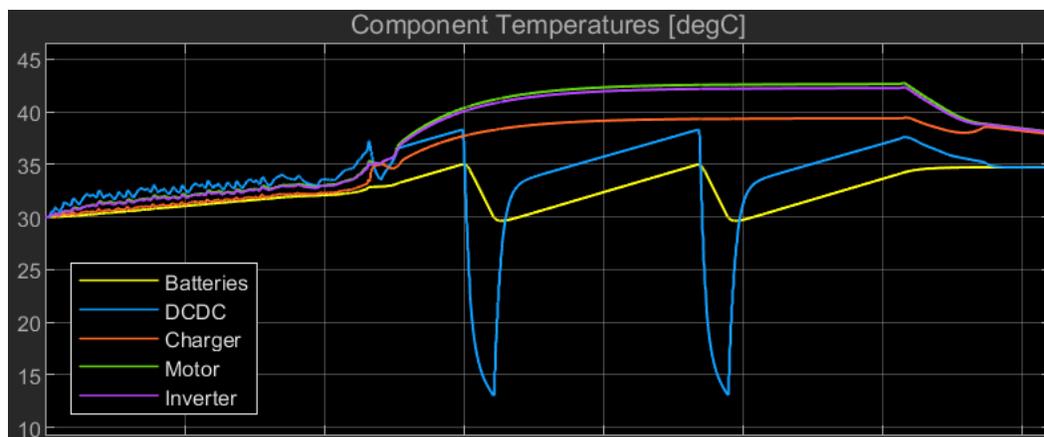
Pipes, Tanks



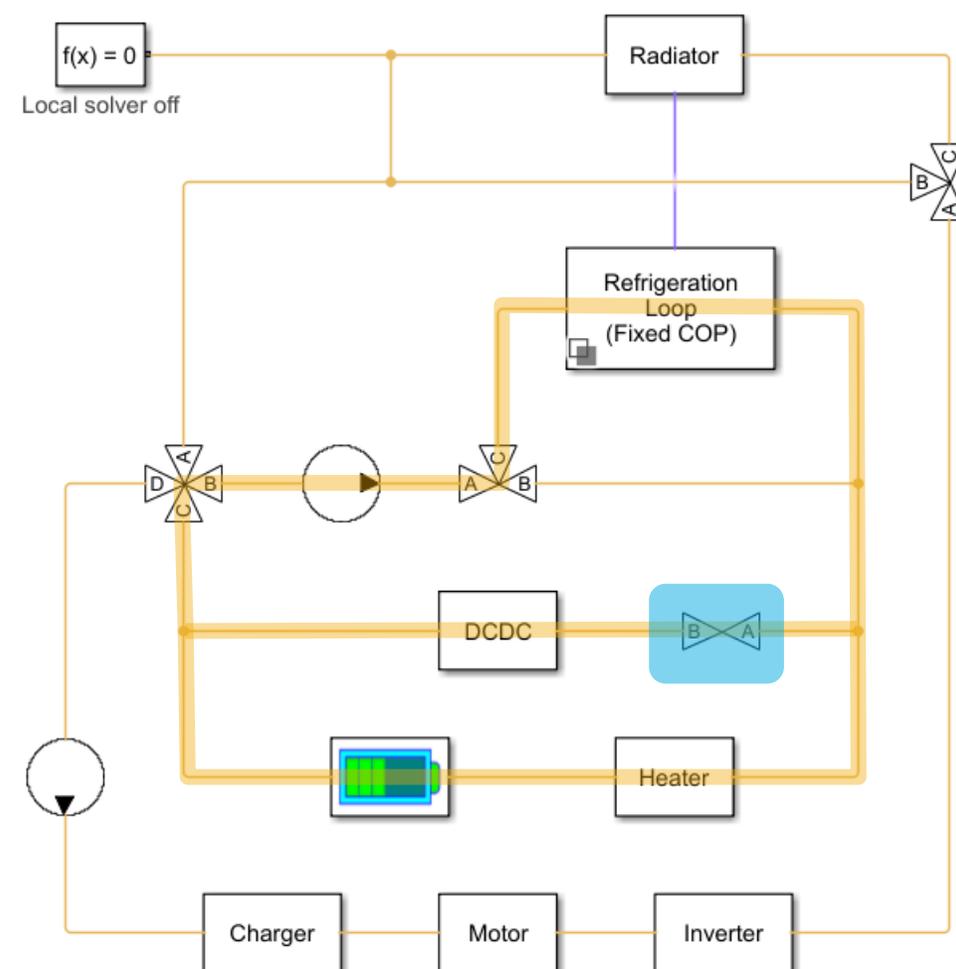
Heat Exchangers



案例：DC-DC 冷却控制优化



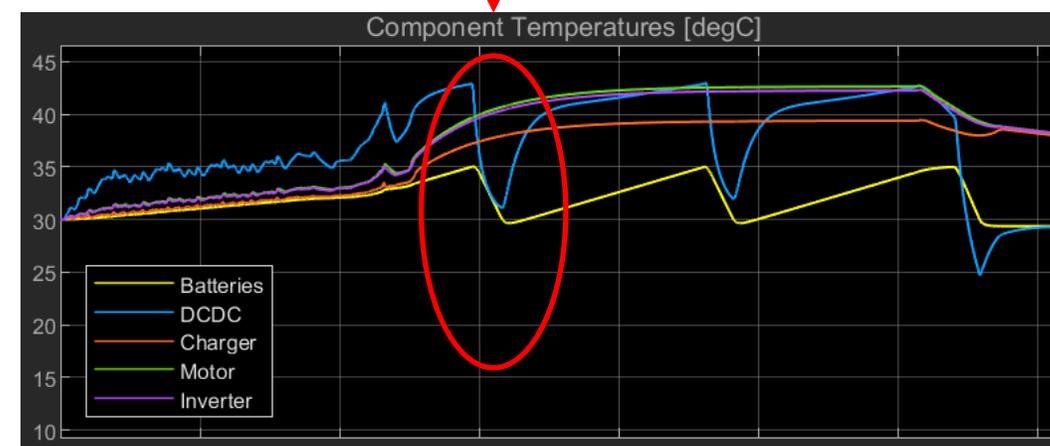
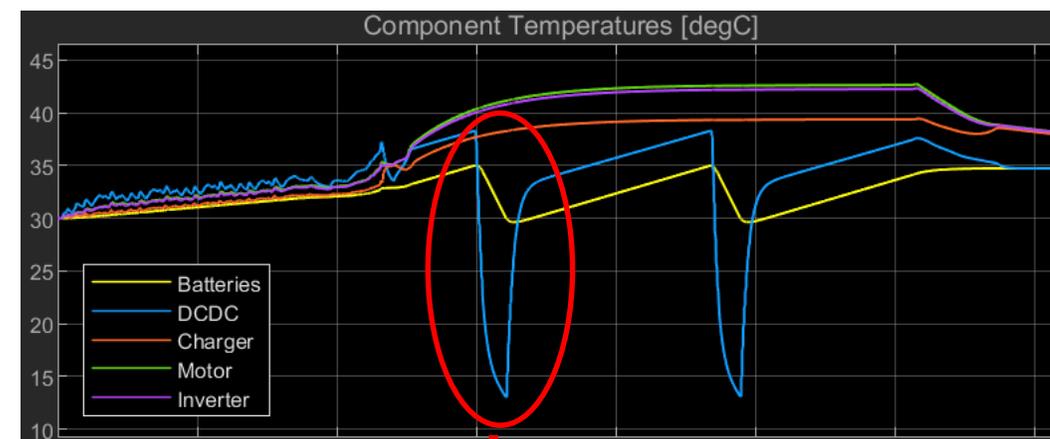
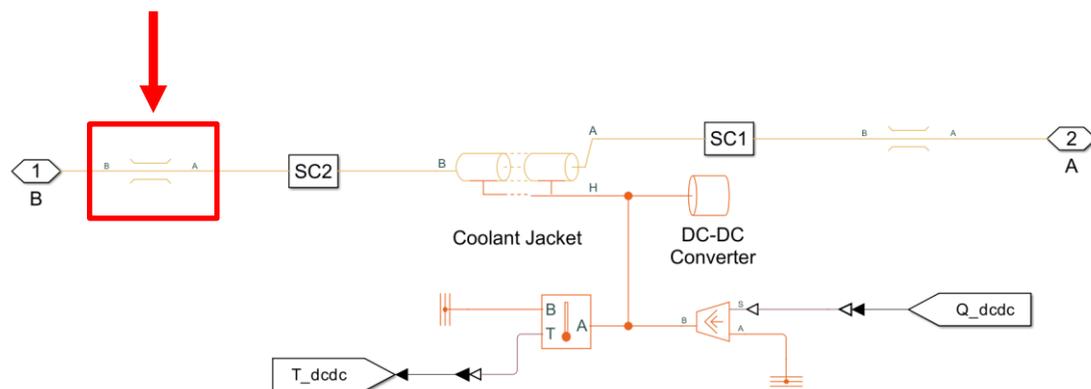
- DC-DC没有加入控制阀之前，水路流量受电池温度影响



案例：DC-DC 冷却控制优化

控制器选型

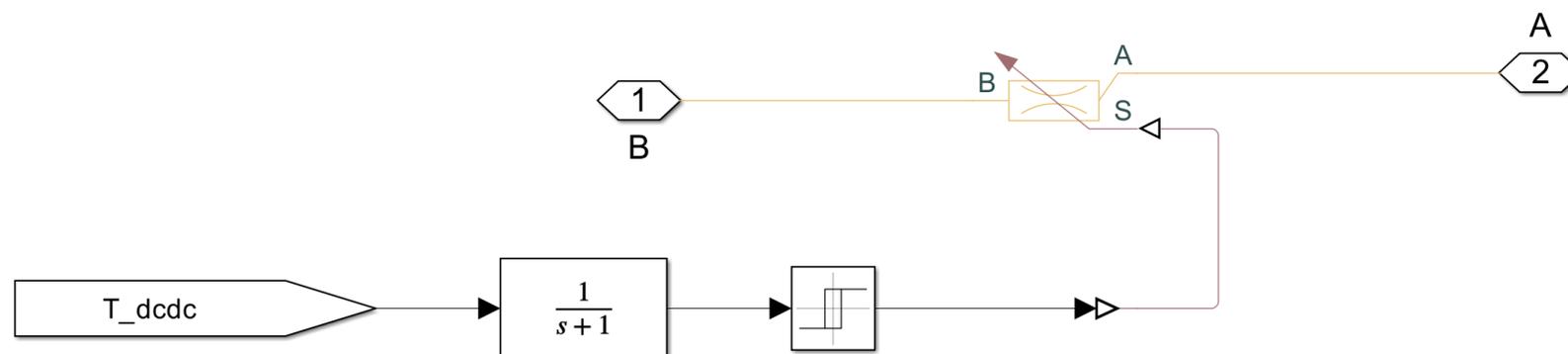
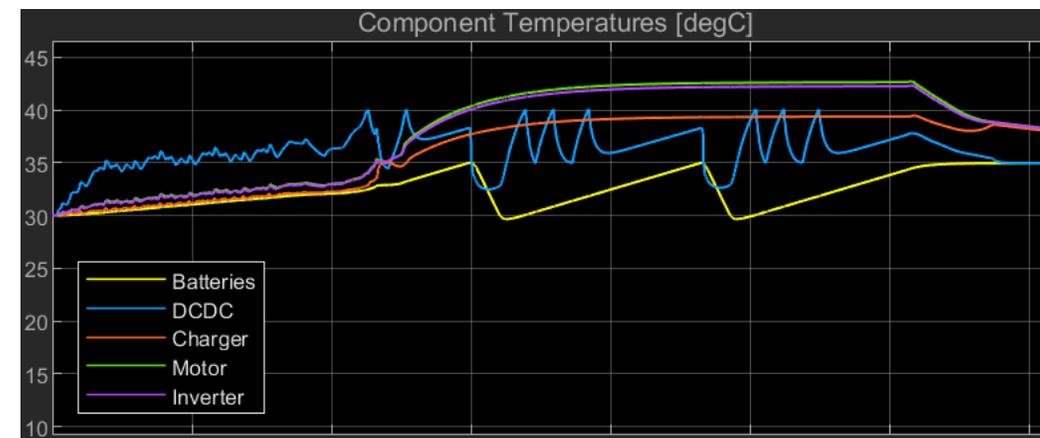
- 定义温度需求
- 快速设计迭代
- 通过流动限制需求选型控制器



案例：DC-DC 冷却控制优化

电磁阀

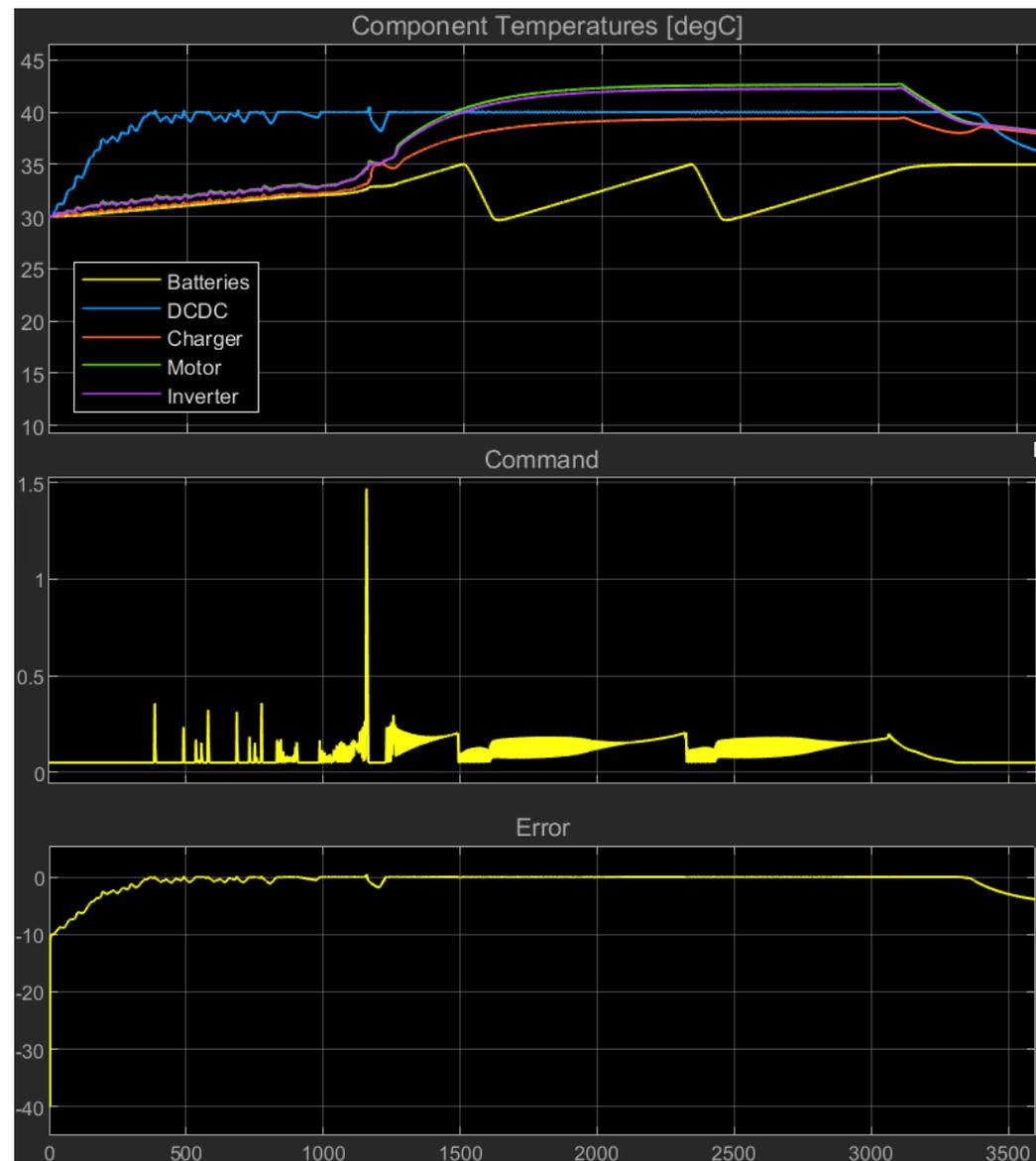
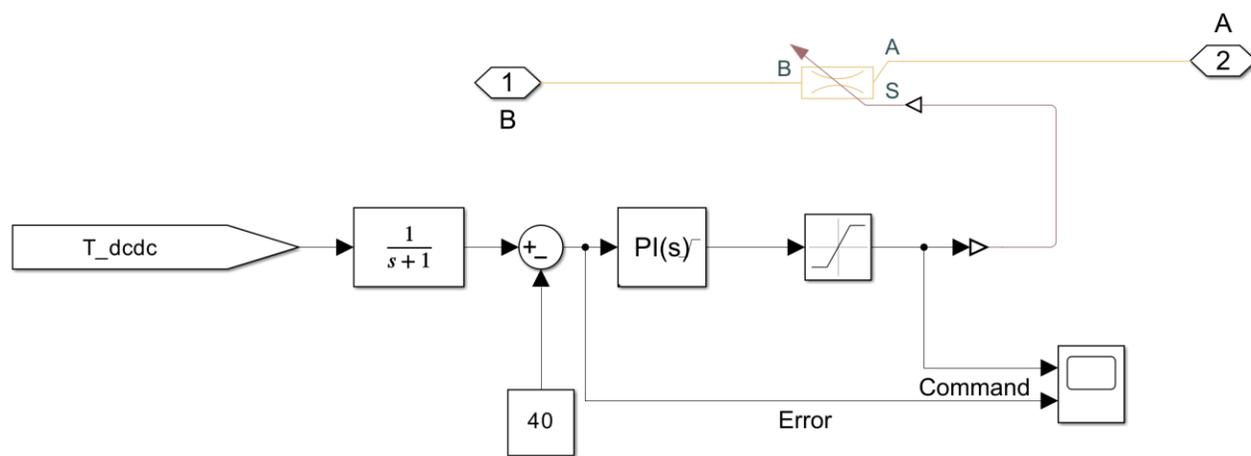
- 简单的阀门控制
- 温度控制
- 可保证DC-DC在所需的温度范围内



案例：DC-DC 冷却控制优化

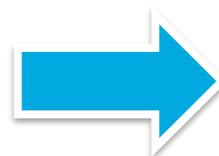
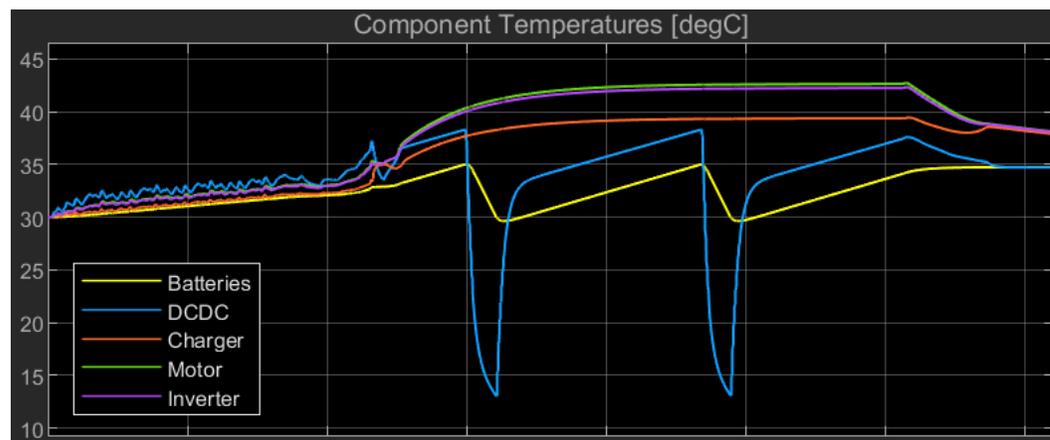
比例阀

- 更为复杂的阀和控制需求
- PI 控制器
- 能更好地追踪目标温度

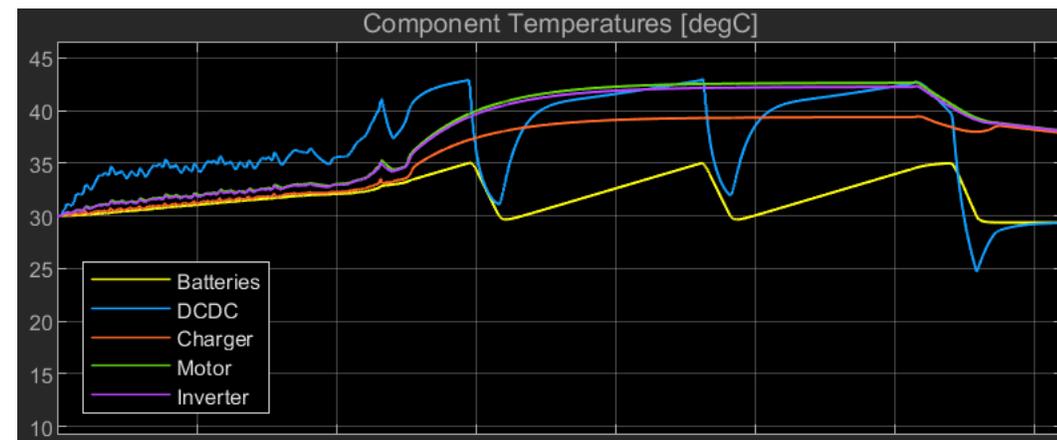


案例：DC-DC 冷却控制优化

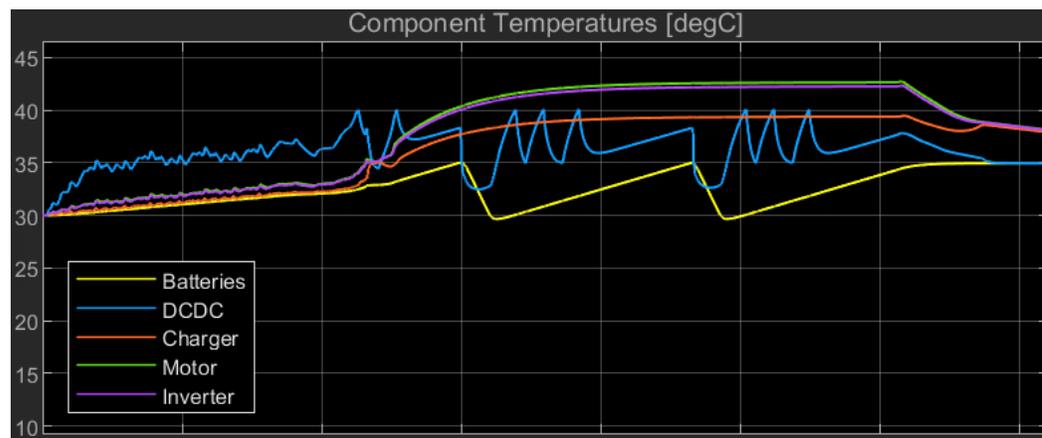
Baseline



流阻



电磁阀

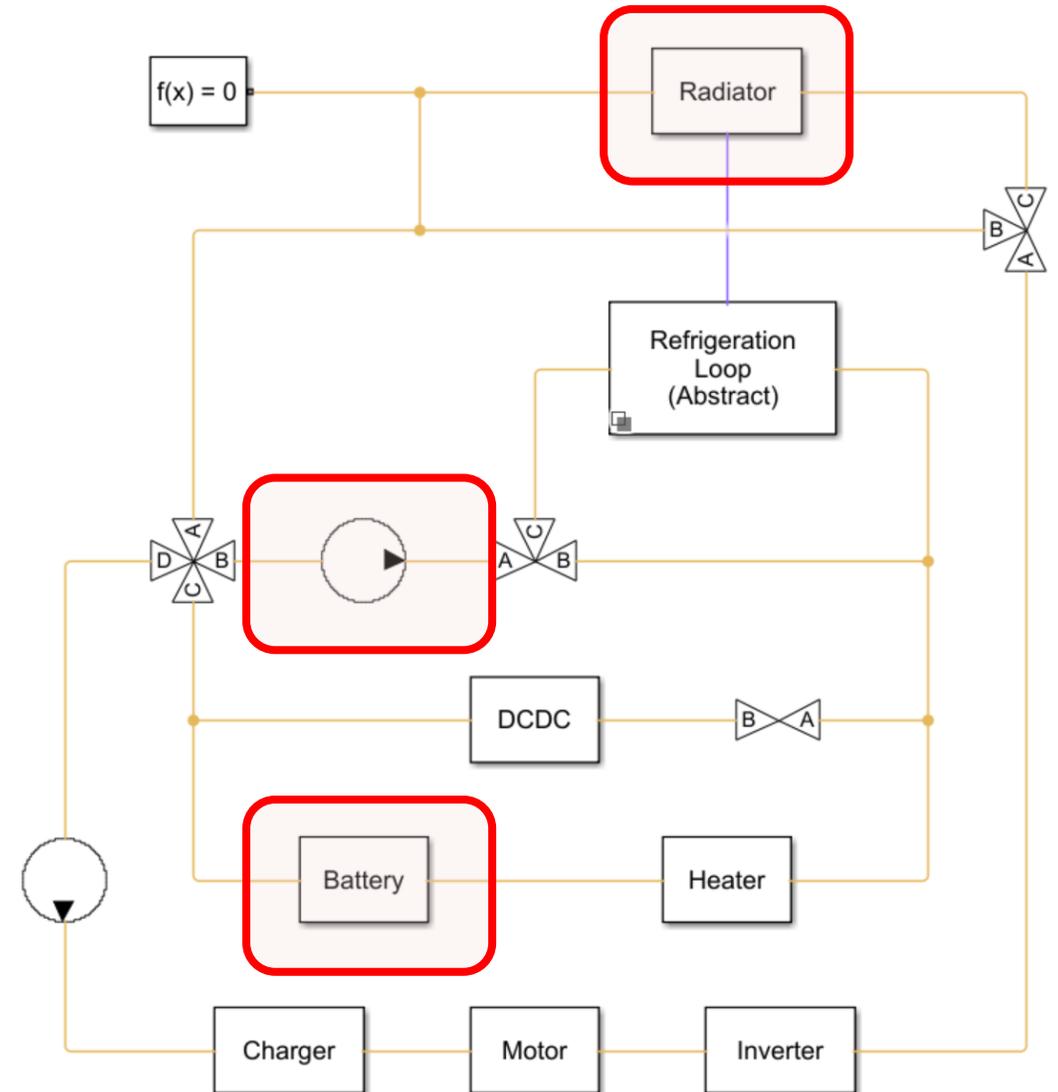


比例阀



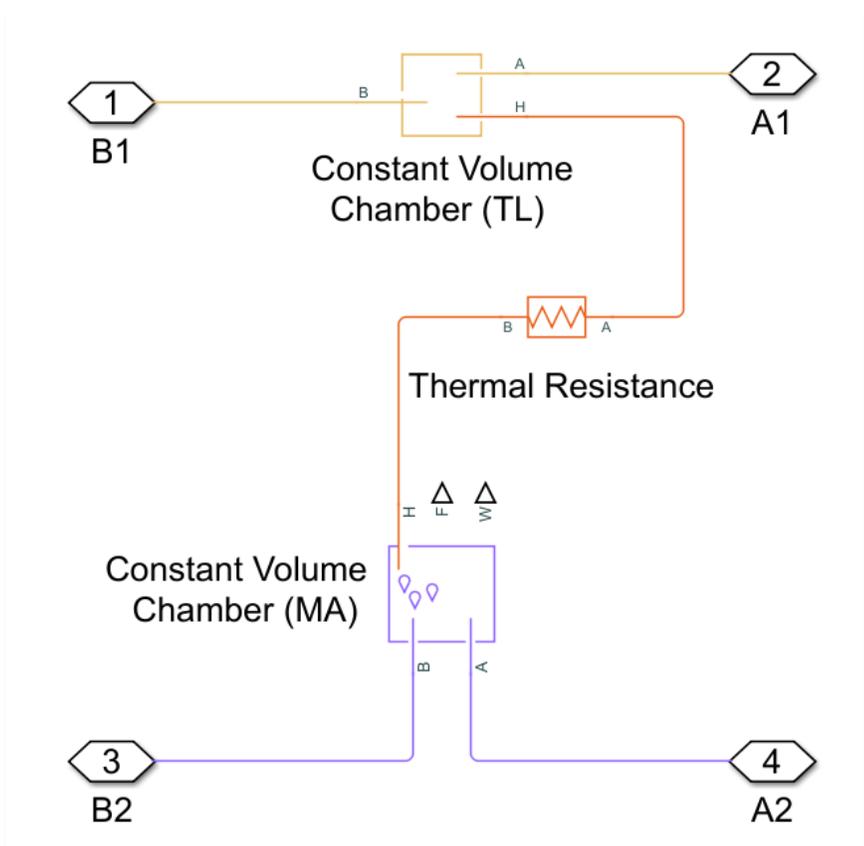
抽象、系统级和部件级建模方式

- 根据工程目标及设计阶段选取适合的建模方式



抽象、系统级和部件级建模方式

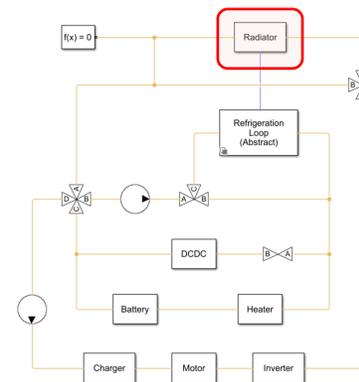
例: 散热器



模块参数: Thermal Resistance

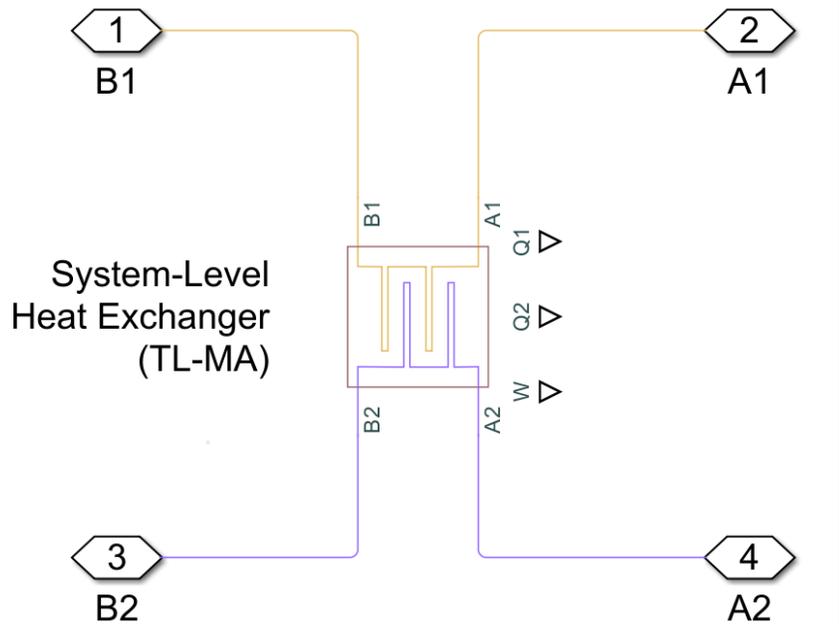
Thermal Resistance 自动应用

名称	值
Parameters	
Thermal resistance	1 K/W
Initial Targets	
Nominal Values	



抽象、系统级和部件级建模方式

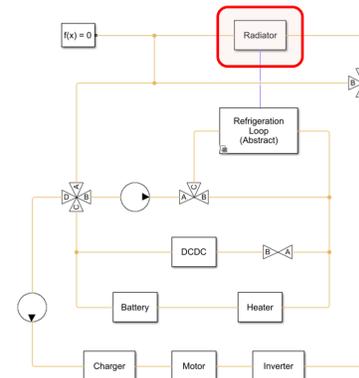
例: 散热器



模块参数: System-Level Heat Exchanger (TL-MA)

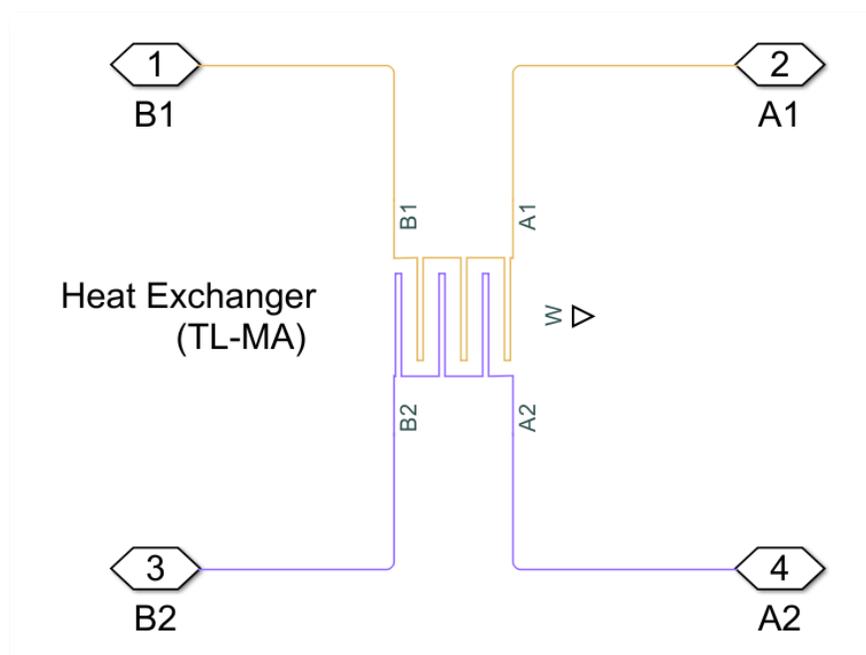
System-Level Heat Exchanger (TL-MA) 自动应用

名称	值
> Configuration	
Thermal Liquid 1	
Nominal operating condition	Heat transfer from thermal liquid to moist air
> Nominal mass flow rate	0.1 kg/s
> Nominal pressure drop	0.01 MPa
> Nominal inlet pressure	0.101325 MPa
> Nominal inlet temperature	333.15 K
Heat transfer capacity specification	Rate of heat transfer
> Nominal rate of heat transfer	1 kW
> Thermal liquid volume	0.001 m ³
Initial condition specification	Same as nominal operating condition
> Moist Air 2	
> Correlation Coefficients	

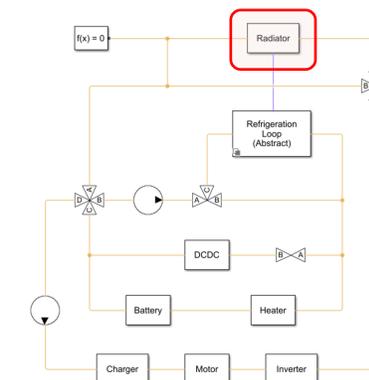
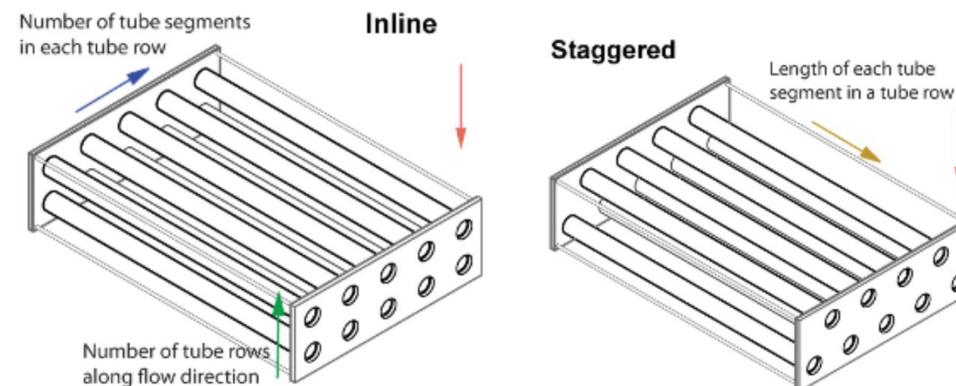
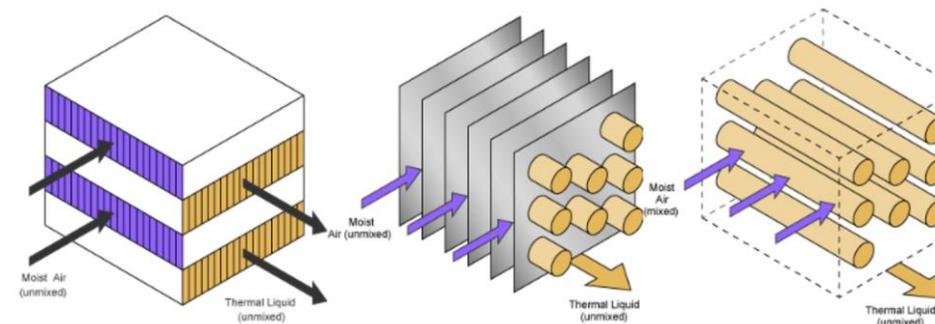


抽象、系统级和部件级建模方式

例: 散热器

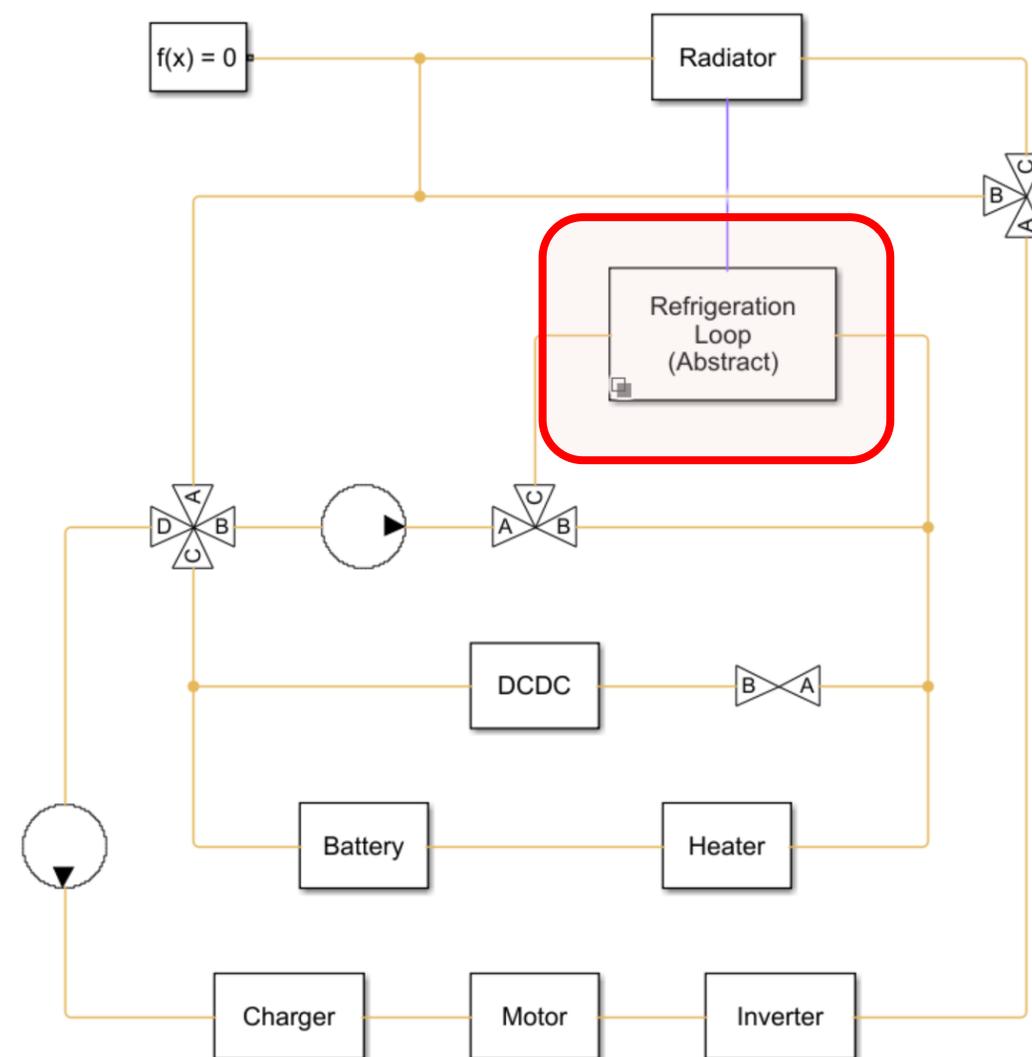


Sample Cross-Flow Configurations



抽象、系统级和部件级建模方式

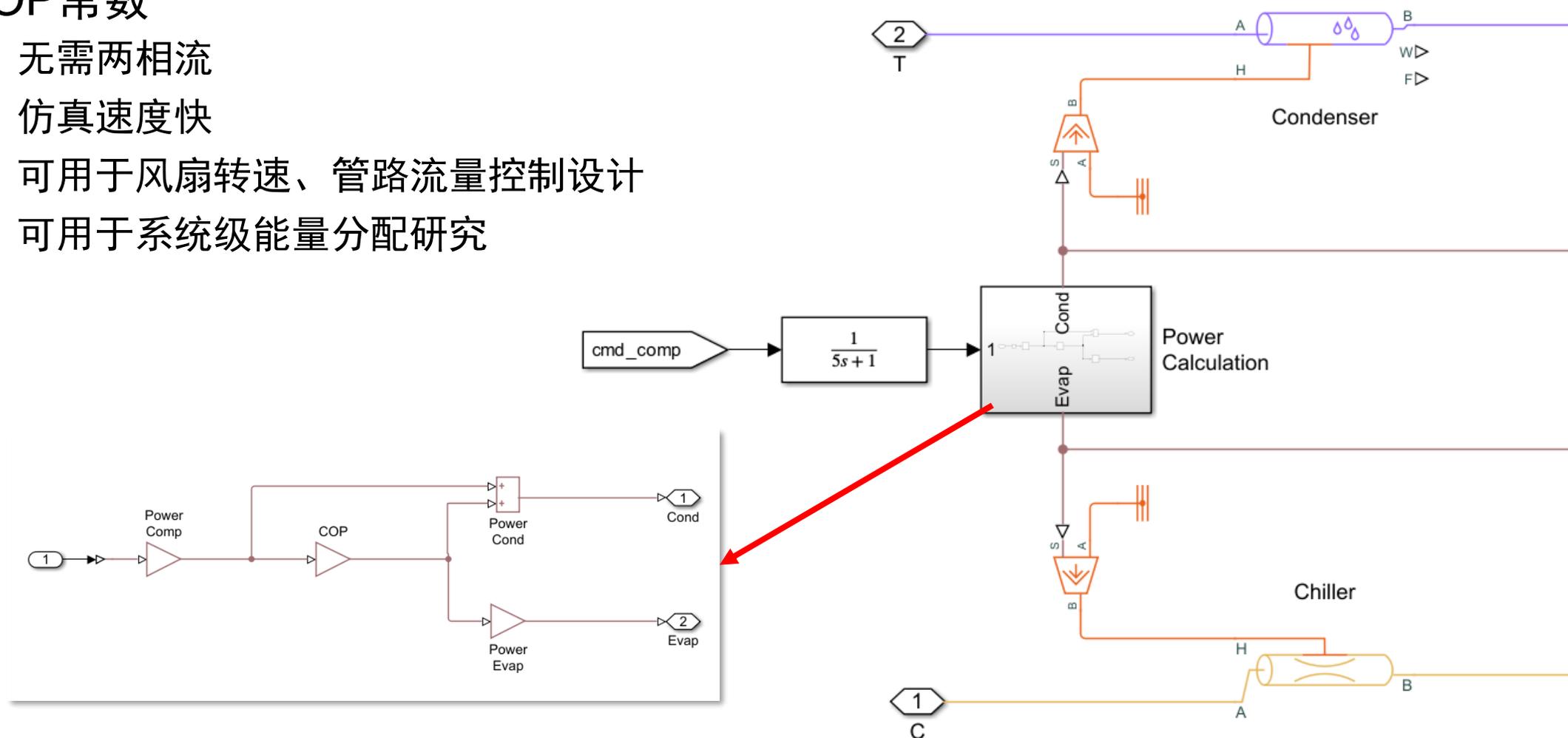
- 根据工程目标及设计阶段选取适合的建模方式



抽象、系统级和部件级建模方式

■ COP常数

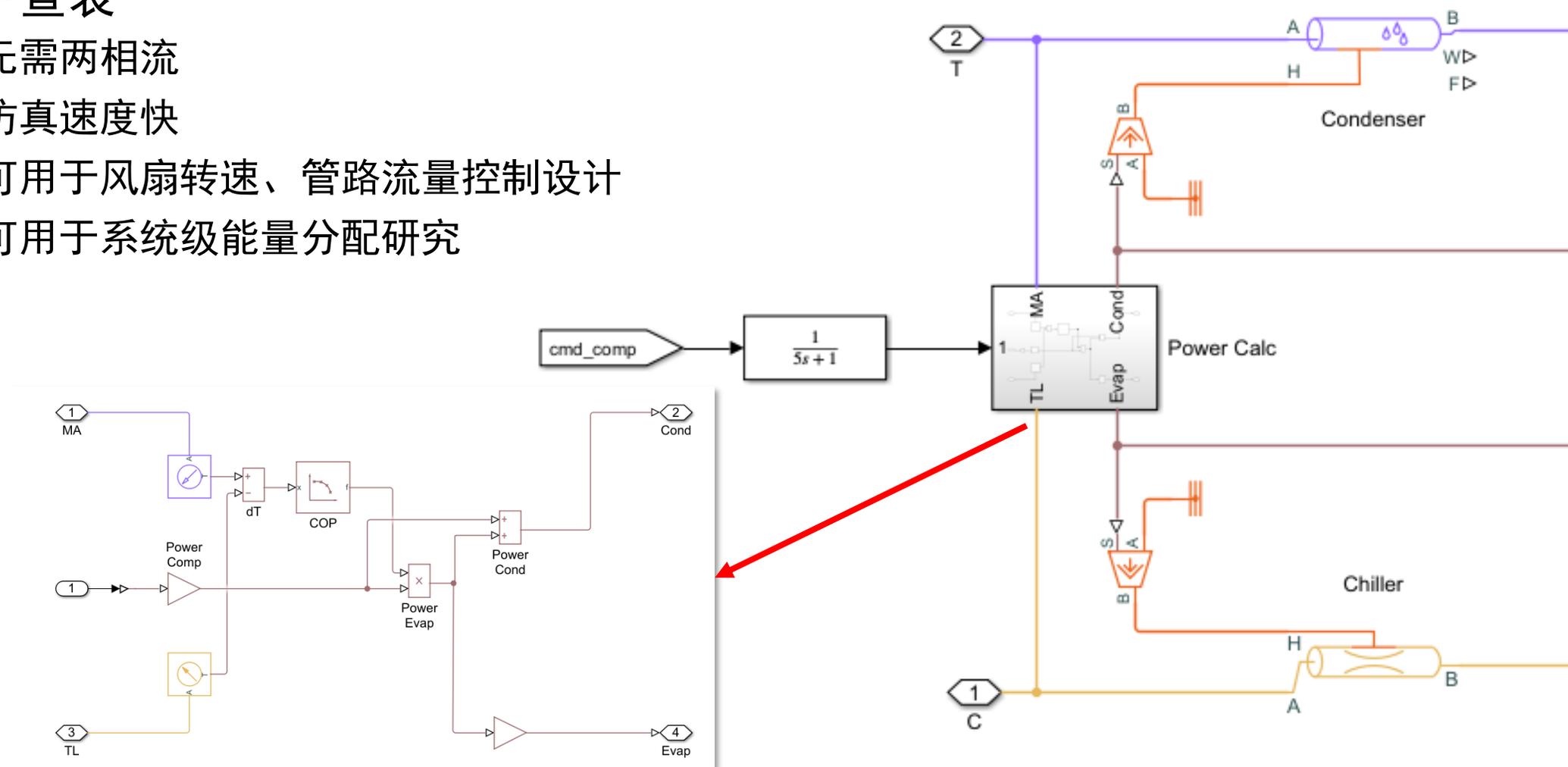
- 无需两相流
- 仿真速度快
- 可用于风扇转速、管路流量控制设计
- 可用于系统级能量分配研究



抽象、系统级和部件级建模方式

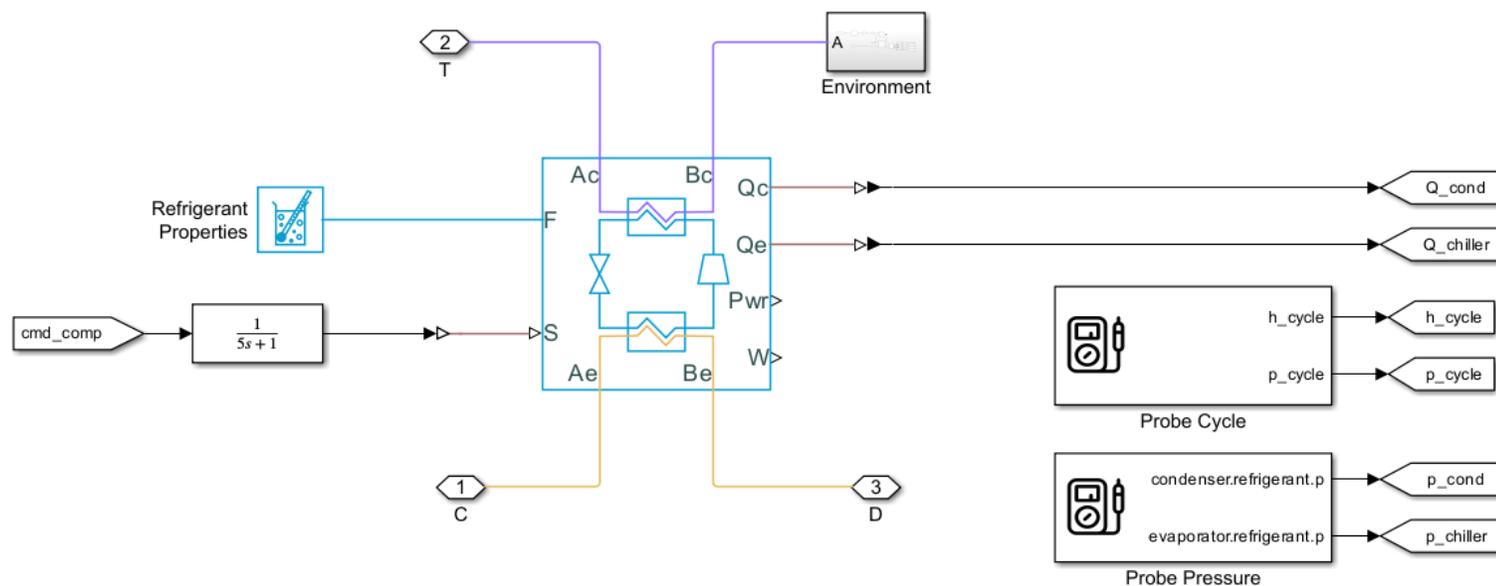
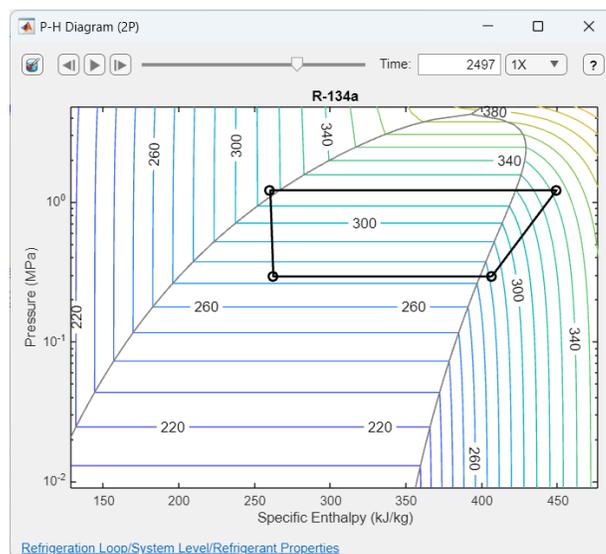
■ COP查表

- 无需两相流
- 仿真速度快
- 可用于风扇转速、管路流量控制设计
- 可用于系统级能量分配研究



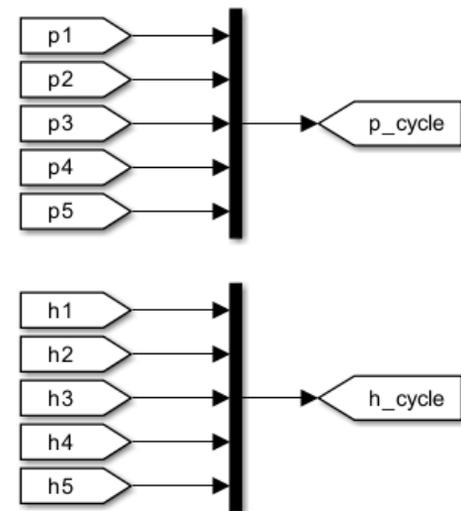
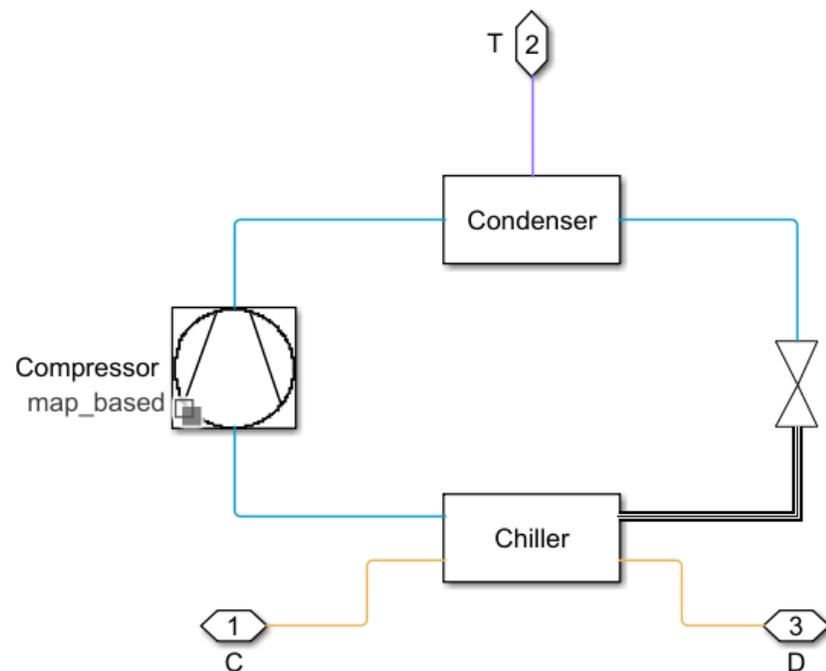
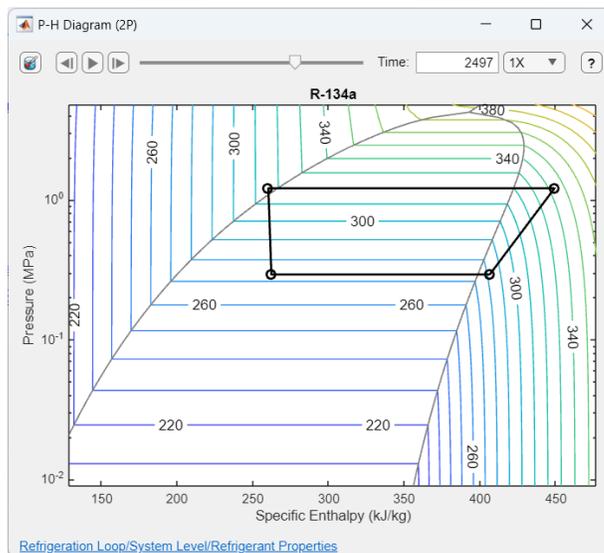
抽象、系统级和部件级建模方式

- 系统级制冷循环 (发布于2023a)
 - 制冷循环集成模块
 - 根据工况点配置制冷循环
 - 多种流体介质选择
 - 适用于分析热力学状态



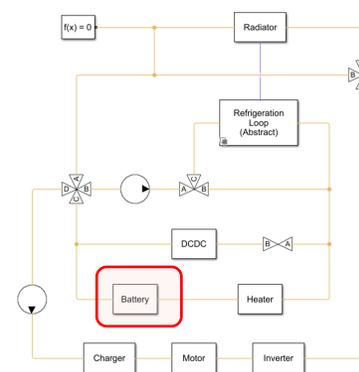
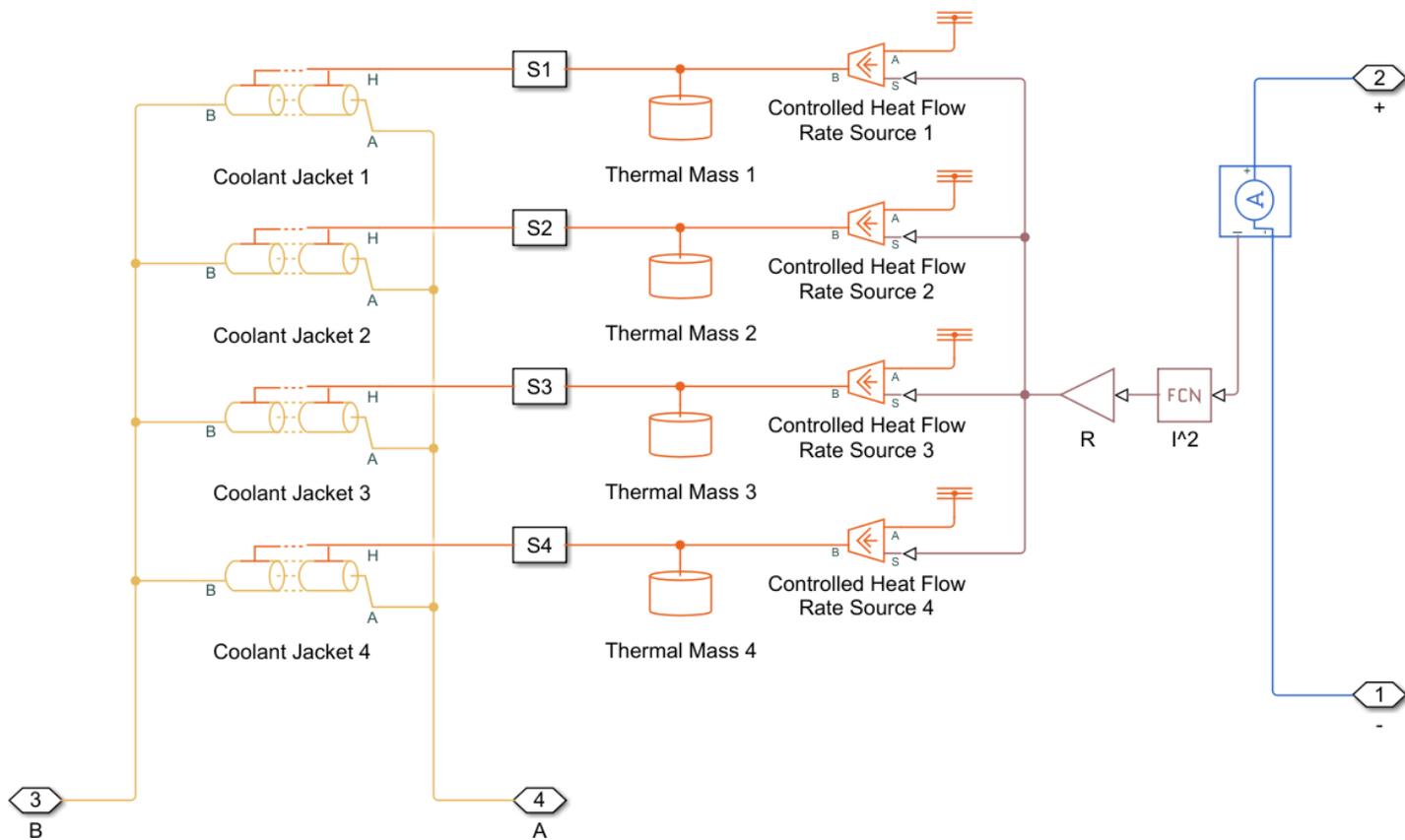
抽象、系统级和部件级建模方式

- 组件单独建模的制冷循环
 - 可以进行详细、部件级的设计
 - 可以做不同制冷架构设计
 - 组件选型和匹配研究
 - 灵活建模各个组件



抽象、系统级和部件级建模方式

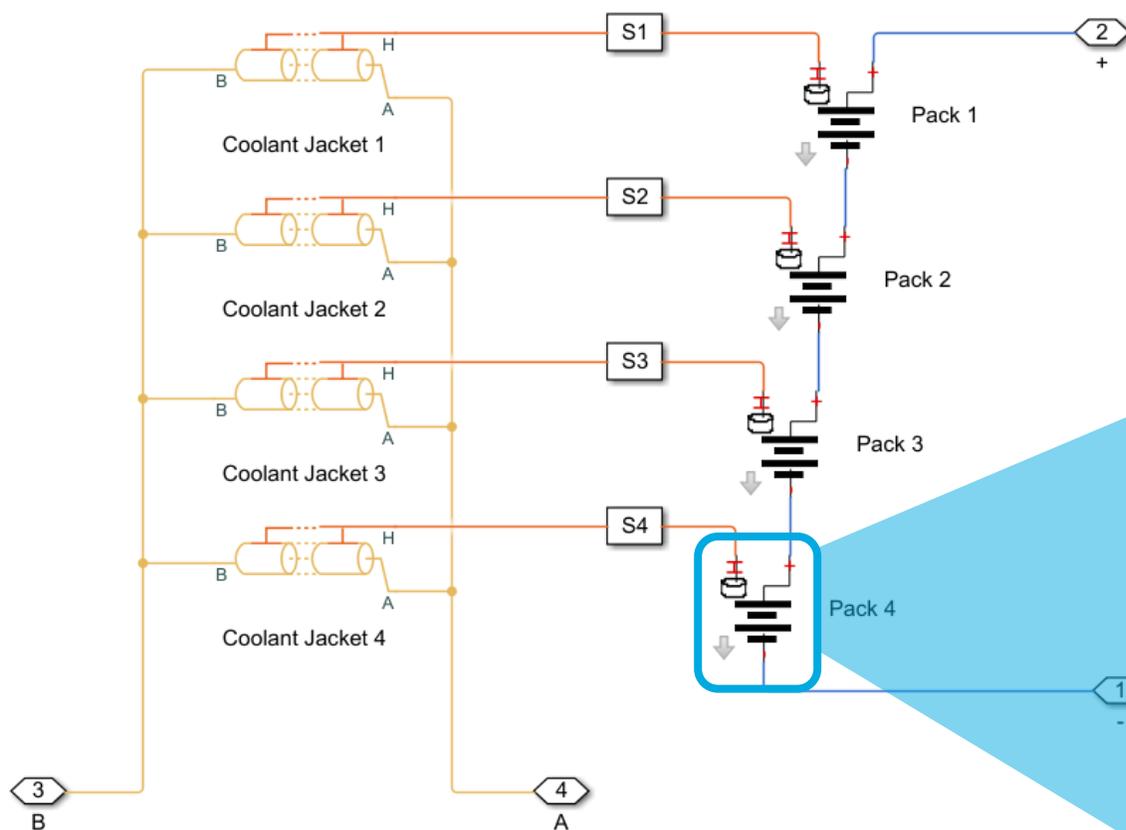
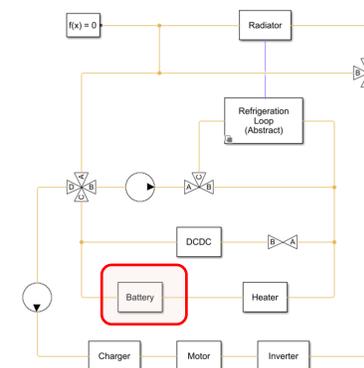
■ 电池



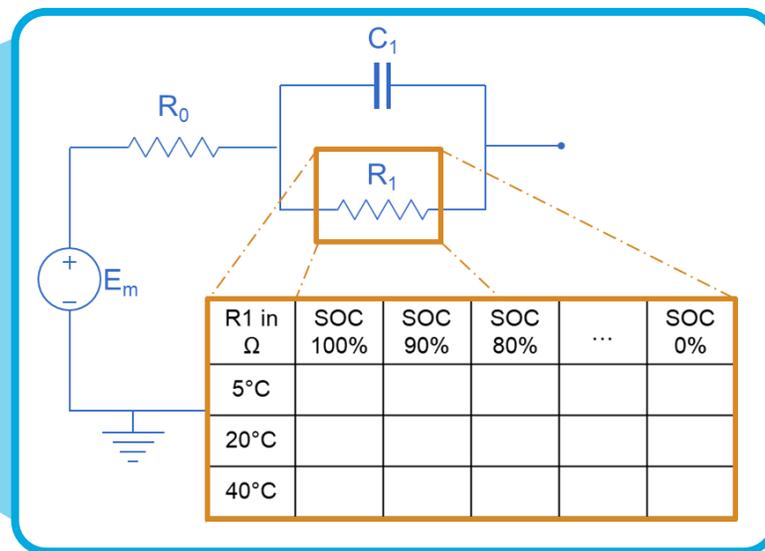
- 电流、热阻计算电池发热量

抽象、系统级和部件级建模方式

■ 电池

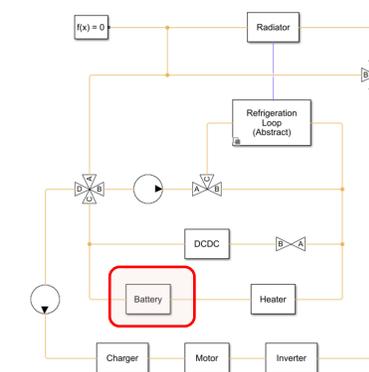
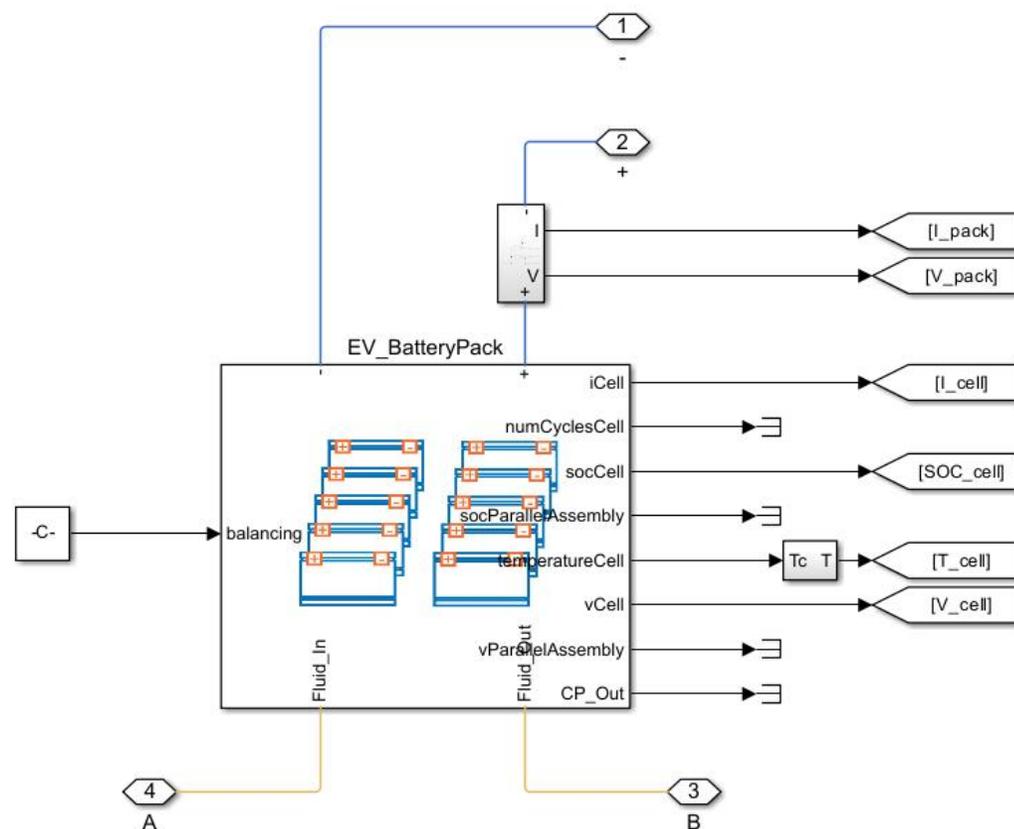


- 自定义电池模块
- 一阶动态
- $E_m, R_0, R_1, C_1(\text{SoC}, T)$



抽象、系统级和部件级建模方式

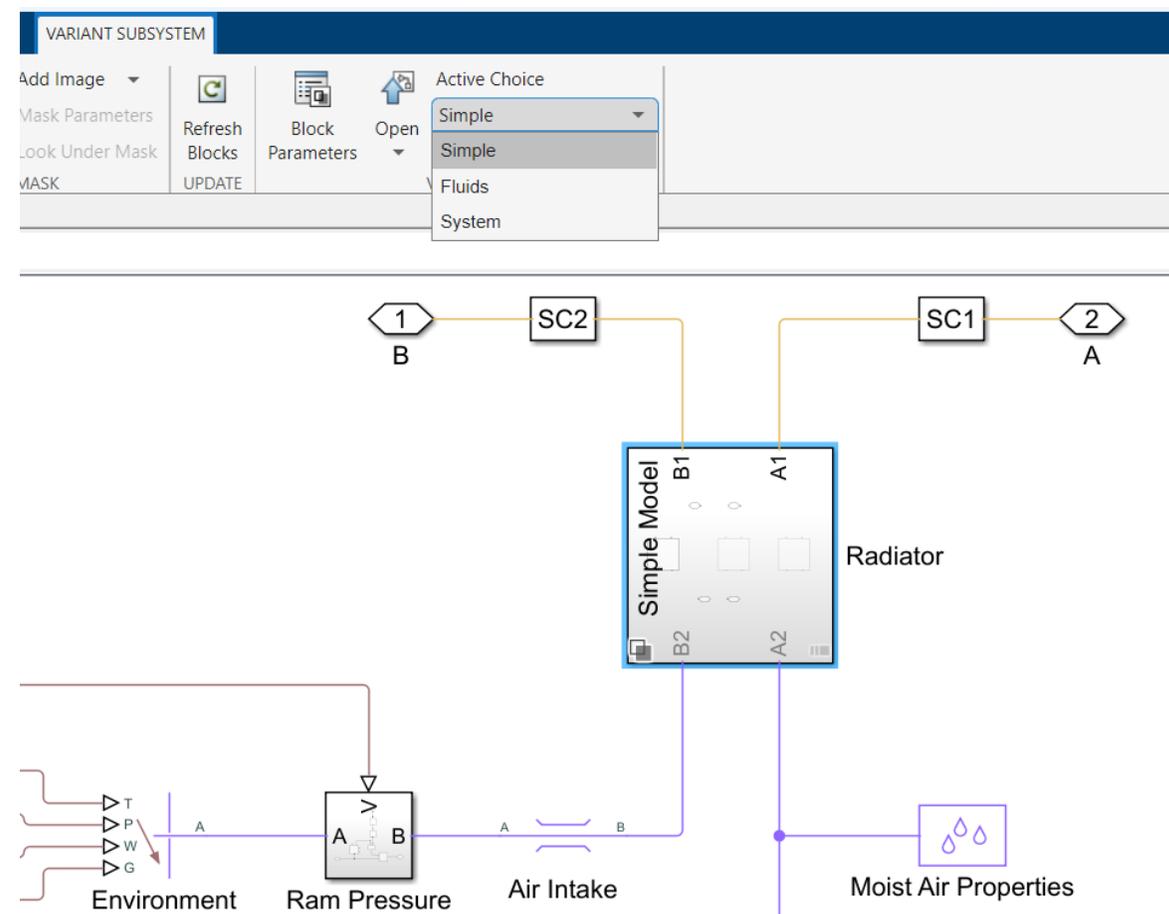
■ 电池



- 使用Simscape Battery构建详细电池包模型

使用变体管理模型颗粒度

- 可将不同颗粒度的模型置于同一模型中
- 可使用标签或变量激活变体
- 工具箱：变体管理器



MathWorks 支持基于模型以及基于学习的控制模块 设计和调整反馈补偿器

Feedback Control Systems
with MATLAB and Simulink

Explore more capabilities for designing and tuning controllers.

Traditional **Data-Driven and AI**

Controller Method

- PID CONTROL** (with **MPC DESIGNER**)
- FREQUENCY DOMAIN COMPENSATORS** (TF, ZPK, FRD, ...)
- GAIN SCHEDULING**
- LQR / LOG SYNTHESIS** (Tune gains by minimizing cost function)
- GRAPHICAL TUNING** (8006, NICHOLS, ...)
- CO-OPTIMIZATION OF PLANT AND CONTROLLER PARAMETERS**
- RESPONSE OPTIMIZER**
- MPC** (LINEAR AND NONLINEAR / ADAPTIVE / EXPLICIT)
- R-INFINITY / MU-SYNTHESIS**
- STATE FEEDBACK**
- POLE PLACEMENT** (Tune gains by choosing pole locations)
- MULTI-LOOP / MULTI-OBJECTIVE TUNING** (SYSTEMS / LOOP SHARING)
- CONTROL SYSTEM TUNER**
- PID CONTROLLER TUNING**
- PID TUNER**
- MRAC** (MODEL REFERENCE ADAPTIVE CONTROL)
- ADRC** (ACTIVE DISTURBANCE REJECTION CONTROL)
- REINFORCEMENT LEARNING**
- EXTREMUM SEEKING**
- DATA-DRIVEN MPC** (IDENTIFIED PREDICTION MODELS)
- FUZZY INFERENCE SYSTEMS** (MAMDANI AND SUGENO TYPE-1 AND TYPE-2)
- FUZZY LOGIC DESIGNER**
- REINFORCEMENT LEARNING DESIGNER**
- REINFORCEMENT LEARNING ALGORITHMS** (SAC, PPO, DQN, ...)
- CLOSED-LOOP PID AUTOTUNER**
- SYSTEM IDENTIFICATION WITH MODEL-BASED TUNING**
- FUZZY INFERENCE SYSTEM TUNING**

Tuning Algorithm

设计和仿真监控逻辑

Stateflow (subchart) of boiler/Bang-Bang Controller/turn_boiler

Bang-Bang Controller

function turn_boiler(mode)

function flash_LED()

function b = cold()

Heater

Off entry: turn_boiler(OFF)

Flash en flash_LED() → after(5,sec)

after(20,sec)

after(40,sec) [Heater:On warm!]

On

mode==ON

color==RED

color==GREEN

LED=color; boiler=mode

Active Disturbance Rejection Control (ADRC)

ADRC

PID controller

Extended State Observer

Plant

$y = f(\theta)$

Objective

Extremum seeking control

Model Reference Adaptive Control (MRAC)

Reference model $A_m = A_m s + B_m$

Plant $x = Ax + B(u + f(x))$

Disturbance model $W(f)$

Learning mechanisms to adapt K_x, K_r and W

Model Predictive Control (MPC) with System Identification

Reference

Optimizer

Prediction model

MPC Controller

Plant

Reinforcement Learning (RL)

RL agent

Observation

Action

Reward

Environment

基于 AI 和其他数据驱动的控制技术

MATLAB/Simulink对于模型预测控制MPC的支持

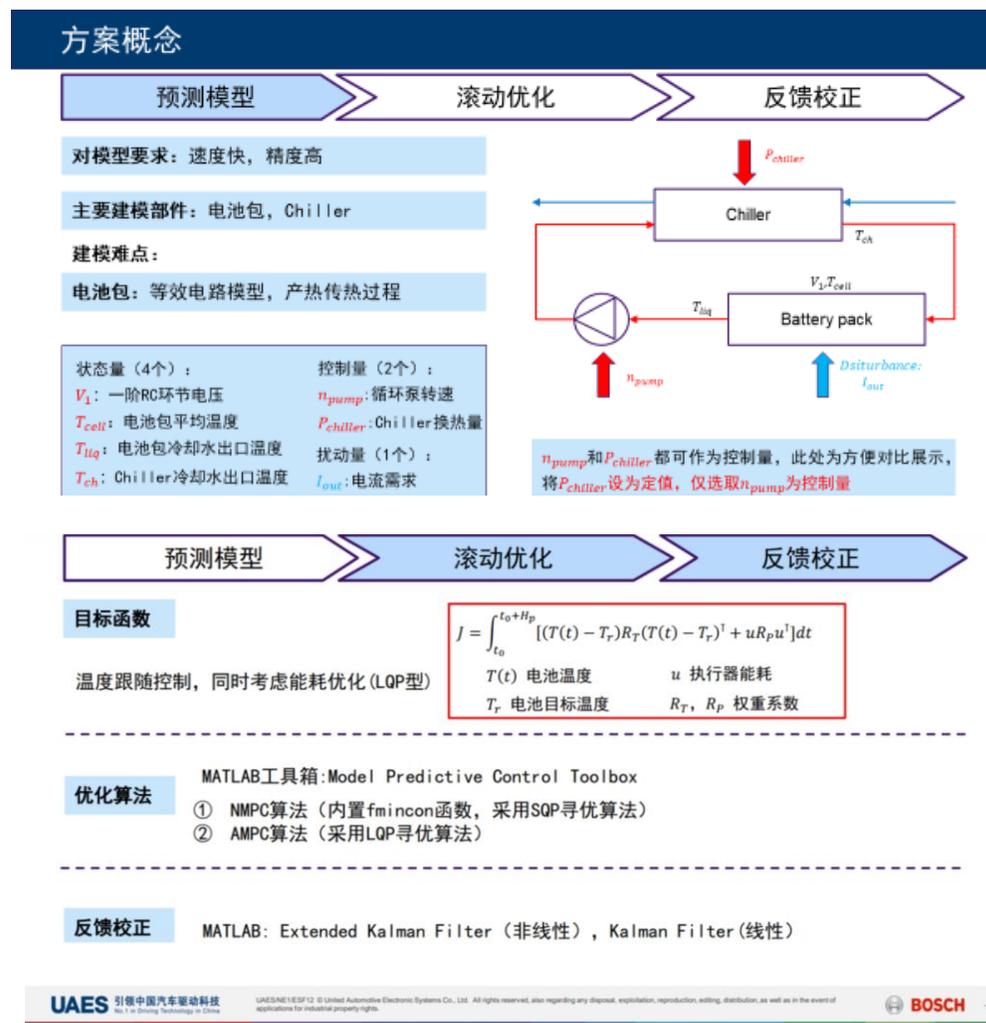
传统的控制方法在热管理中存在调节滞后以及能耗较高的问题

- 基于MATLAB工具箱开发电池热管理

MPC算法

- 生成C代码部署到硬件平台
- 基于智能网联汽车提供的预测信息

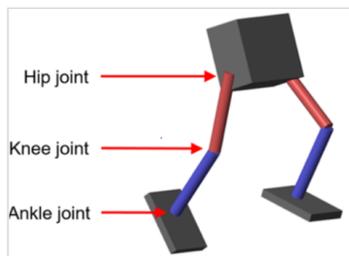
对比有无预测信息的控制效果



MathWorks对于强化学习的支持

Reinforcement Learning Toolbox* 提供

- 内置和自定义强化学习算法
- 与Simulink无缝集成
- 具有强化学习设计器的可视化交互式 workflows
- 将经过训练的策略部署到嵌入式系统
- 强化学习的入门参考示例



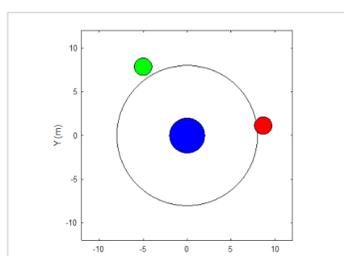
Train Biped Robot to Walk Using Reinforcement Learning Agents

Train a reinforcement learning agent to control a biped walking robot modeled in Simscape Multibody.



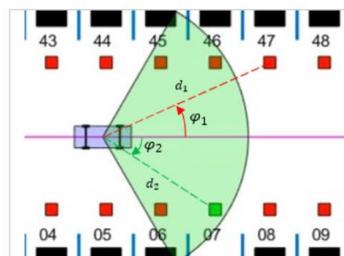
Automatic Parking Valet with Unreal Engine Simulation

Use a reinforcement learning agent with an MPC controller to perform a parking maneuver.



Train Multiple Agents to Perform Collaborative Task

Train two PPO agents to collaboratively move an object.

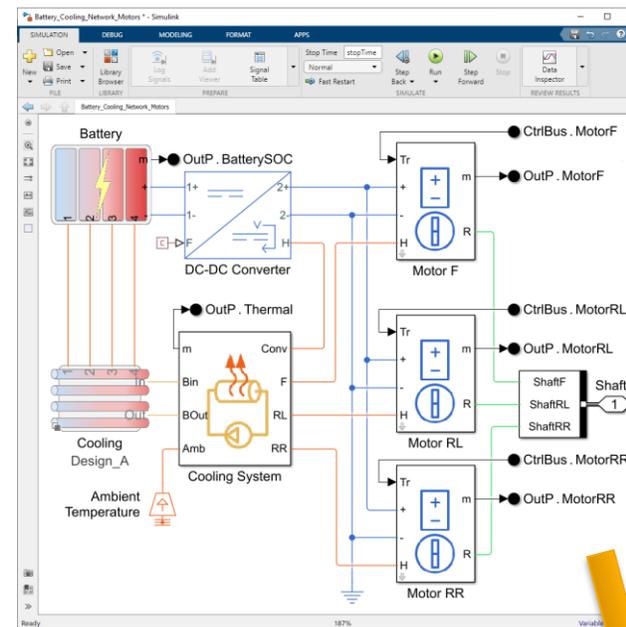


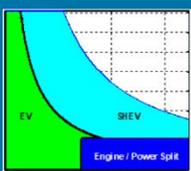
Train PPO Agent for Automatic Parking Valet

Train a reinforcement learning agent to park a car in an open parking space.

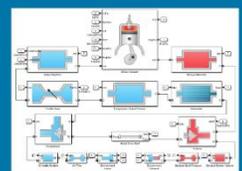
整车热管理系统

- 可与**Powertrain Blockset**（纵向动力学）和**Vehicle Dynamics Blockset**（横向动力学）集成
- 利用整车热管理模型可
 - 评估燃油经济性和动力性
 - 设计控制算法
 - 硬件部署





Design Exploration



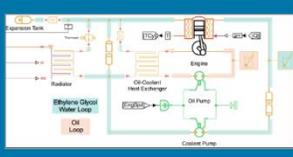
Engine Calibration



Motor Calibration



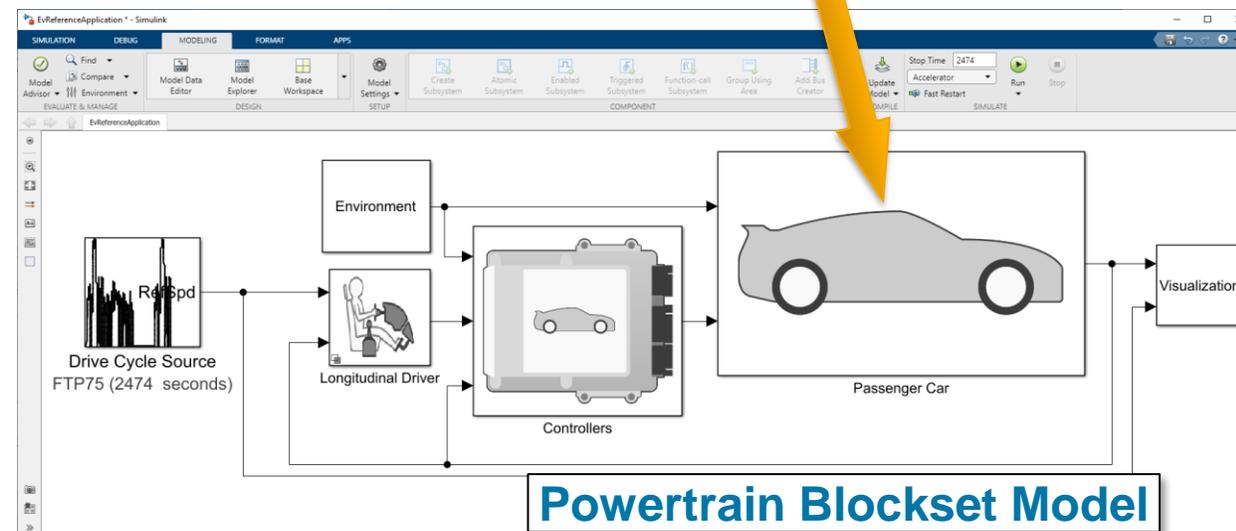
Hardware-in-the-Loop Testing



Energy & Thermal Analysis



Virtual Vehicle Composer app



Powertrain Blockset Model

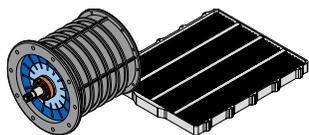
整车热管理系统优化

车型



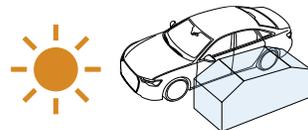
- 中型轿车
- 一名乘员（驾驶员）

驱动



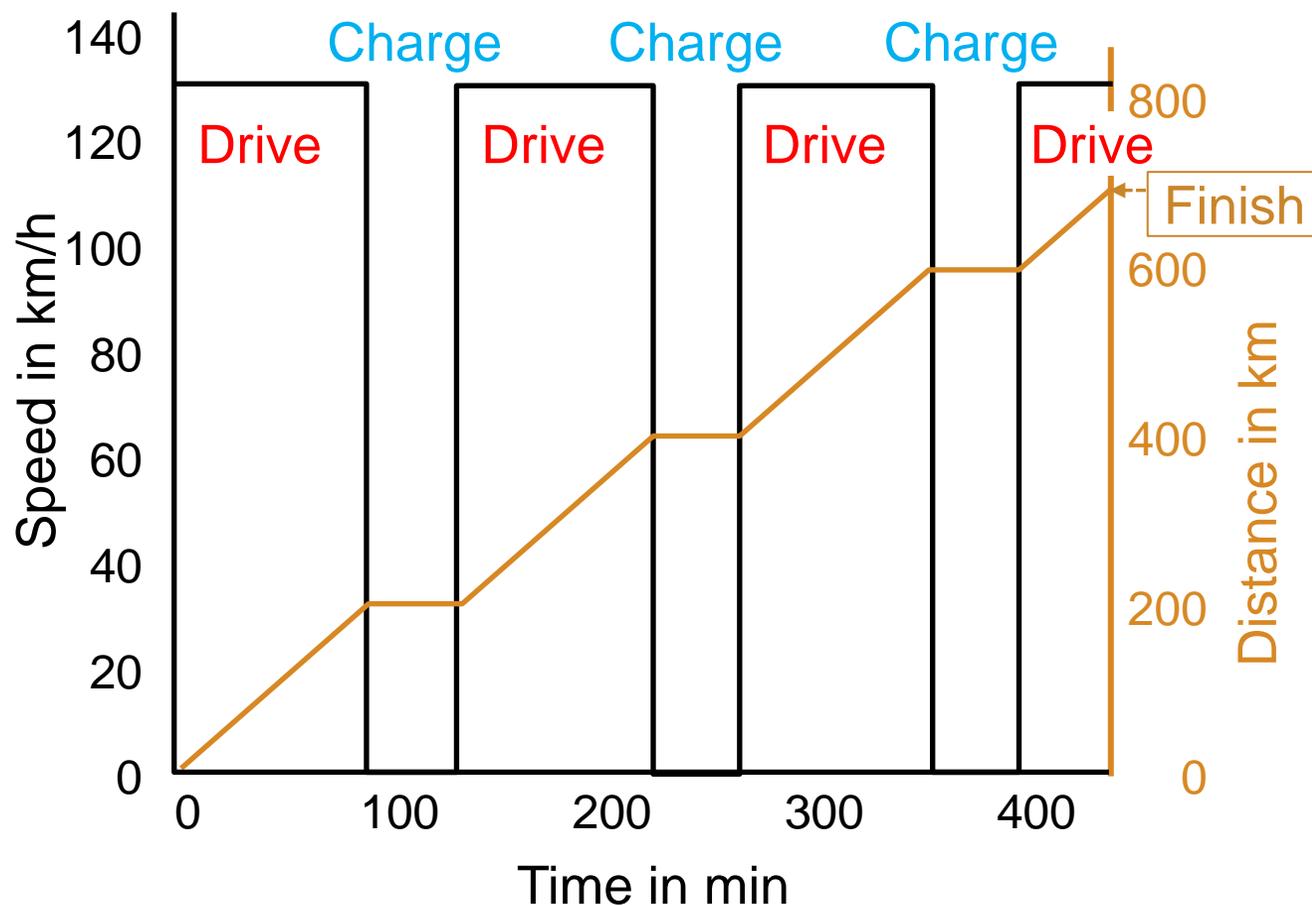
- 后驱
- 电池初始SOC = 90%

座舱和环境

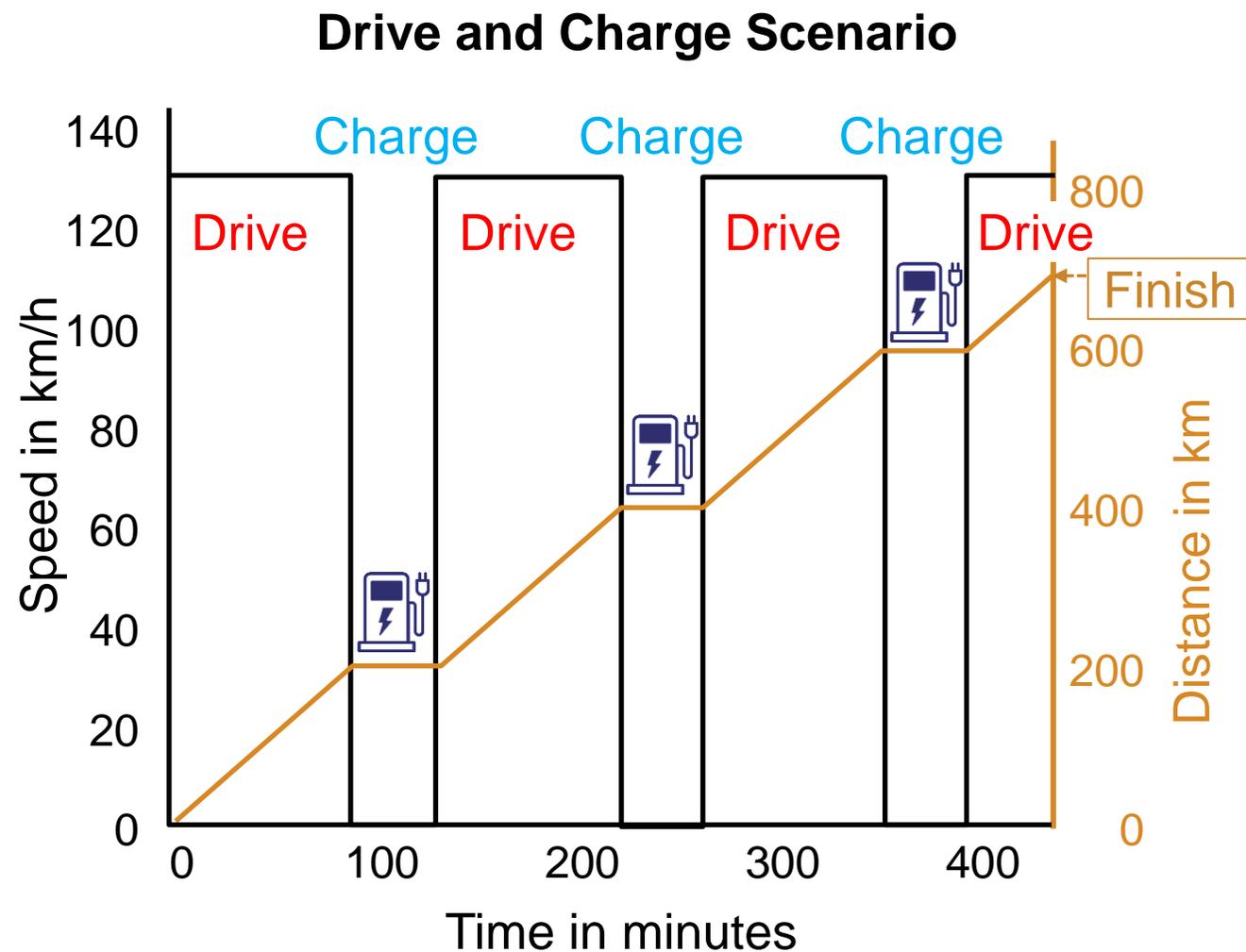
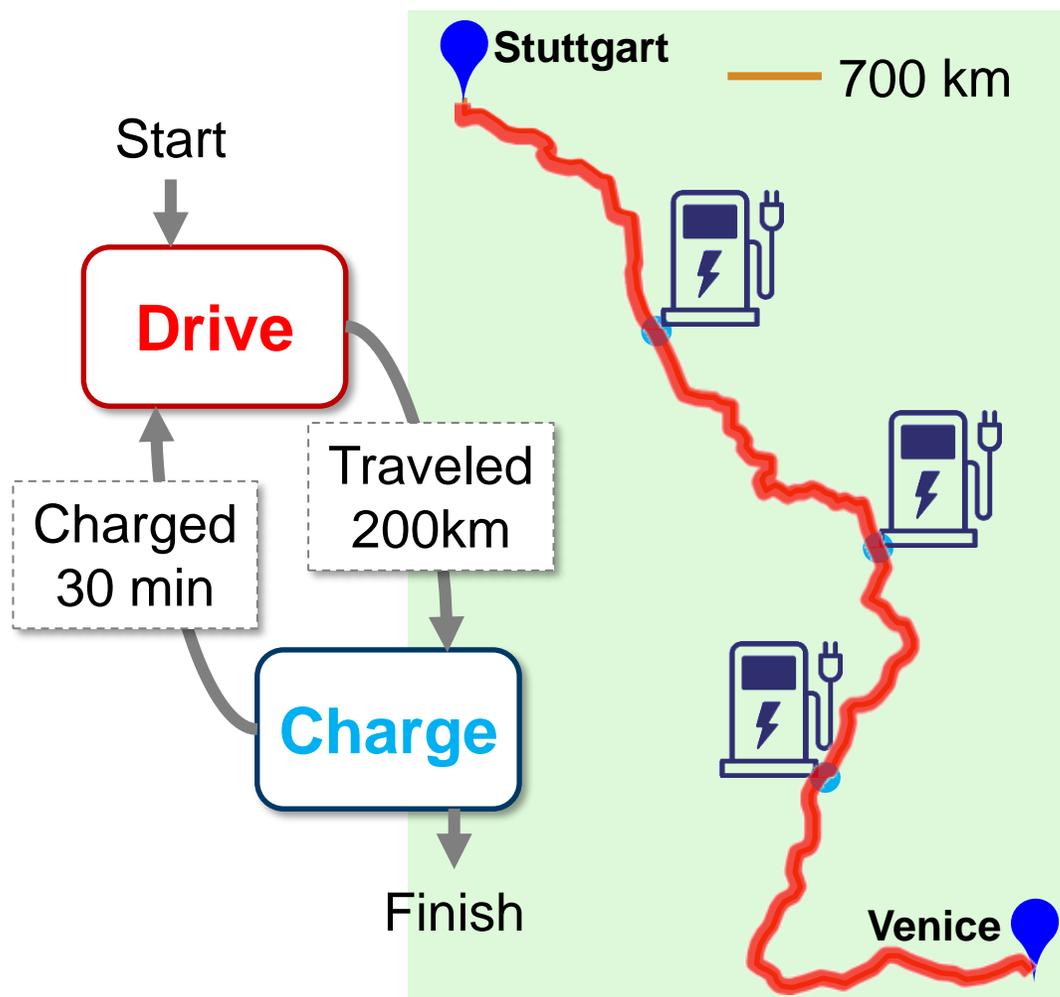


- 夏季工况, $T_{Env} = 40^{\circ}\text{C}$
- 目标座舱温度, $T_{Cab} = 22^{\circ}\text{C}$

Drive and Charge Scenario

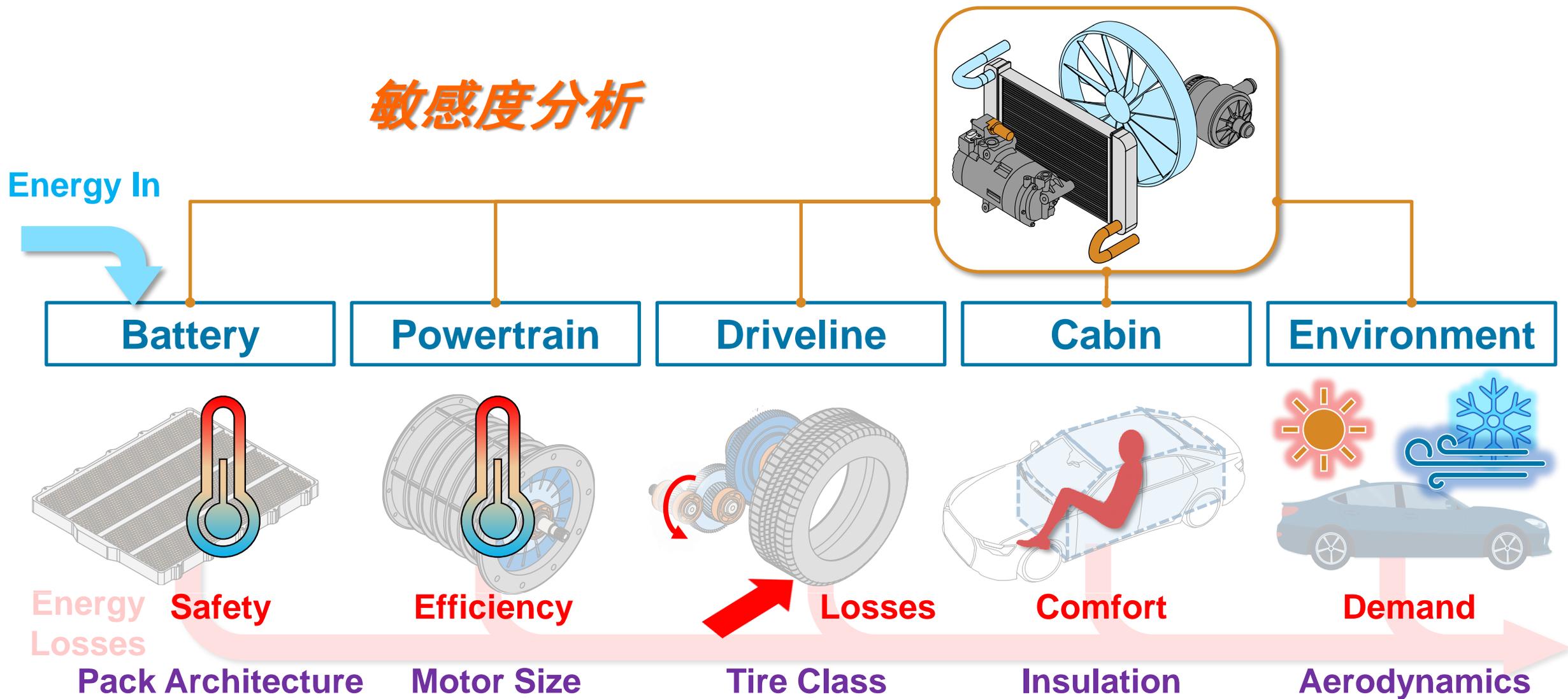


整车热管理系统优化



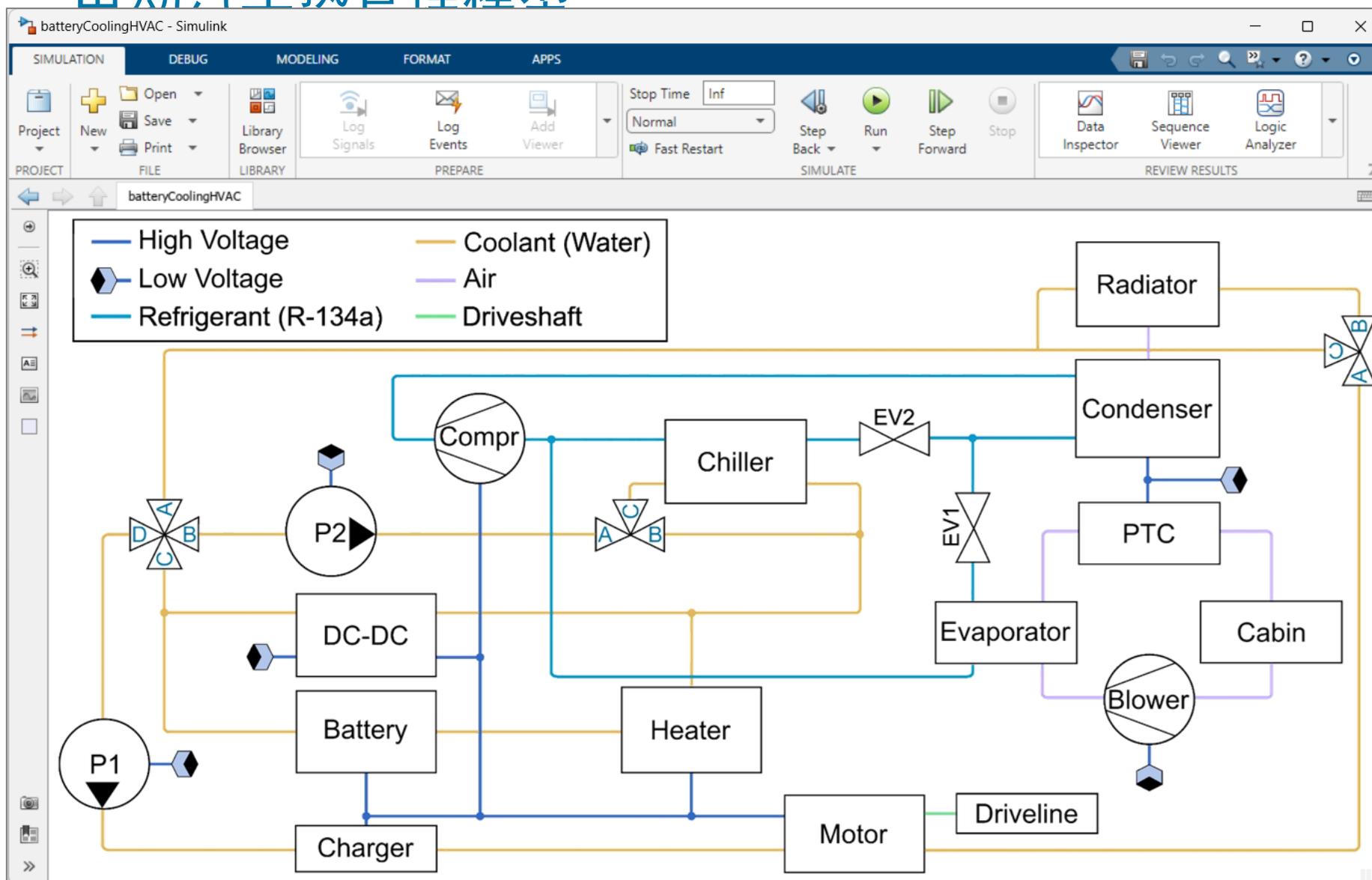
汽车中几乎每个子系统都会影响热管理性能

敏感度分析



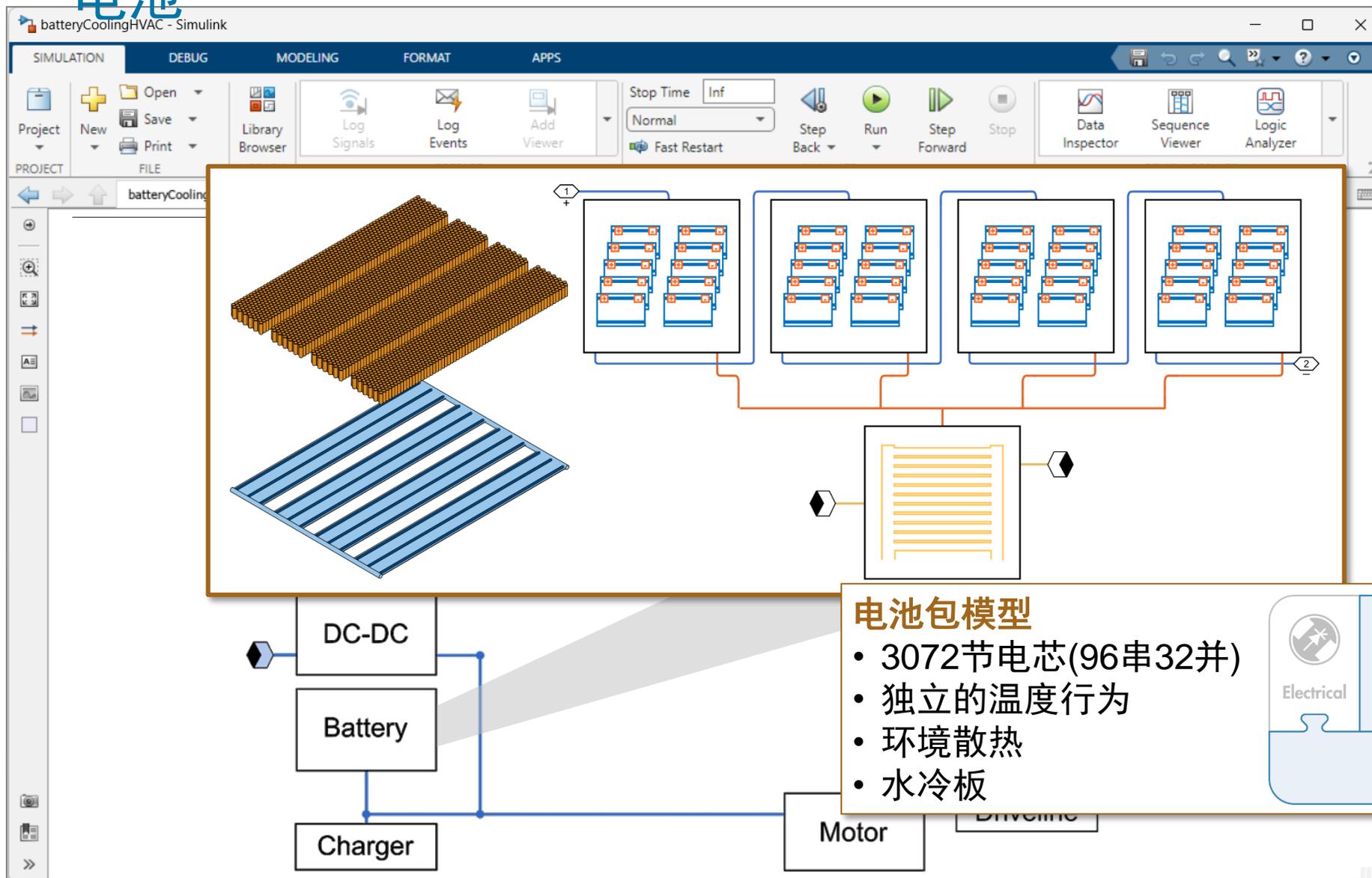
电动汽车热管理模型

Available at: <https://github.com/simscape/EV-Thermal-Management-Simscape-ELIV-2023>

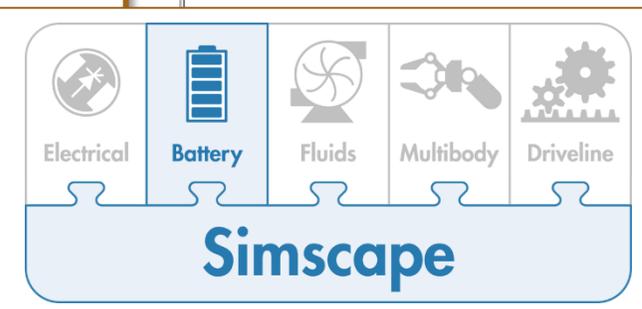


- 电池
- 充电器
- 电驱
- 传动
- 座舱空调
- 制冷回路
- 电机水路
- 电池水路
- 驾驶员控制策略

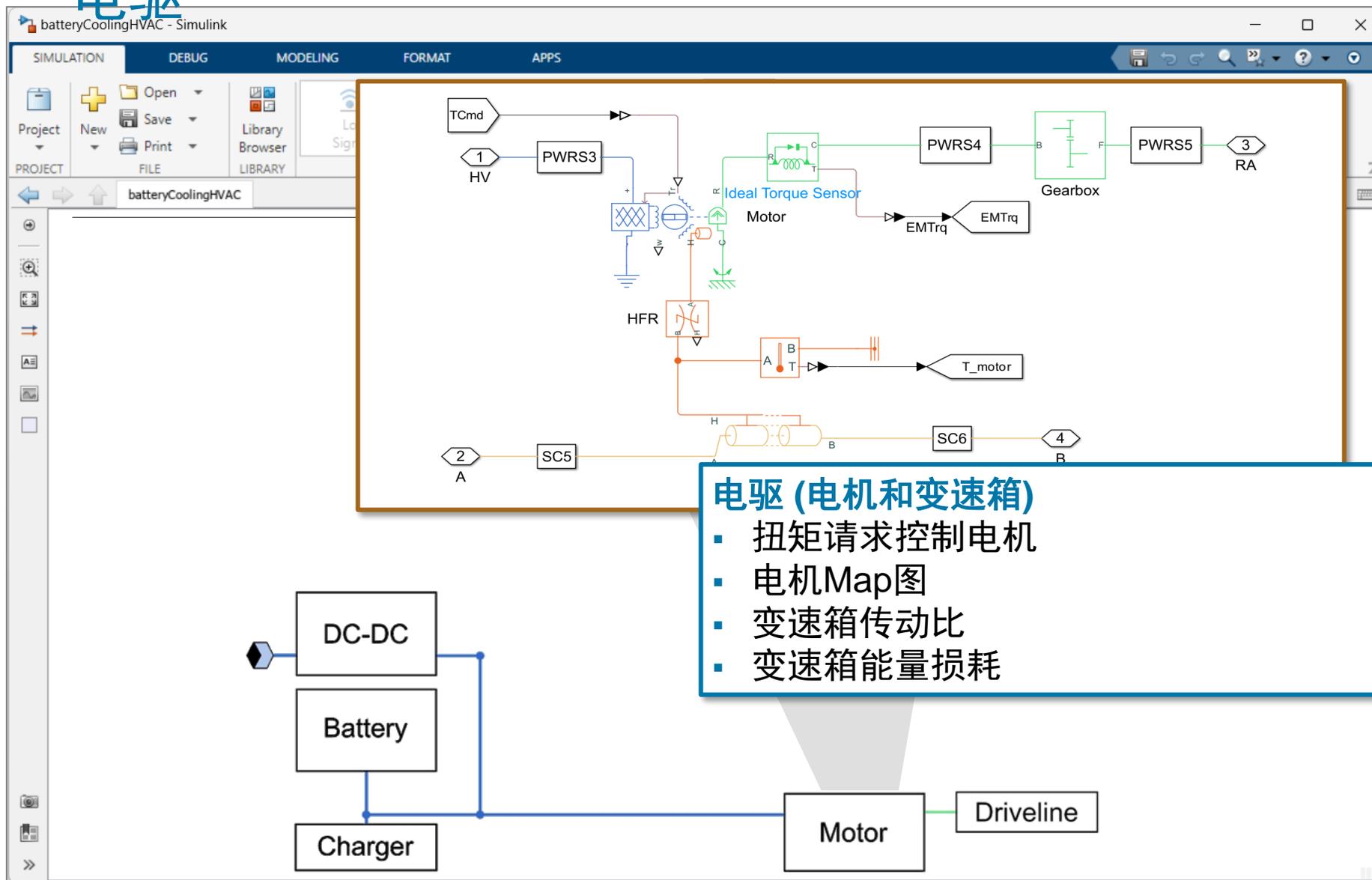
电池



- 电池
- 充电器
- 电驱
- 传动
- 座舱空调
- 制冷回路
- 电机水路
- 电池水路
- 驾驶员控制策略



电驱

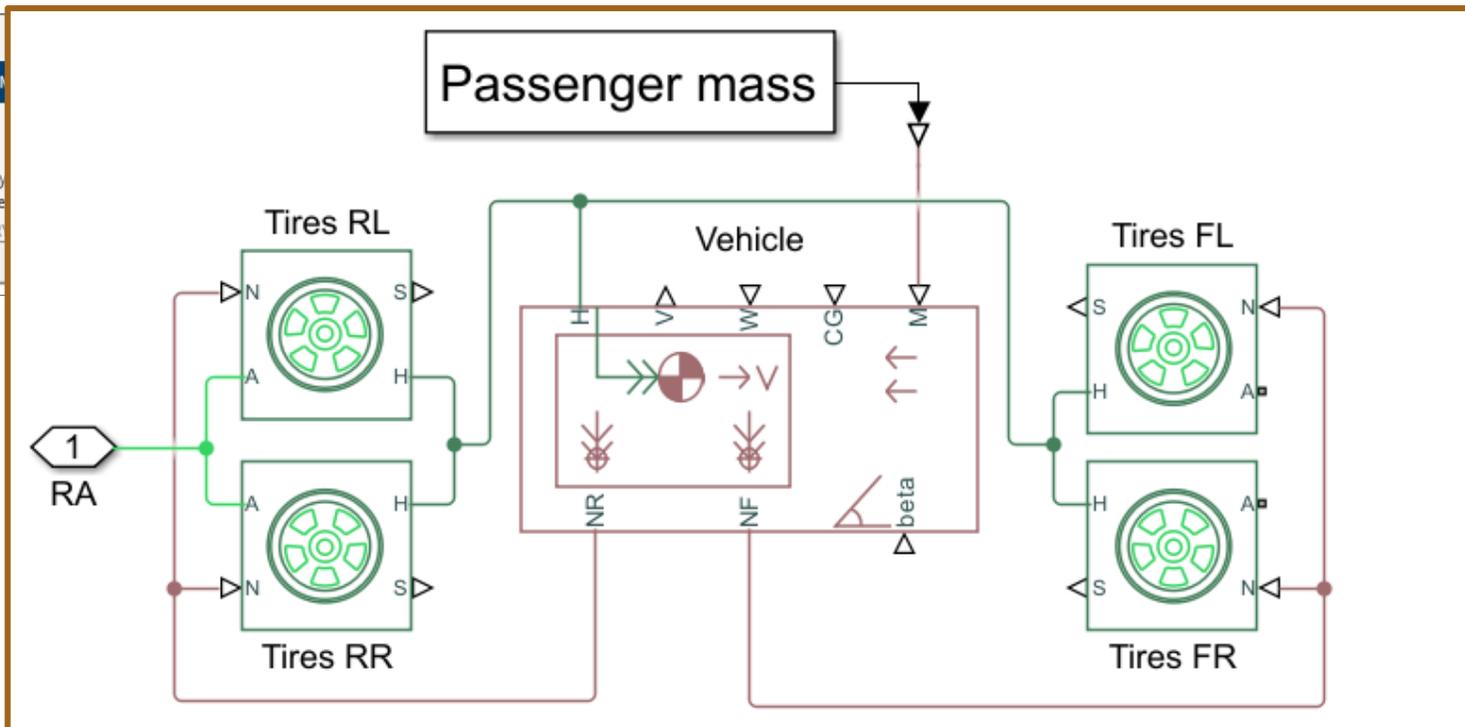
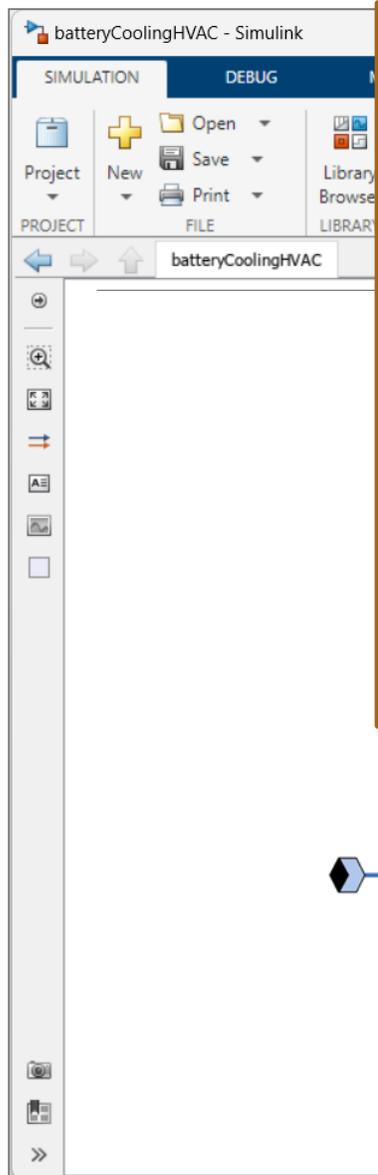


电驱 (电机和变速箱)

- 扭矩请求控制电机
- 电机Map图
- 变速箱传动比
- 变速箱能量损耗

- 电池
- 充电器
- **电驱**
- 传动
- 座舱空调
- 制冷回路
- 电机水路
- 电池水路
- 驾驶员控制策略

传动

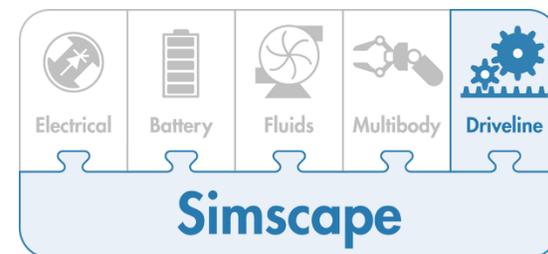


- 电池
- 充电器
- 电驱
- **传动**
- 座舱空调
- 制冷回路
- 电机水路
- 电池水路
- 驾驶员控制策略

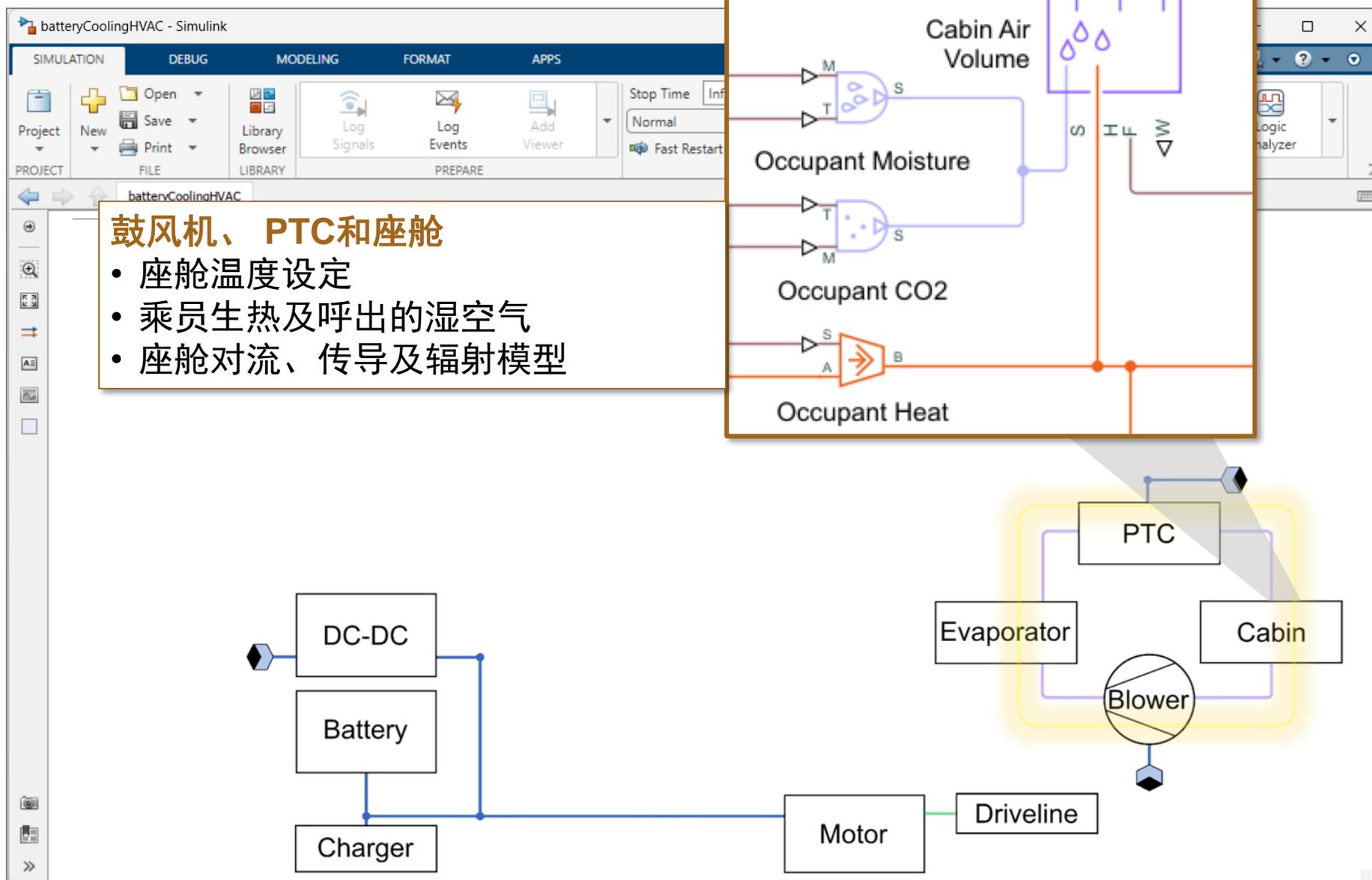


底盘和轮胎

- 空气阻力
- 滚动阻力



座舱空调

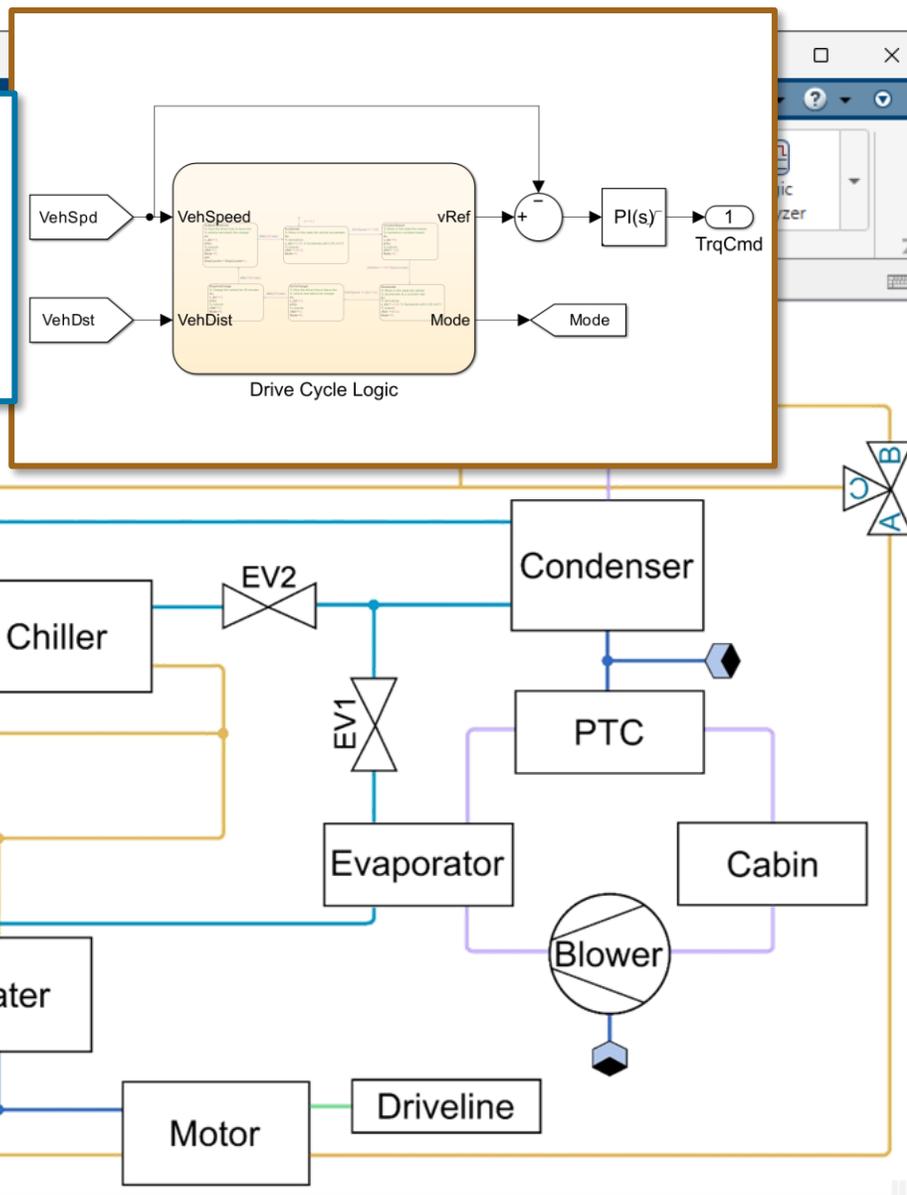


- 电池
- 充电器
- 电驱
- 传动
- **座舱空调**
- 制冷回路
- 电机水路
- 电池水路
- 驾驶员控制策略

驾驶员控制策略

驾驶员

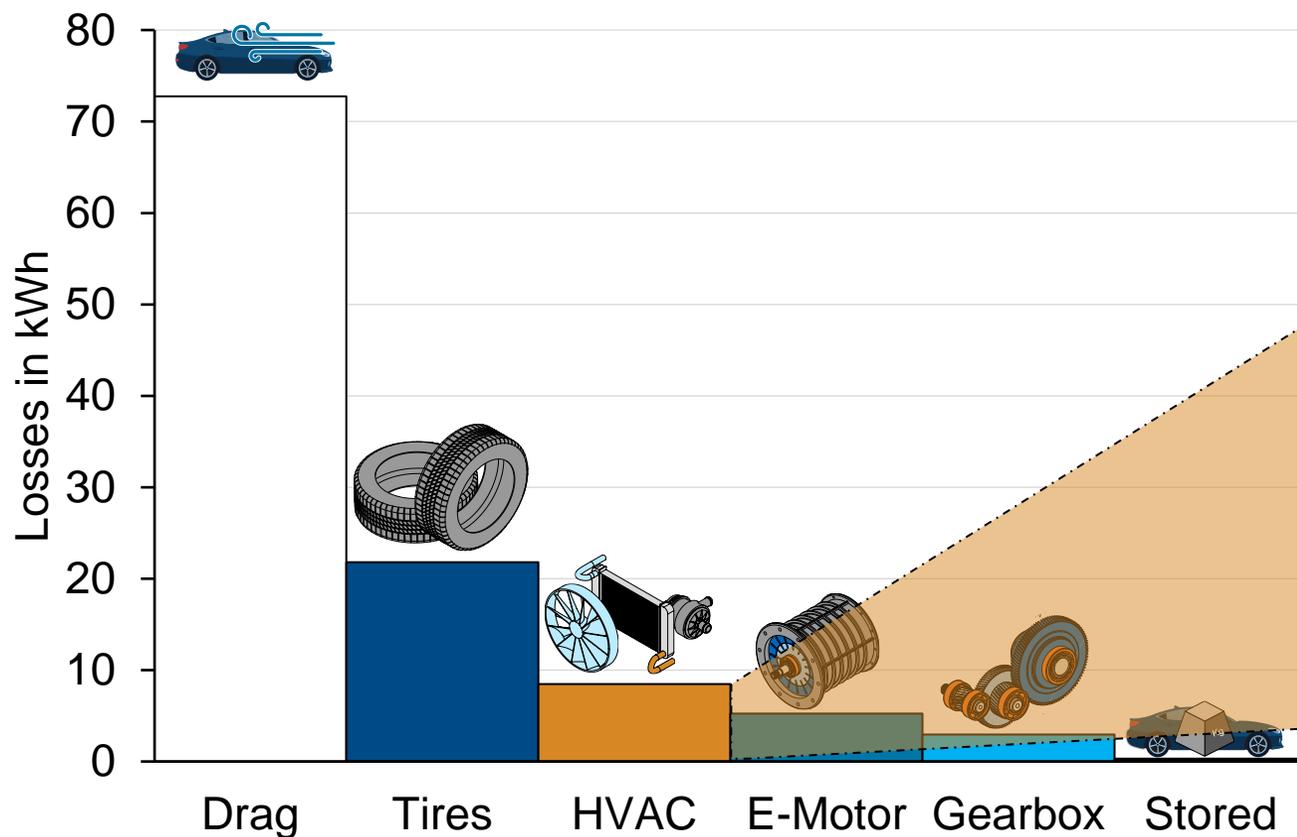
- 计算速度指令
- 6种状态模式
- 根据速度和行驶距离进行模式切换
- PI控制器将速度指令转换为扭矩指令



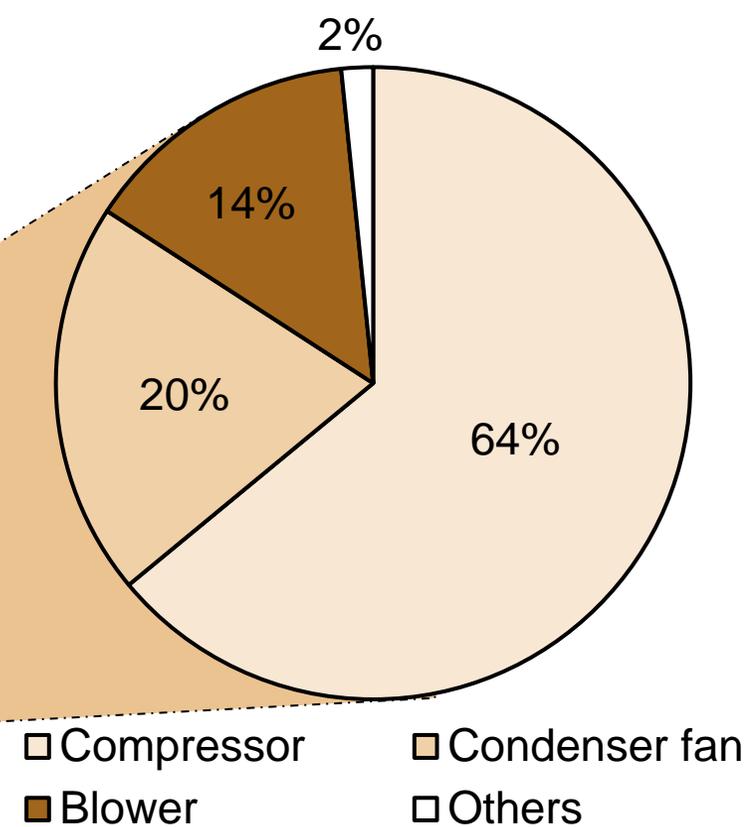
- 电池
- 充电器
- 电驱
- 传动
- 座舱空调
- 制冷回路
- 电机水路
- 电池水路
- 驾驶员控制策略

分析各子系统的能量损耗

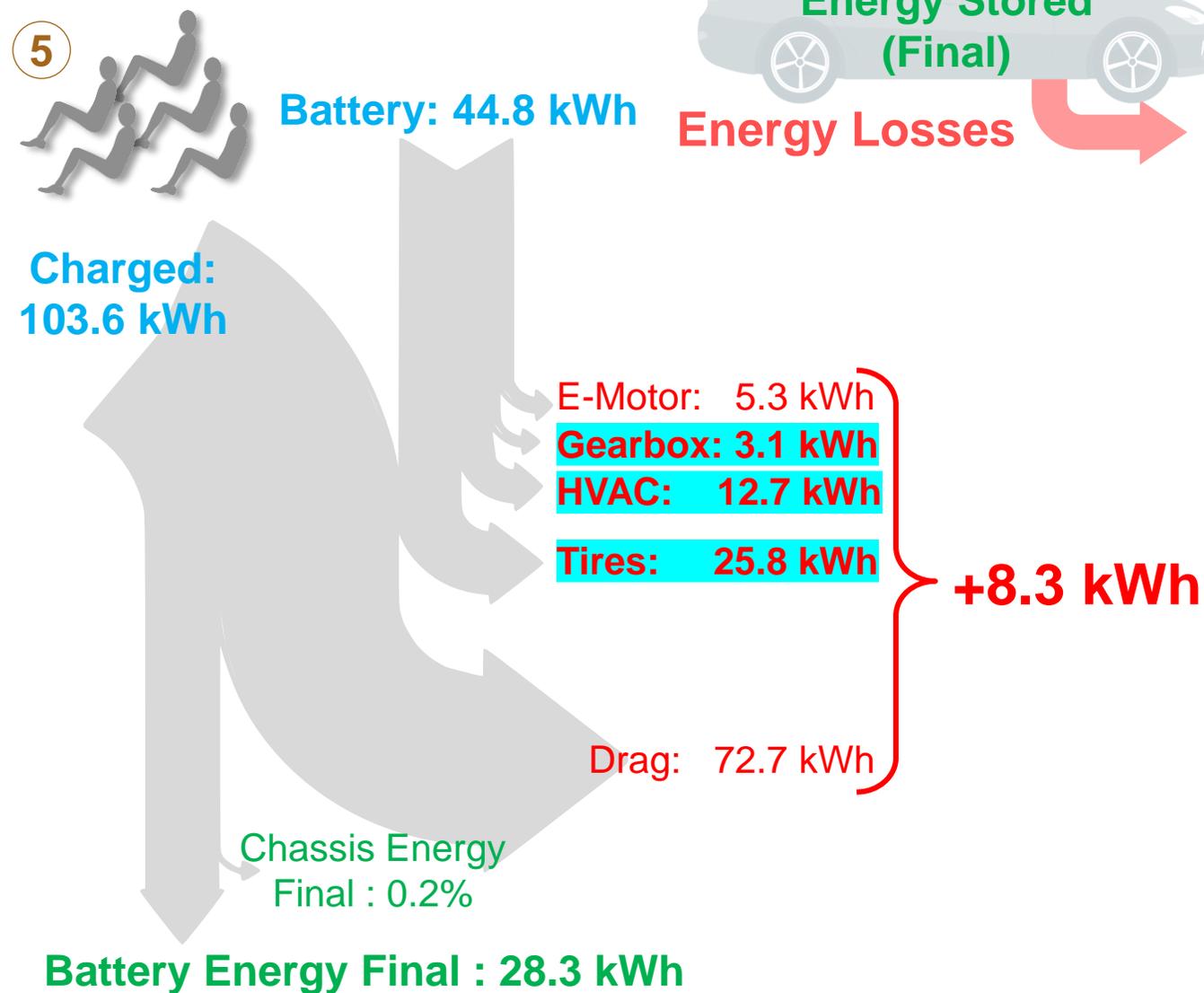
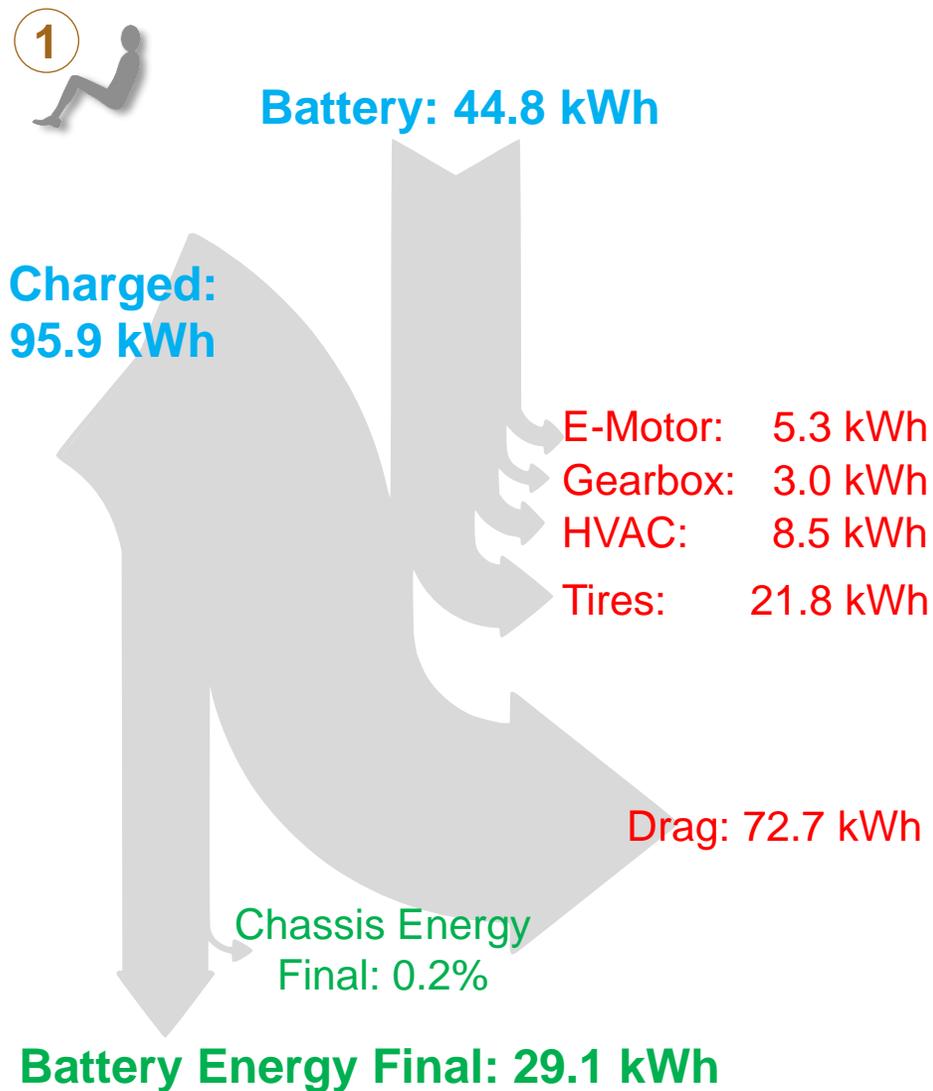
能量分布



HVAC Losses in %

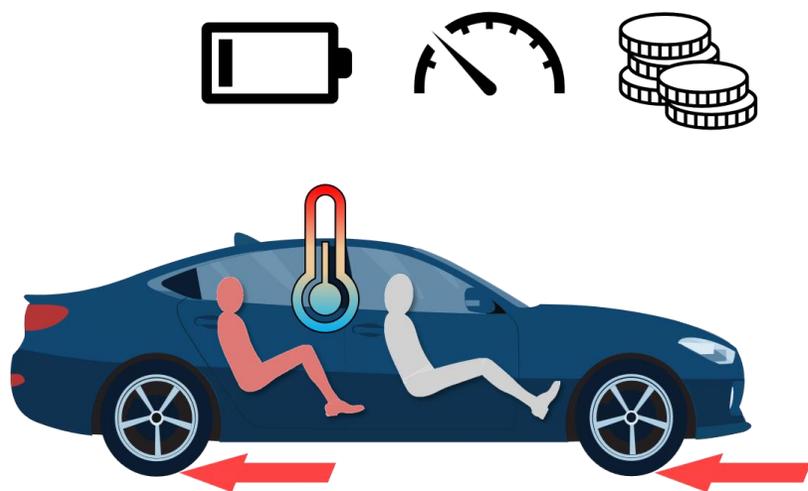


能量流: 1名乘员 VS 5名乘员

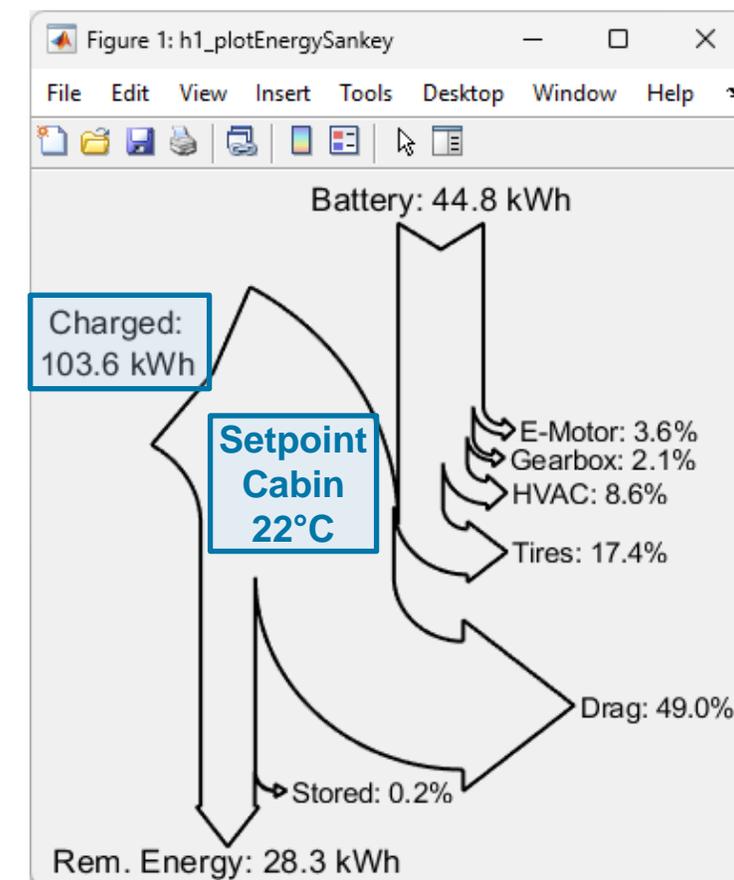
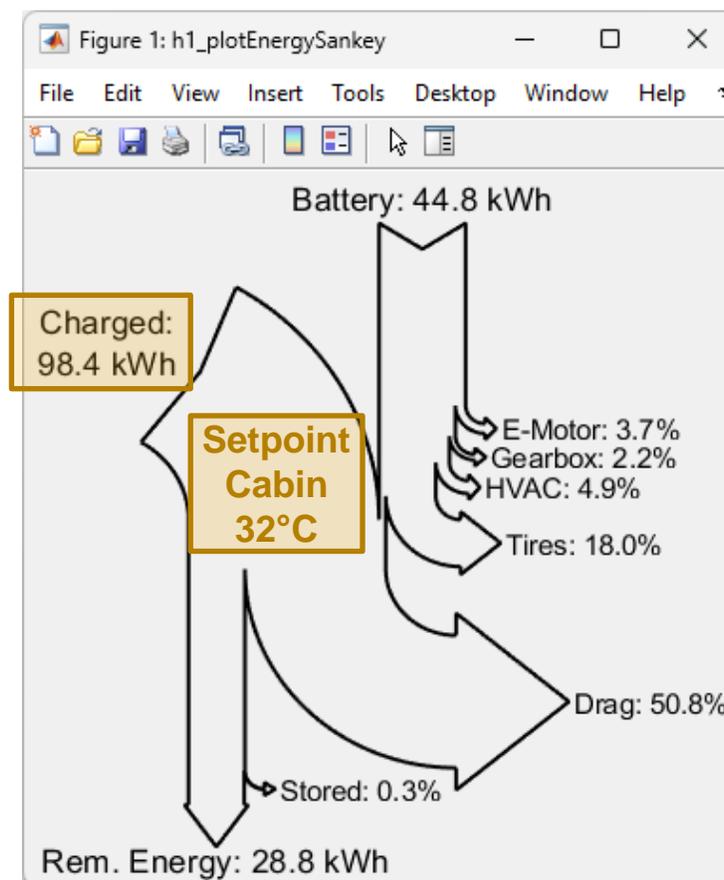


敏感度分析

- 模型参数化的便于开展更多的敏感性分析



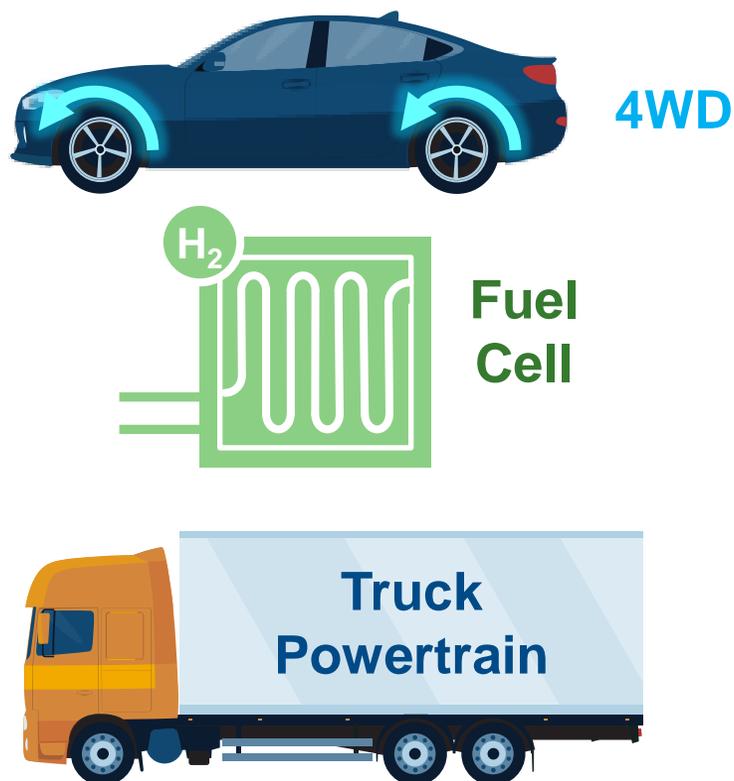
其他参数研究: 座舱设定温度



模型拓扑

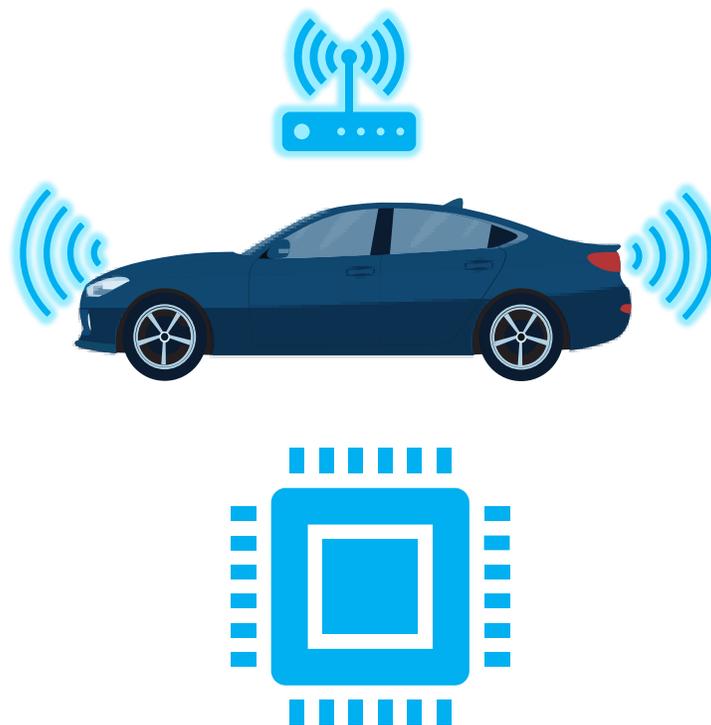
参数化整车热管理模型

- 探索不同车型的热管理性能



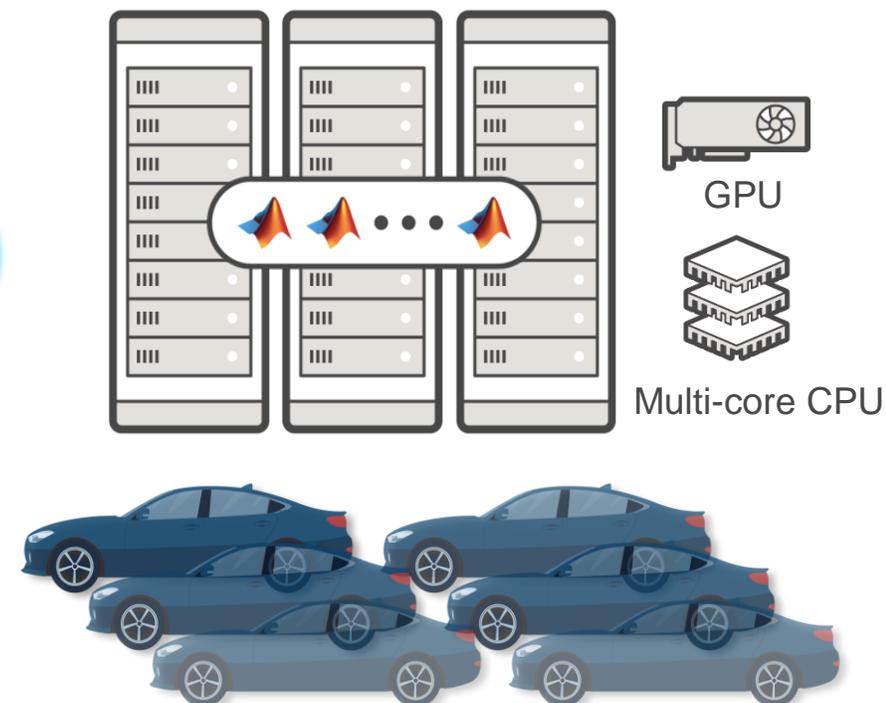
优化硬件和算法

- 硬件选型匹配车辆控制算法



加速设计迭代

- 并行计算&云部署

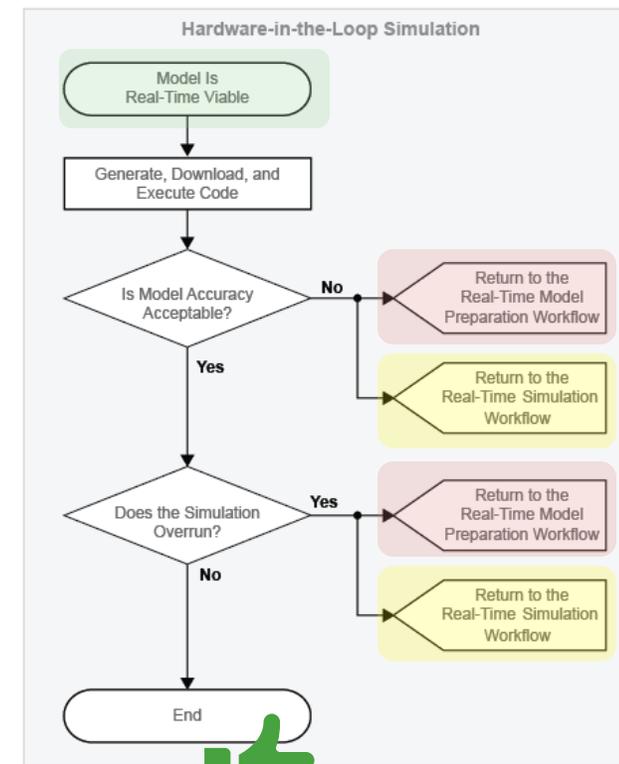
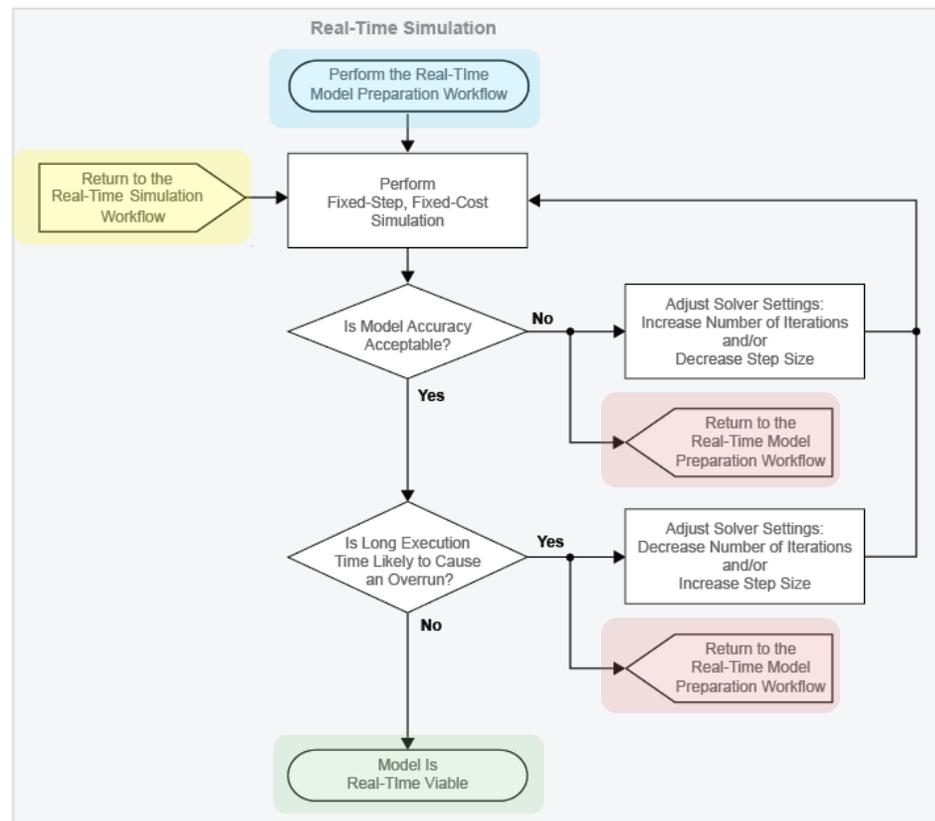
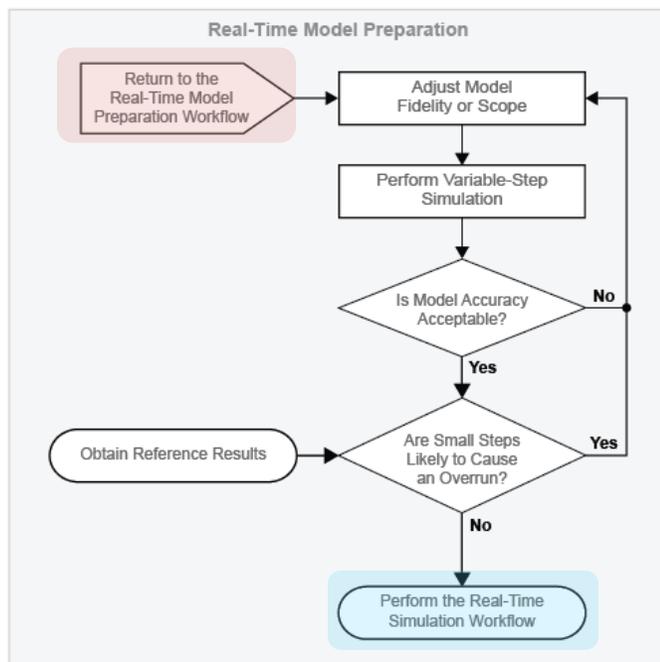
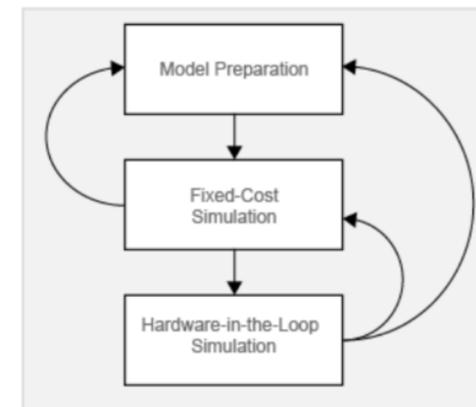


持续集成测试及数据驱动降阶技术加速热管理开发

硬件在环测试

实时仿真 - MATLAB & Simulink - MathWorks 中国

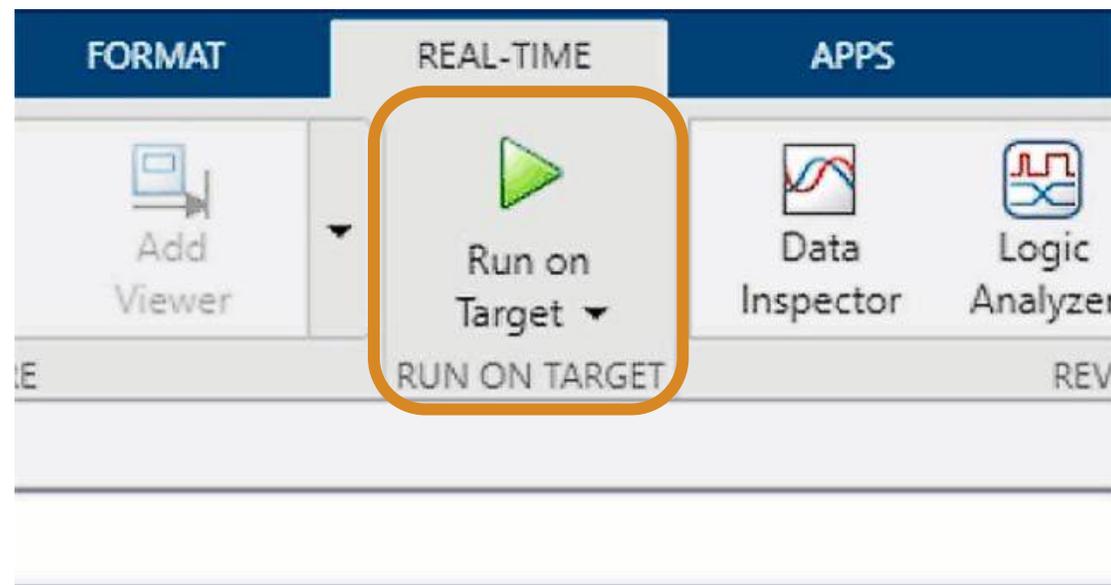
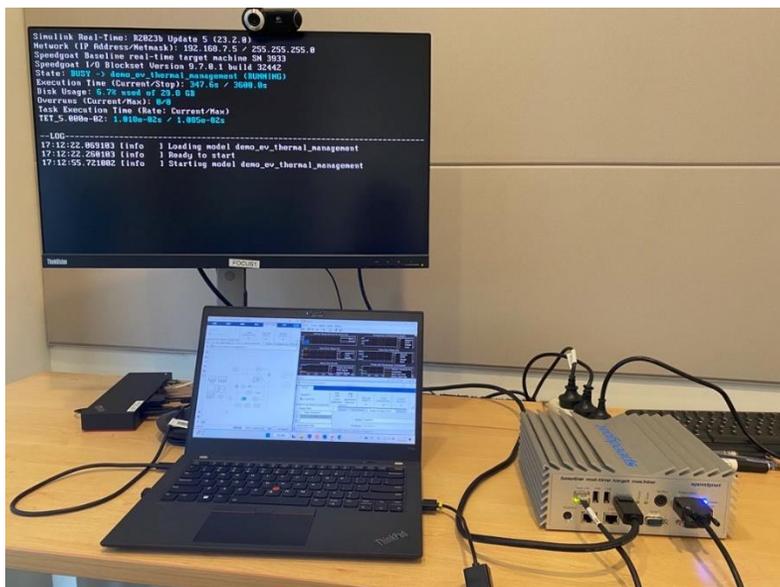
- 需要调整模型颗粒度
- workflow如下:



Solver Profiler
Local Solver Settings

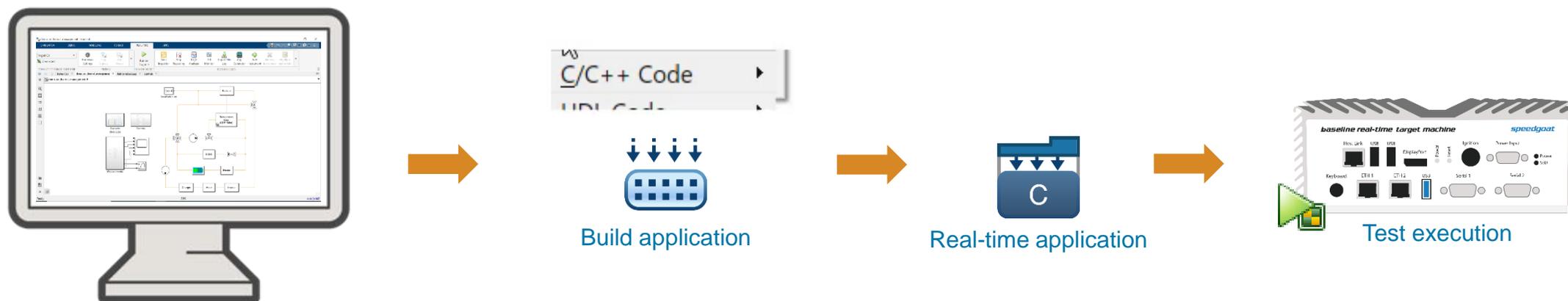


硬件在环仿真 workflow



构建实时应用程序

- 从桌面仿真一键进入实时测试，无需离开 MATLAB 和 Simulink
- 配置模型，编译、运行实时应用程序并与之交互



Neural State-Space Model

Starting R2022b

- 使用神经网络来表示状态空间模型中状态的导数
 - 用于复杂非线性系统
 - 动态/瞬态模型
 - 脚本化模型训练 ([tutorial](#))
- 项目应用
 - 燃料电池系统(6输入, 2输出)
 - 热交换器 (4输入, 1输出)
 - 制冷循环 (5输入, 2输出)
 - 输入: % 负载, 冷却水温度& 流量, 空气温度&流量
 - 输出: 制冷量, 压缩机功耗
 - 使用Simscape仿真数据进行训练

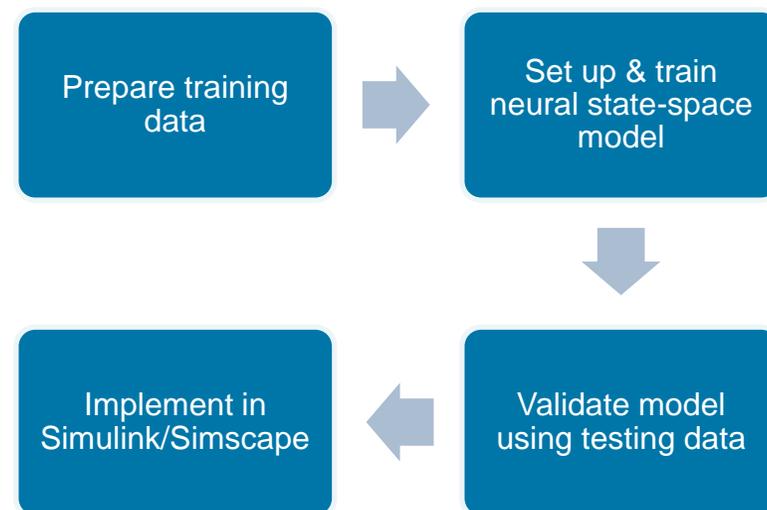
Neural State-Space Models

Neural state-space models are a type of nonlinear state-space models

$$\dot{x}(t) = F(x(t), u(t))$$

$$y(t) = H(x(t), u(t))$$

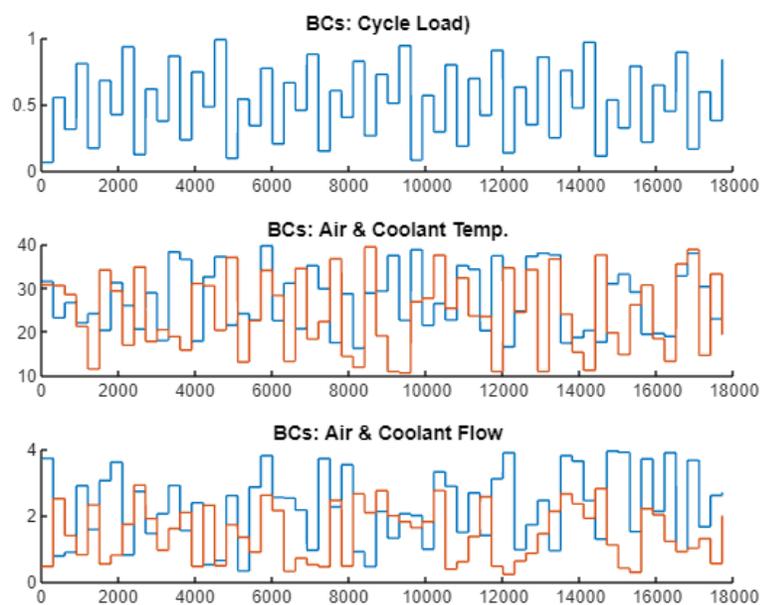
where F and H are implemented using neural networks.



Neural State-Space Model

制冷循环

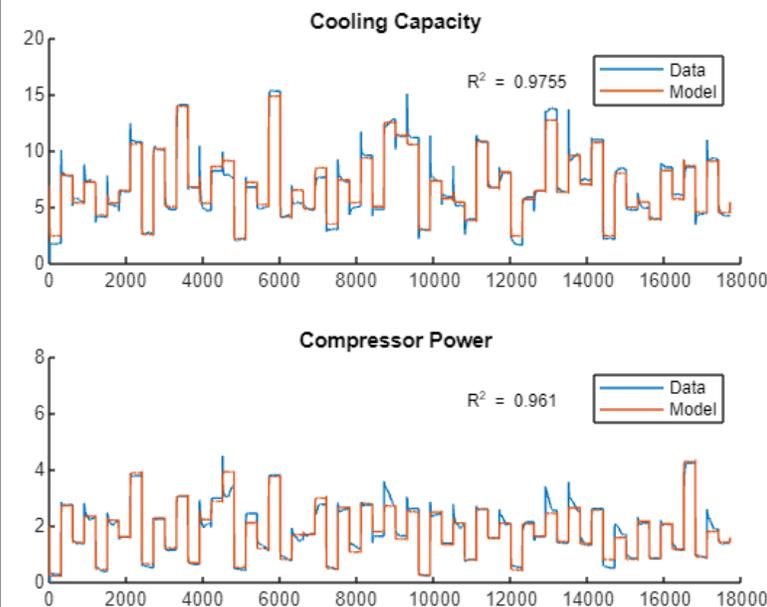
- 训练集：150个随机生成的条件序列
- 测试集：60个随机生成的条件序列



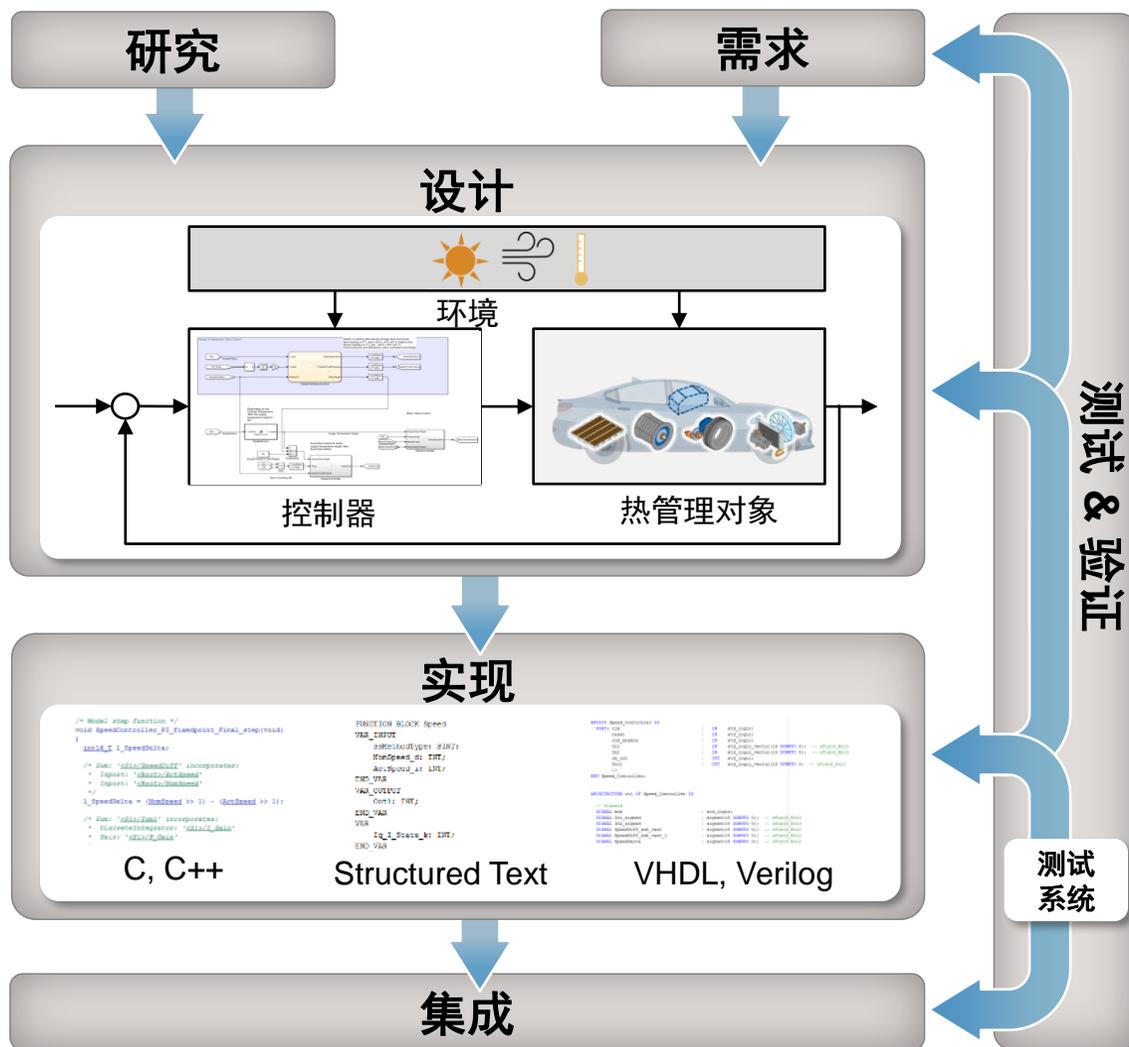
Inputs

Test Set

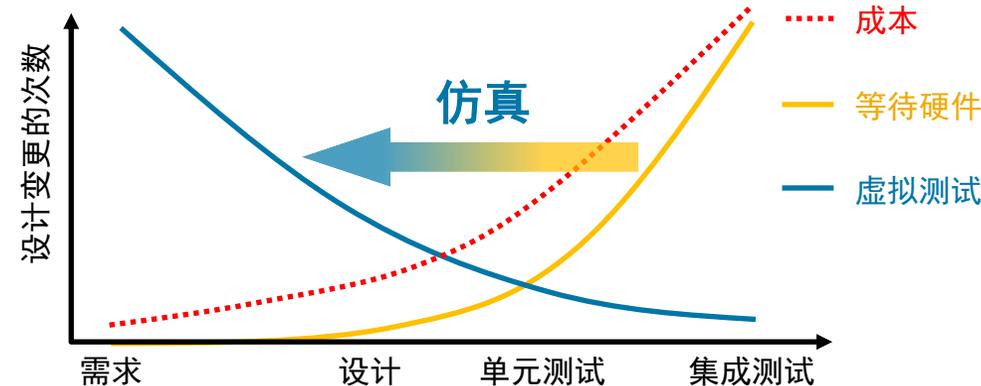
Outputs



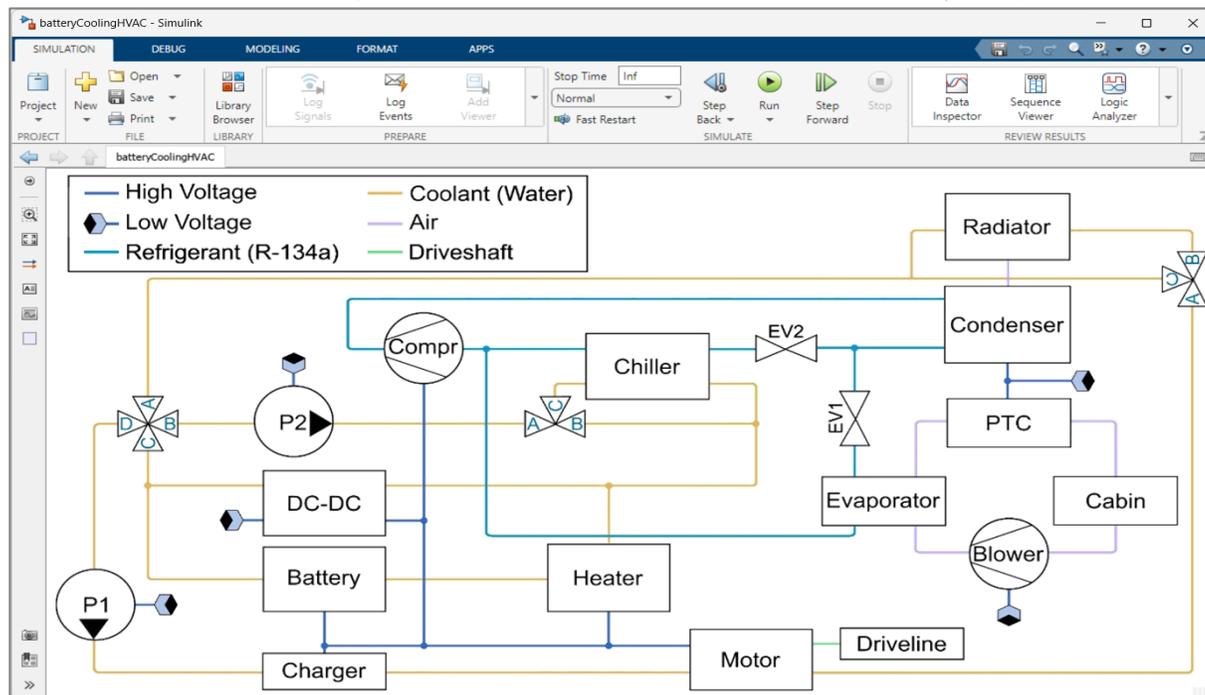
总结



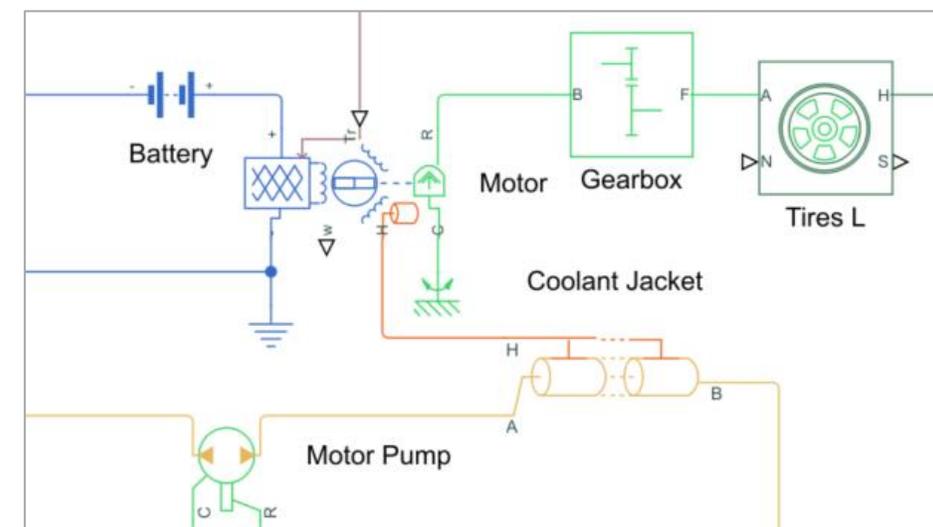
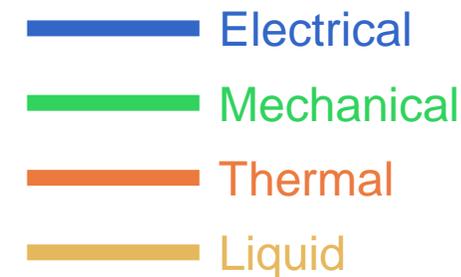
- 细化设计需求
 - 从需求出发，基于模型同步需求
 - 可通过系统模型权衡系统性能
 - 避免昂贵的样件迭代设计
- 虚拟测试
 - 可替代部分台架或路试，从而减少试验成本和缩短开发周期
 - 更早发现设计中的问题,降低后期设计变更的成本



案例：电动汽车的热管理系统模型



多域
示意图
(Simscape)



- 多域整车模型
- 与控制策略集成

更多详情: <https://github.com/simscape/EV-Thermal-Management-Simscape-ELIV-2023>

控制
逻辑
(Simulink)

