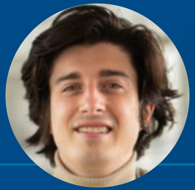
Optimizing a Battery Electric Vehicle Thermal Management System

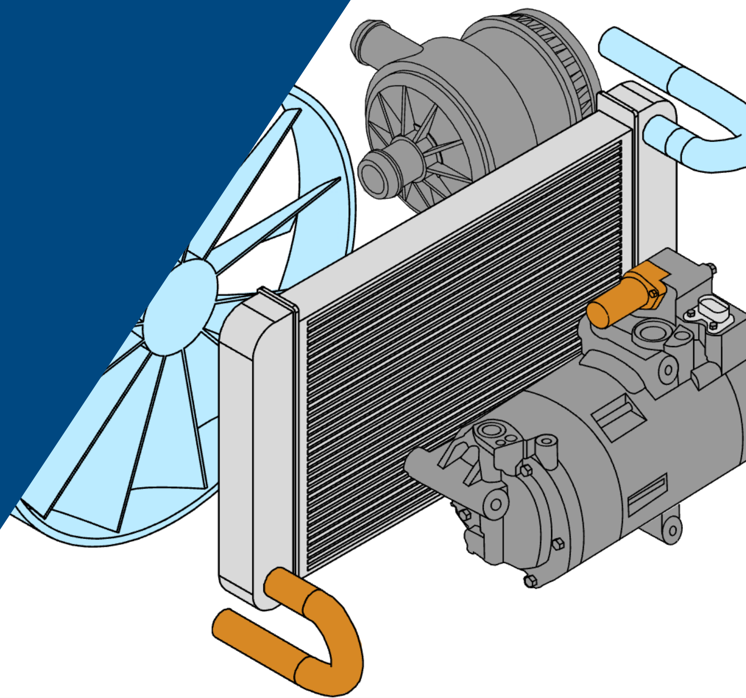


Lorenzo Nicoletti

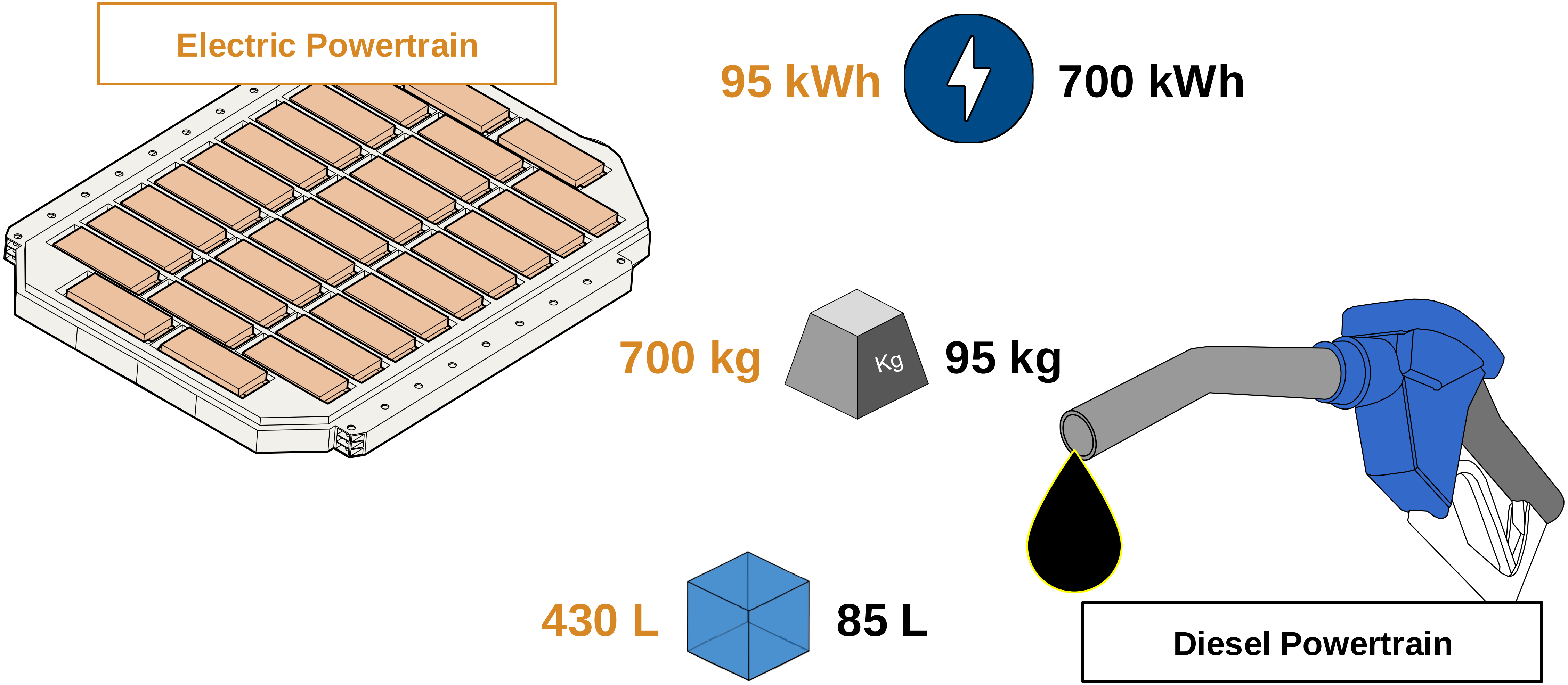
Application Engineering Virtual Vehicle
MathWorks
lnicolet@mathworks.com

Steve Miller

Product Marketing Simscape
MathWorks
smiller@mathworks.com

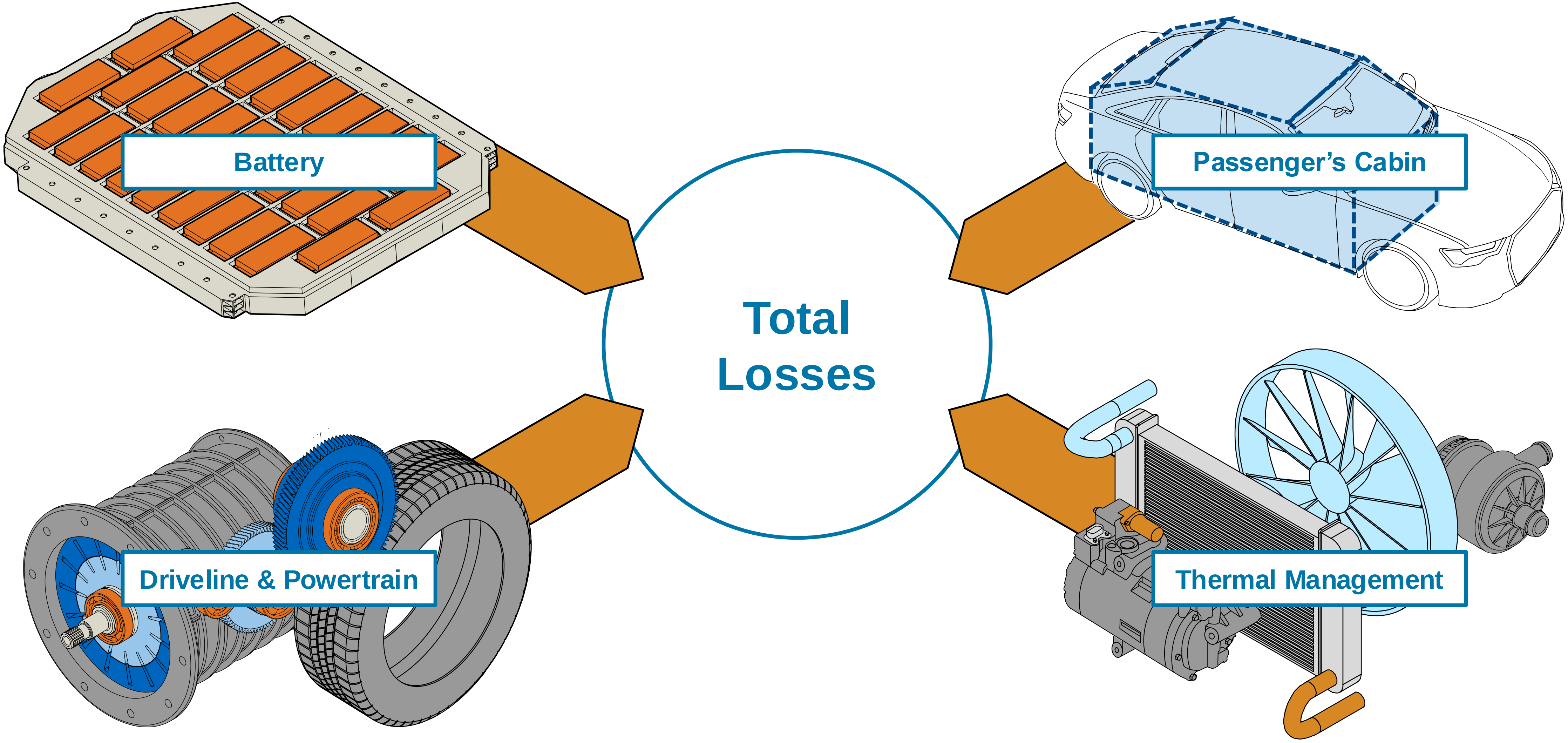


The achievable range is still a major challenge for Battery Electric Vehicles (BEVs)



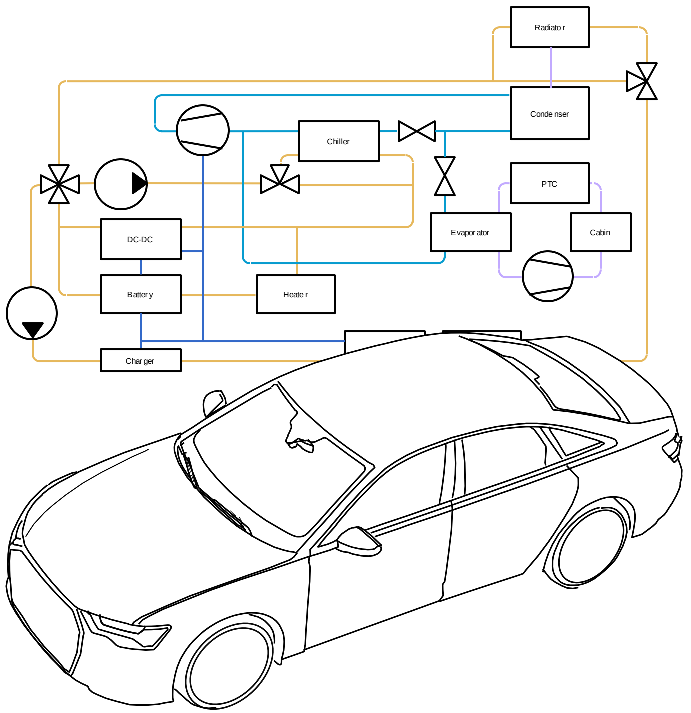
Source: L. Nicoletti, Parametric Modeling of Battery Electric Vehicles in the Early Development Phase. Ph.D. Thesis, 2022

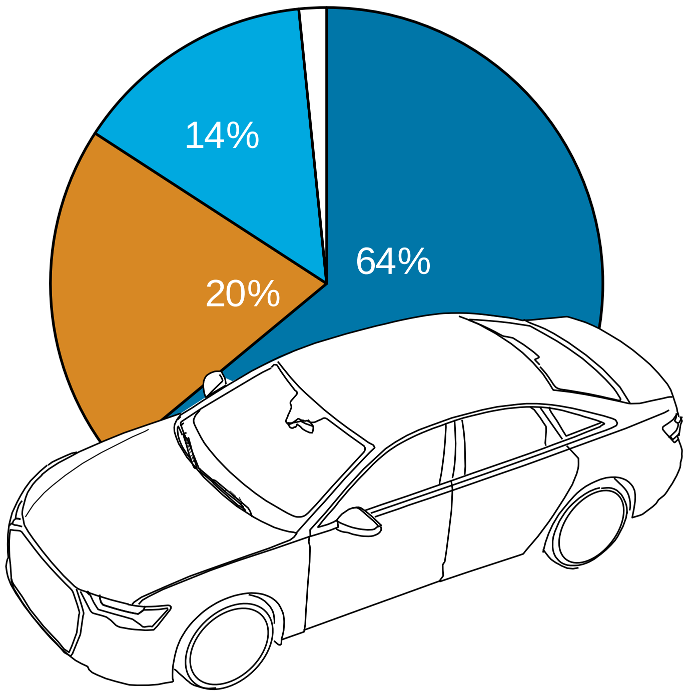
Increasing the range of BEVs requires optimizing all vehicle components following a holistic approach*

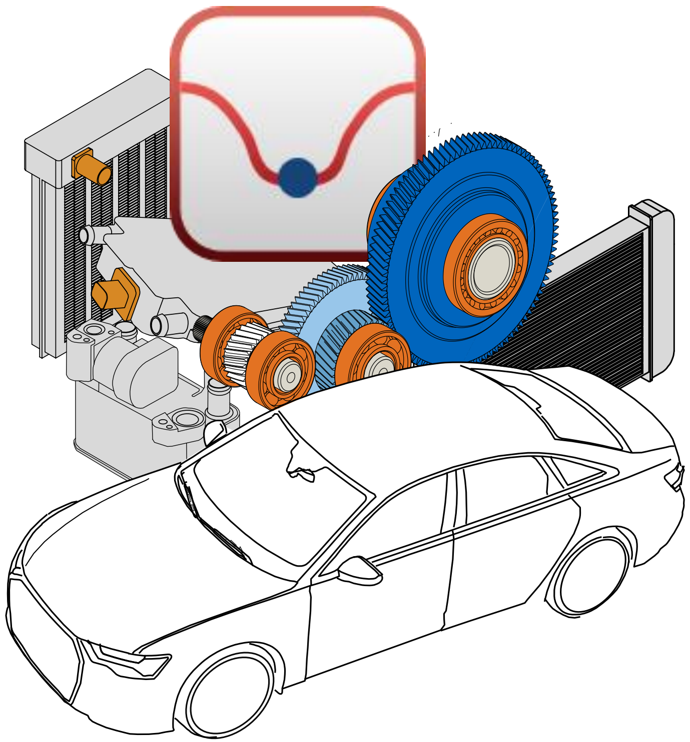


*S. Miller and L. Nicoletti, “A Holistic Approach for Designing a Battery Electric Vehicle Thermal Management System”, ELIV, Bonn, 2023

This presentation shows how to build a holistic BEV model and achieve an optimal design





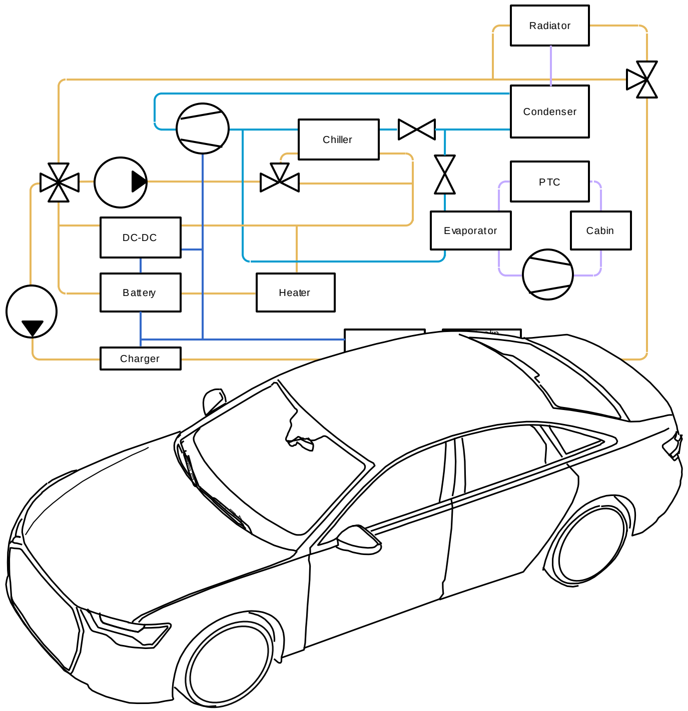


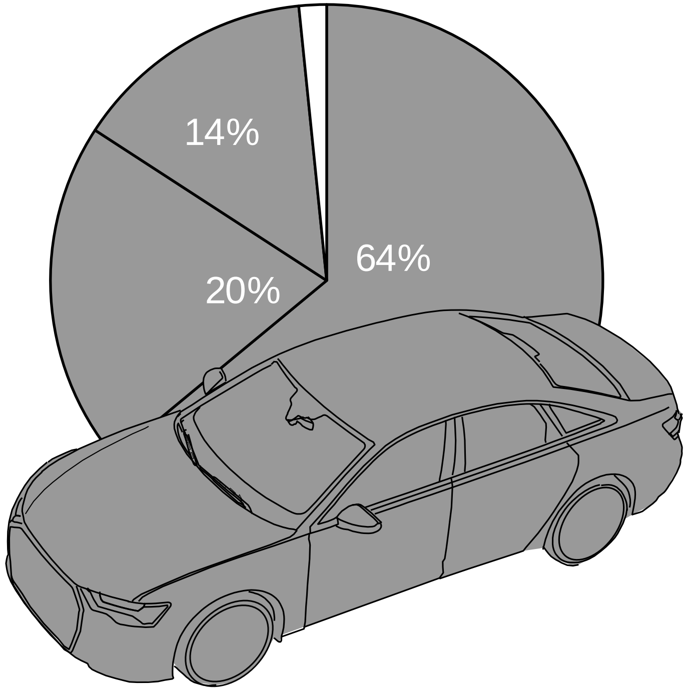
Build Holistic BEV Model

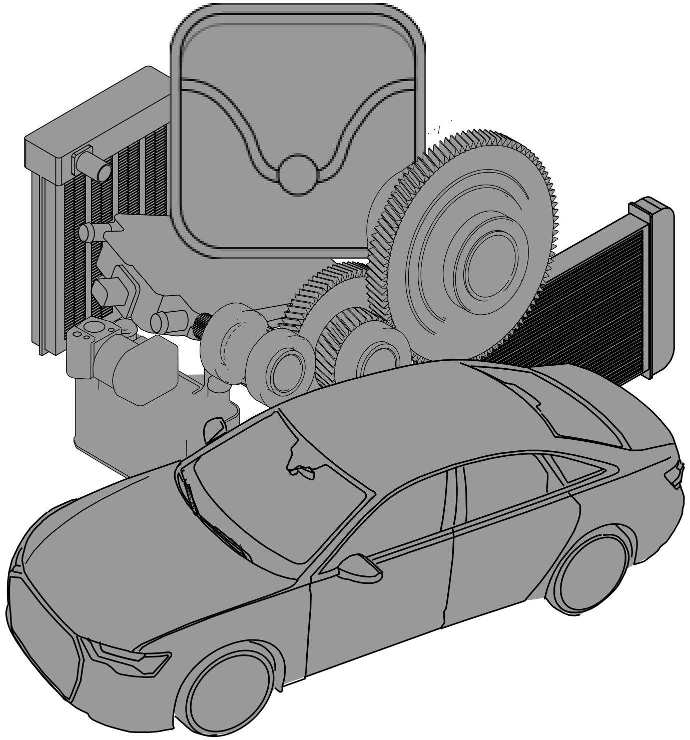
Simulate & Analyze

Optimize

Implementing your own BEV model is **fast and intuitive**





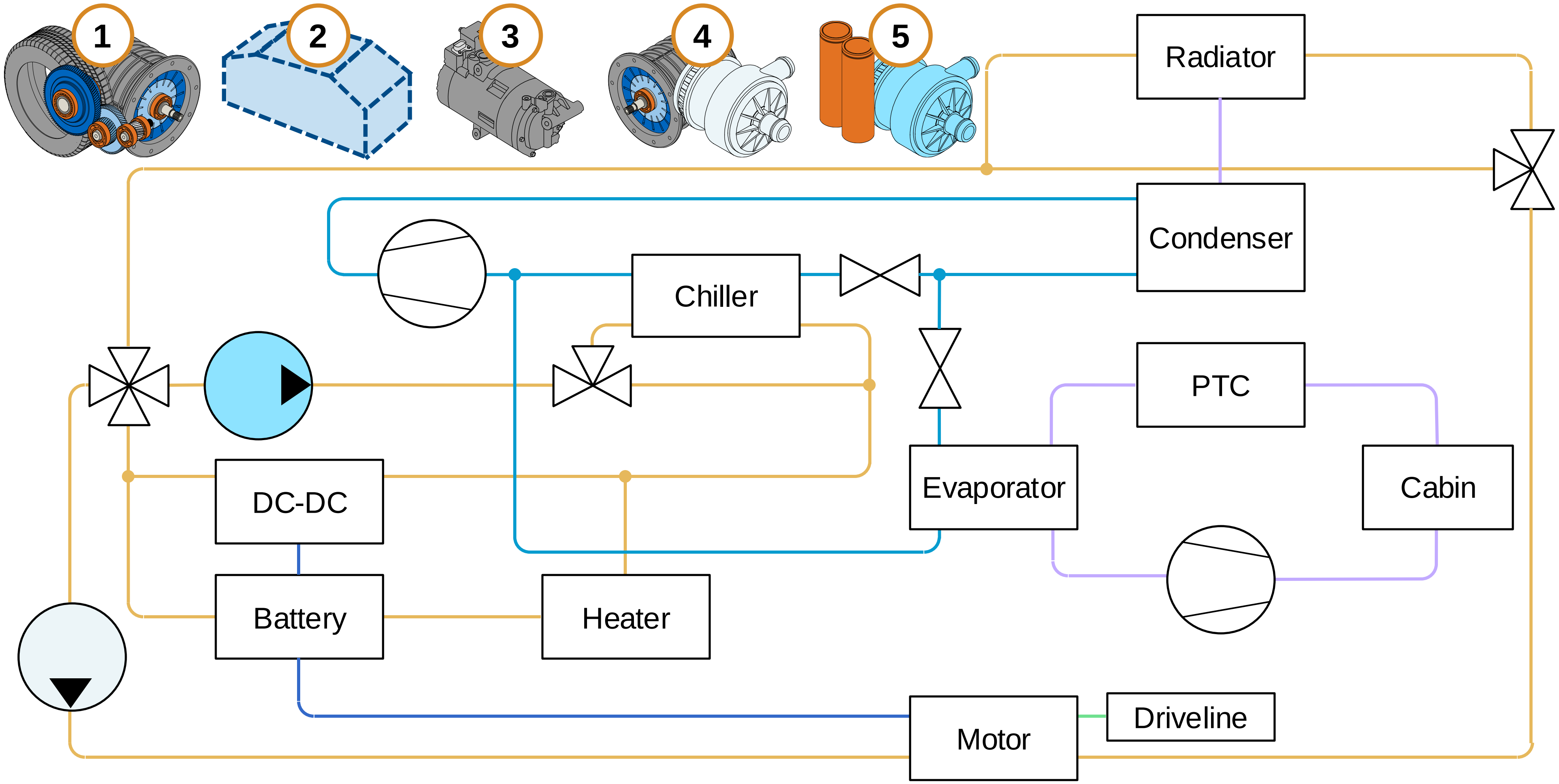


Build Holistic BEV Model

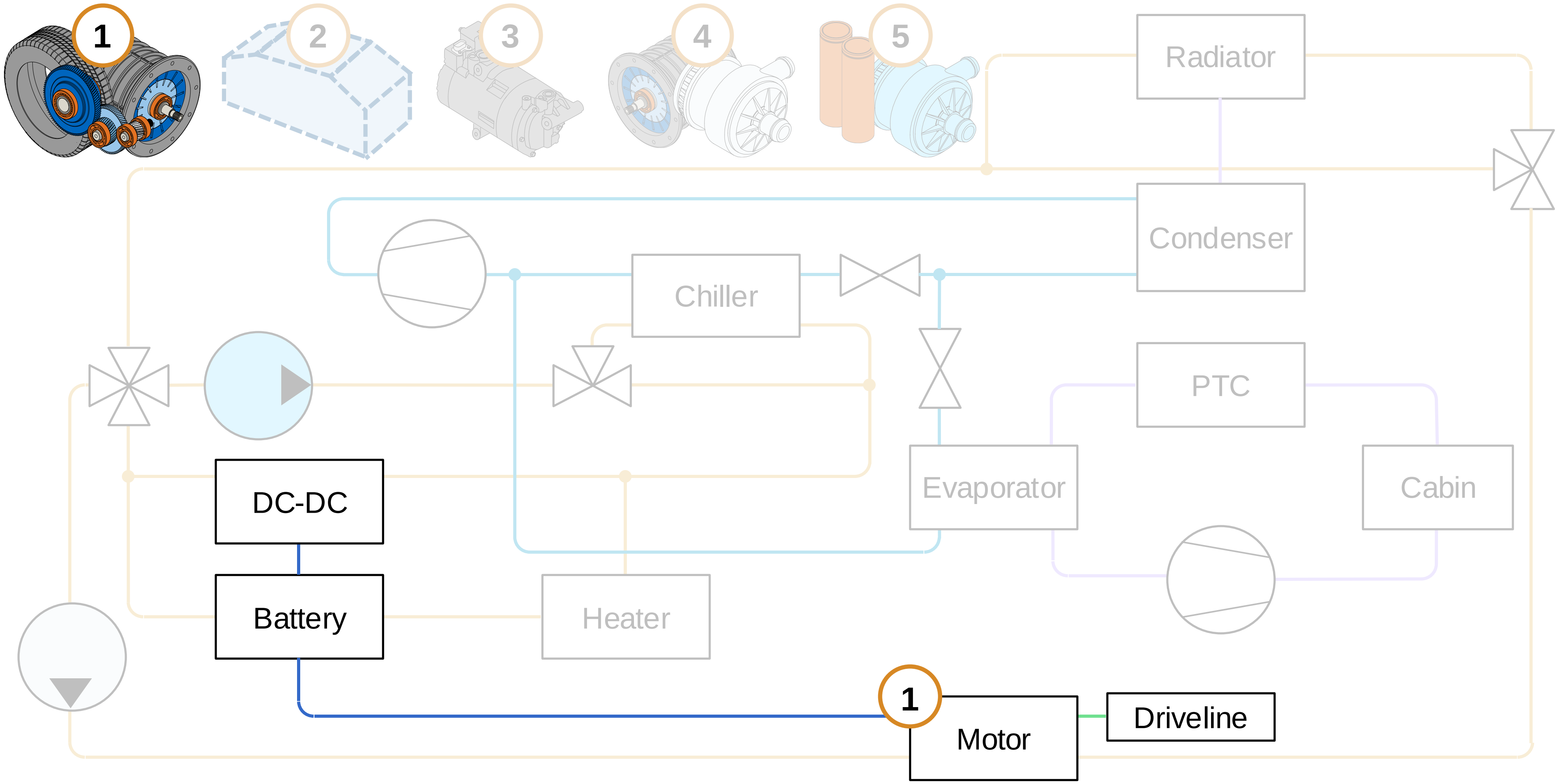
Simulate & Analyze

Optimize

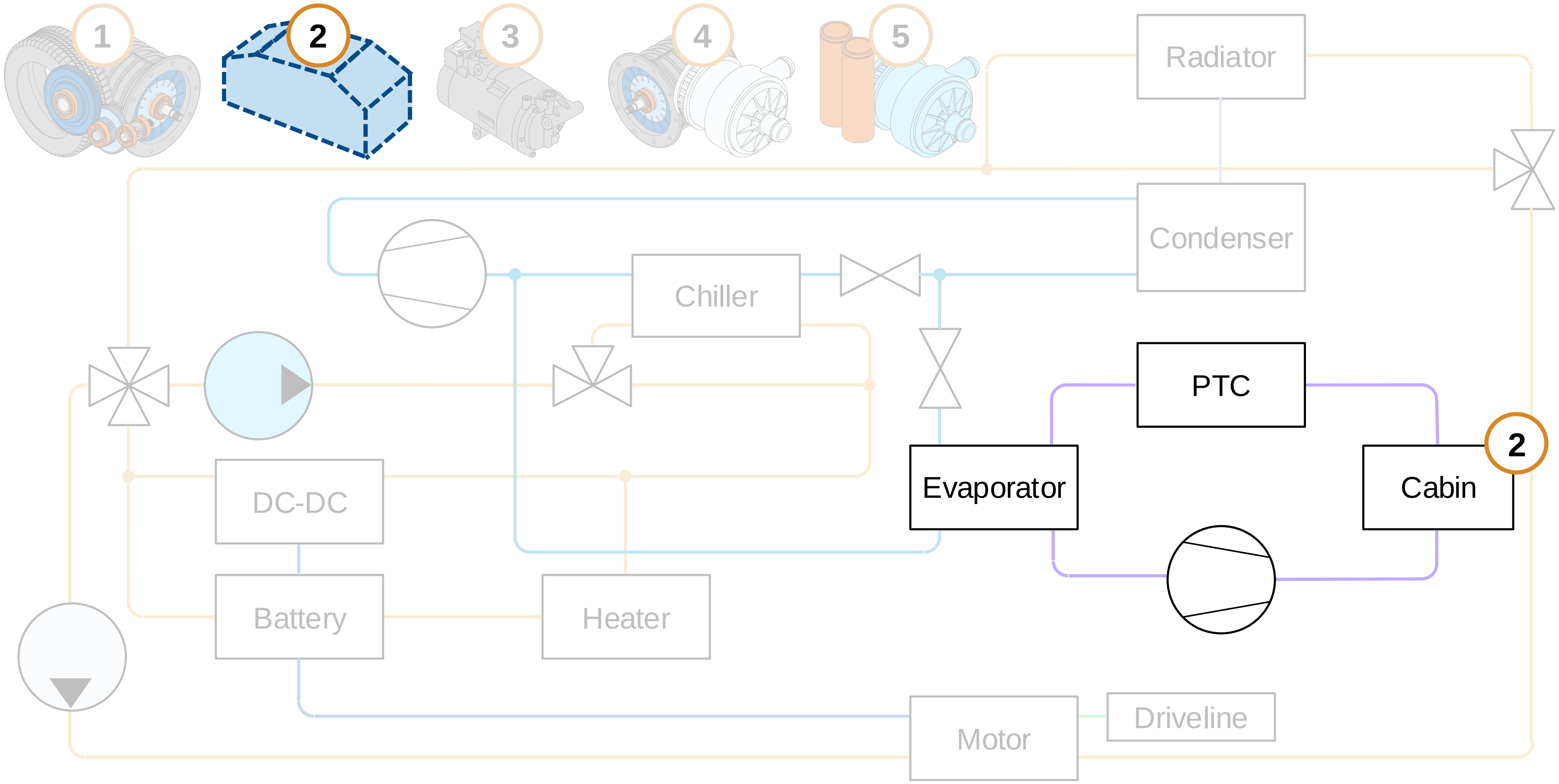
The BEV model allows for a **full vehicle simulation***



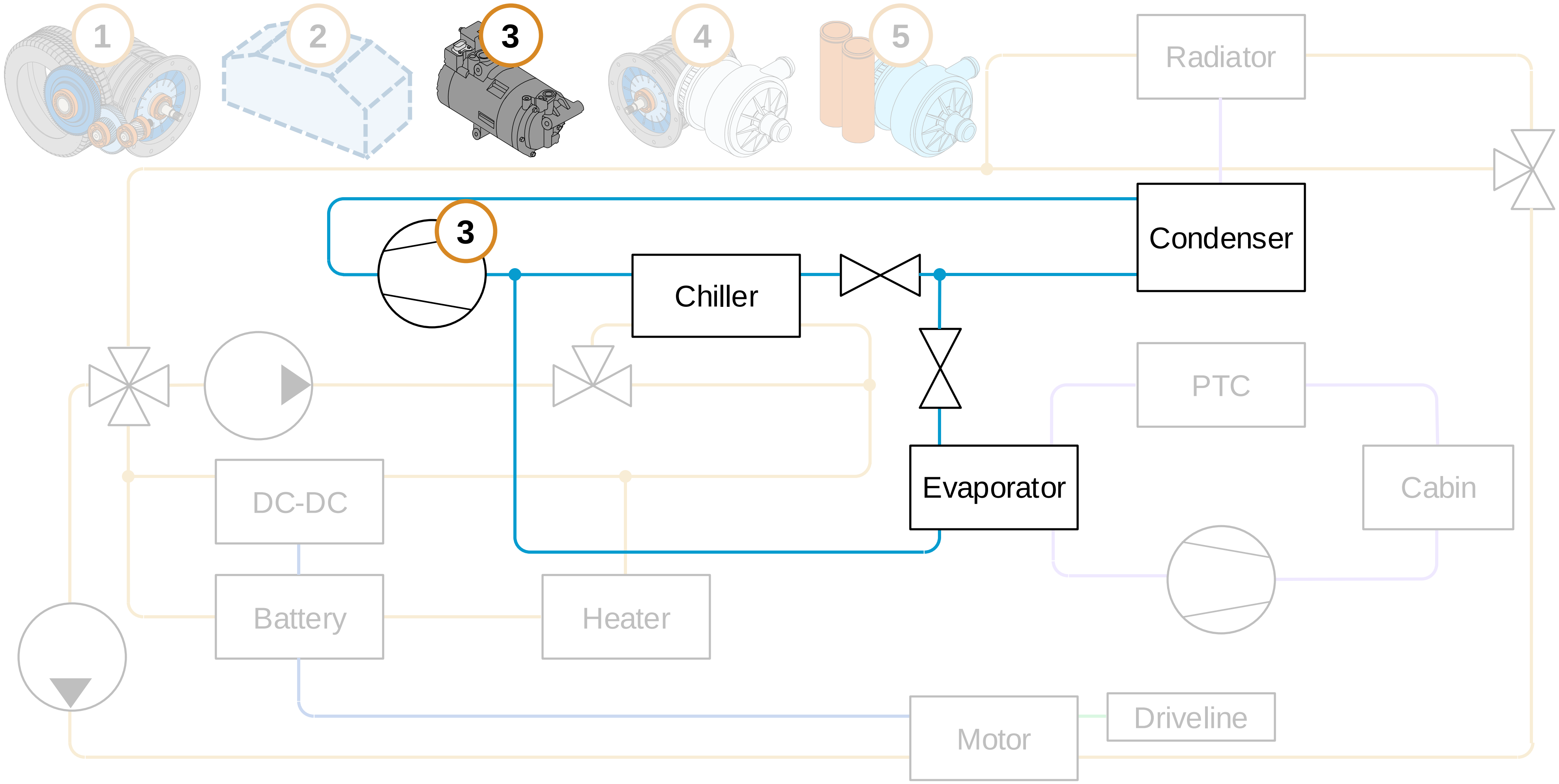
Powertrain & driveline models capture vehicle behavior



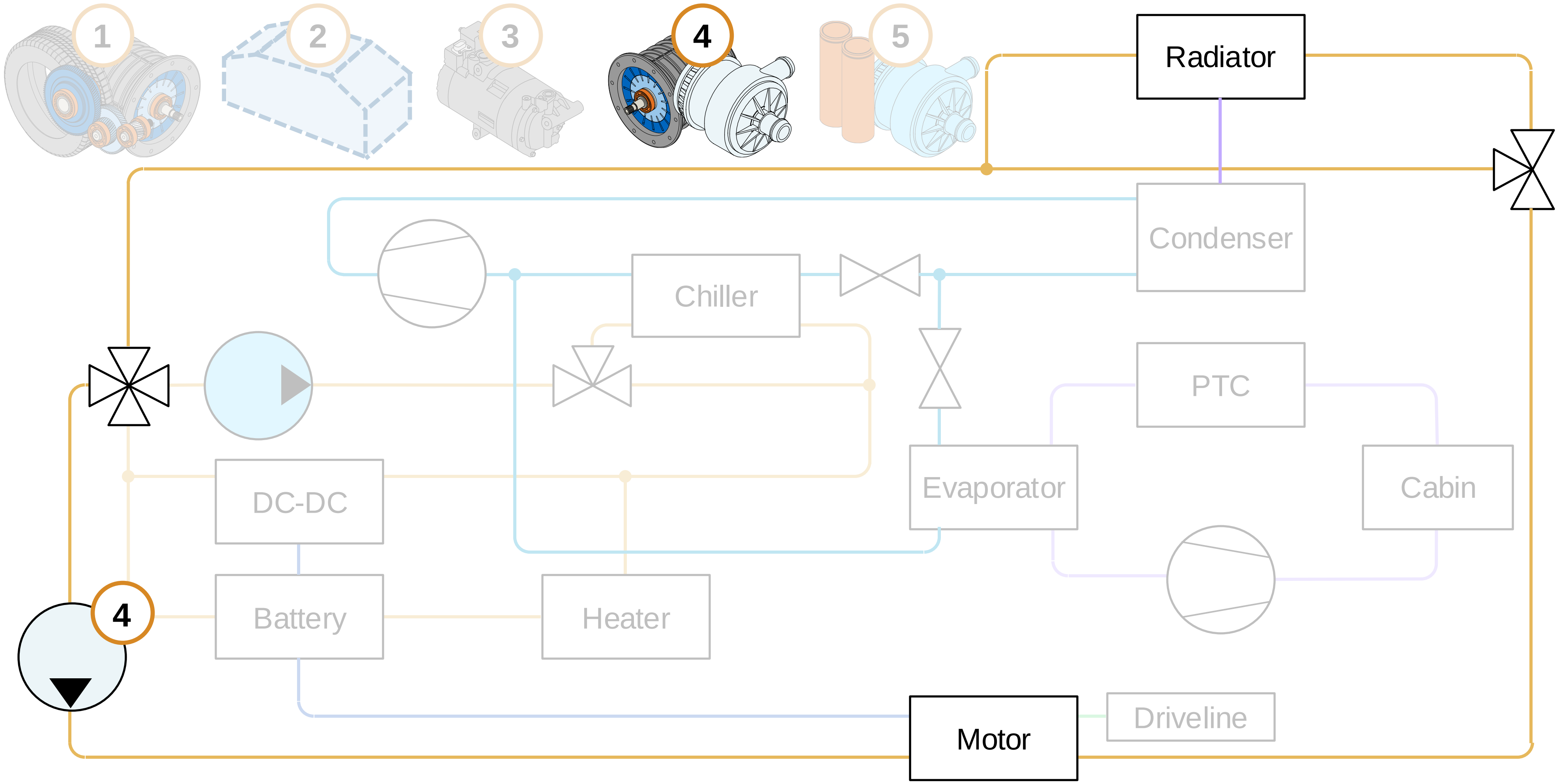
Cabin loop controls the cabin's temperature



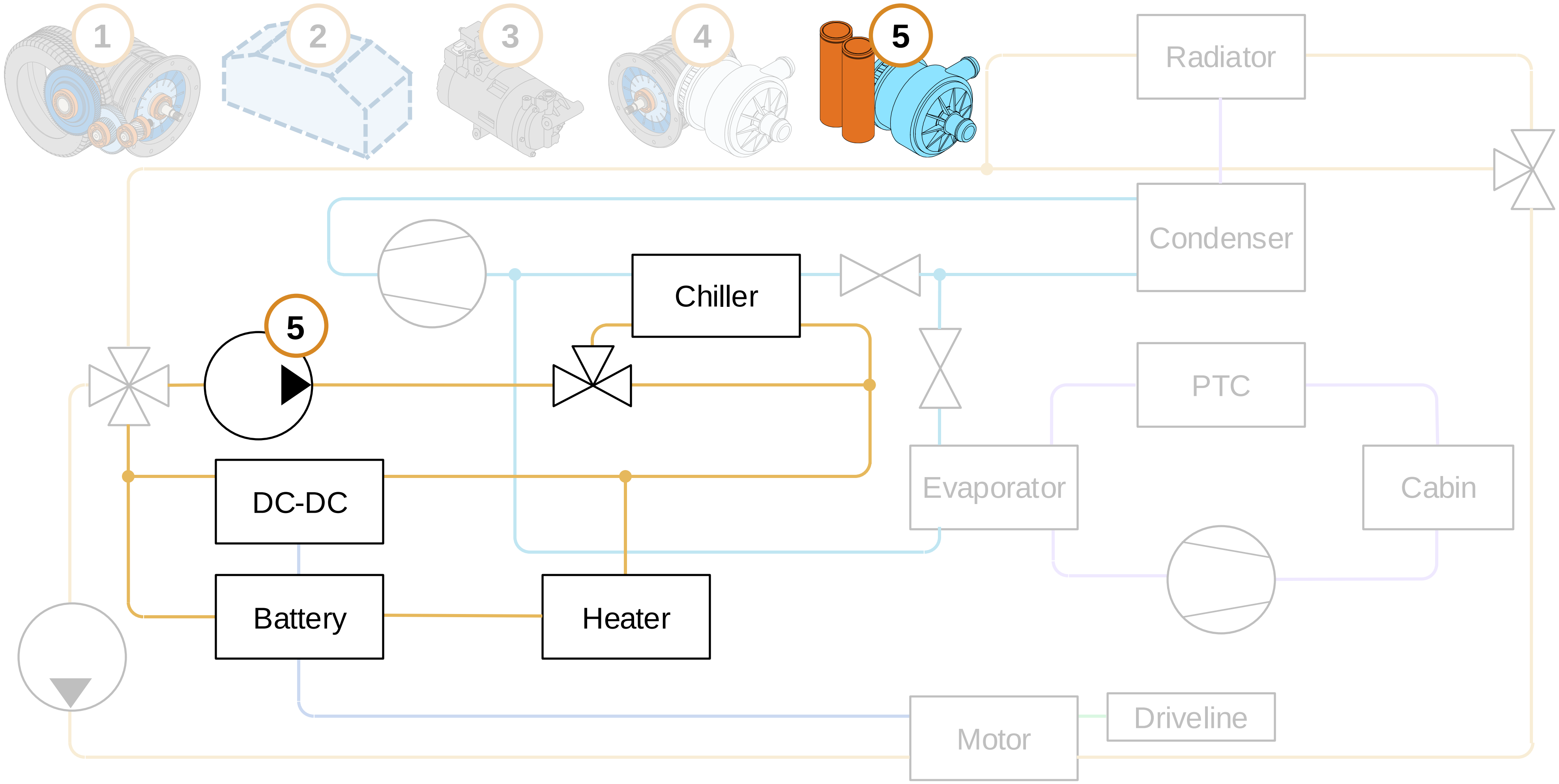
Refrigerant loop dissipates heat from cabin & powertrain



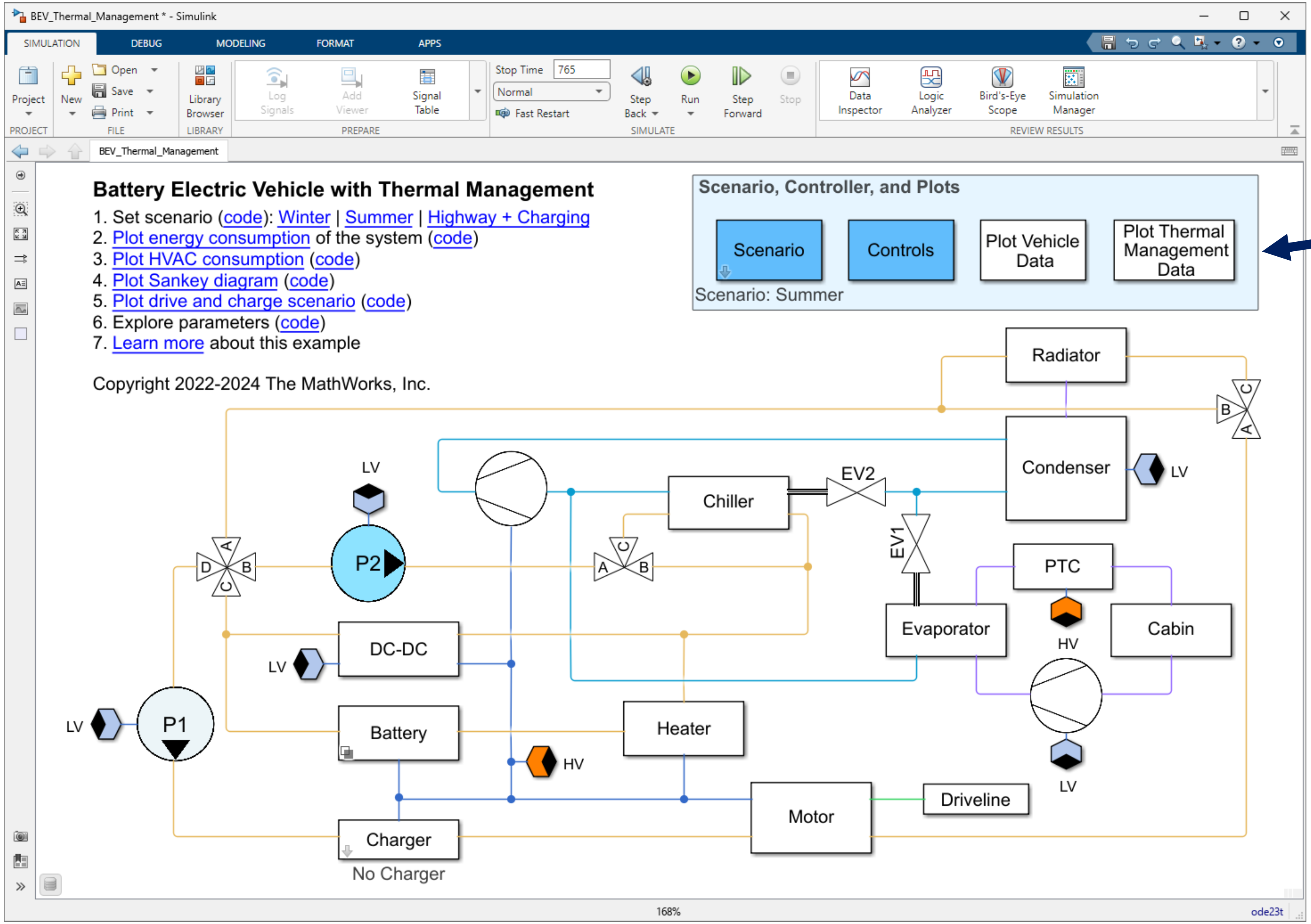
Outer coolant loop controls motor temperature



Inner coolant loop controls battery temperature



The BEV model allows for a **full vehicle simulation***

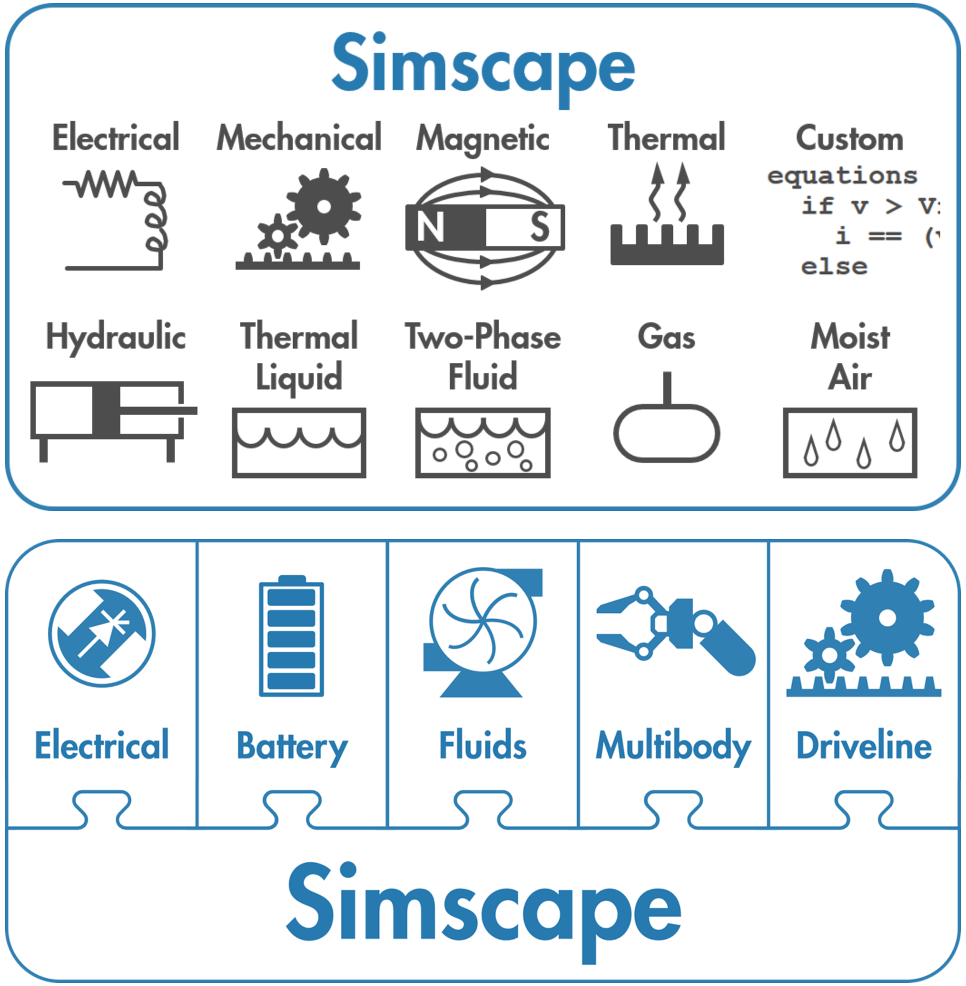


Simulation model using Simscape

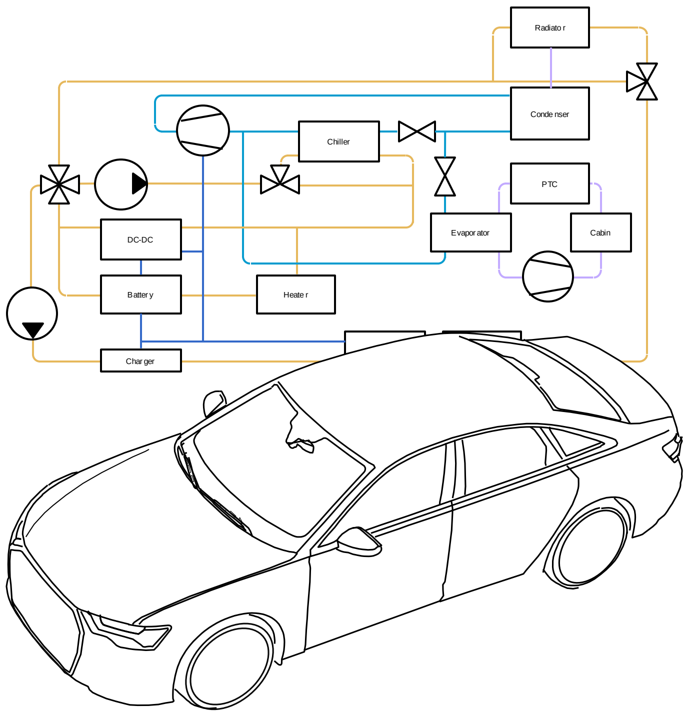
- Model assembles components in a schematic
- Integrates the physical design with the control system

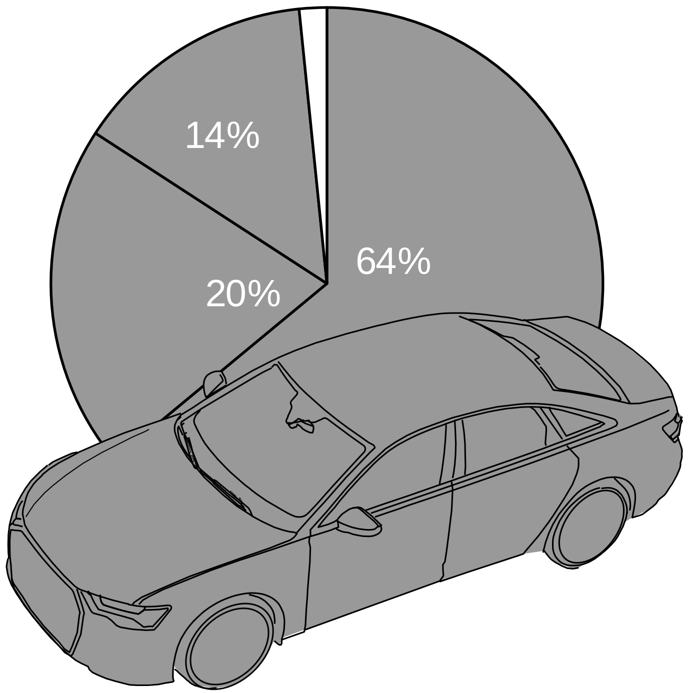
Simscape Makes Modeling Physical Systems Easy

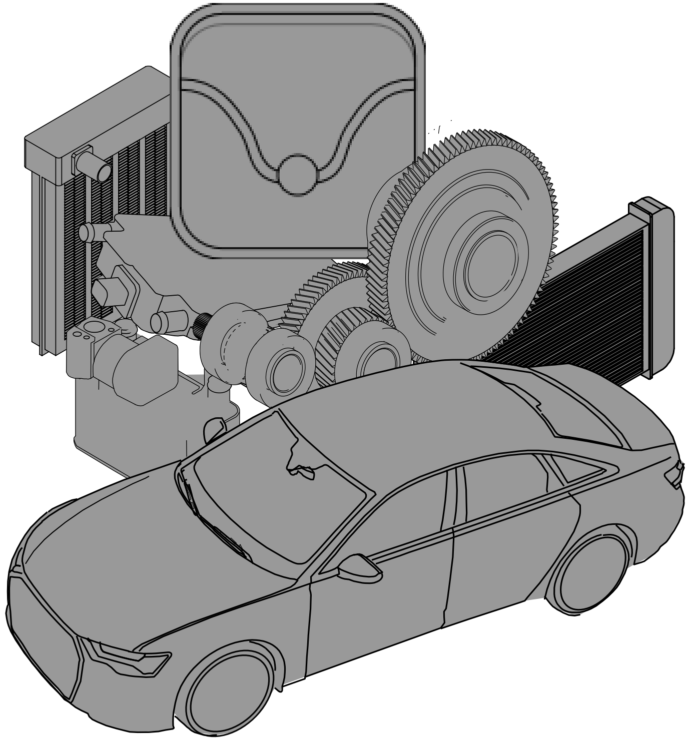
- Simscape platform
  - Foundation libraries in many domains
  - Language for defining custom blocks
    - Extension of MATLAB
  - Simulation engine and custom diagnostics
- Simscape add-on libraries
  - Extend foundation domains with components, effects, parameterizations
  - Multibody simulation
  - Editing Mode permits use of add-ons with Simscape license only
  - Models can be converted to C code



Implementing your own BEV model is **fast and intuitive**





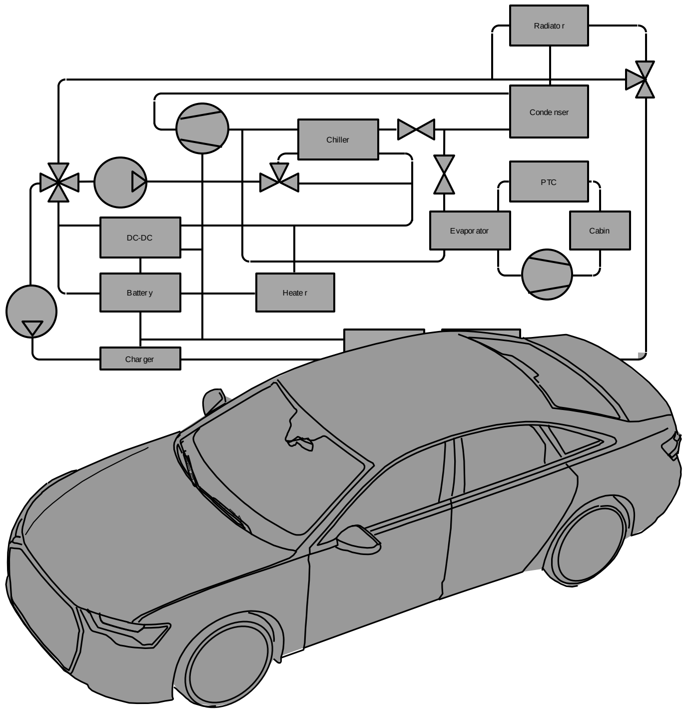


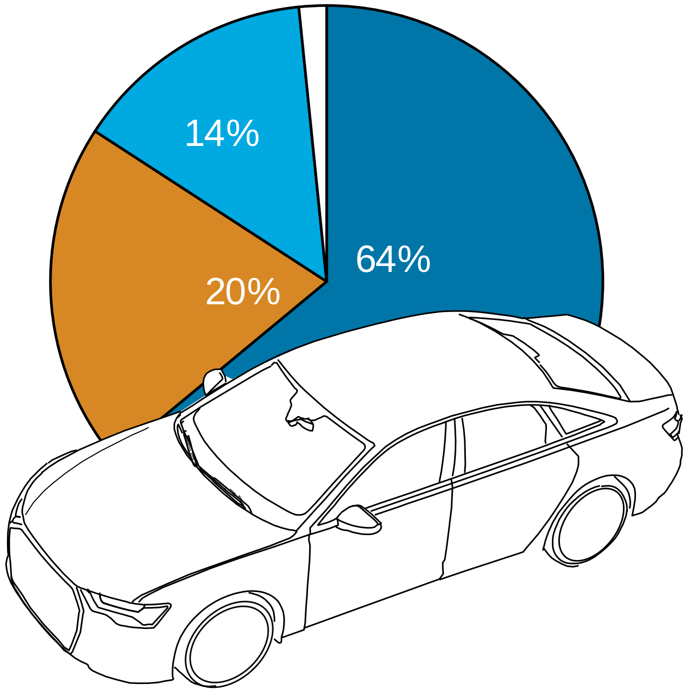
Build Holistic BEV Model

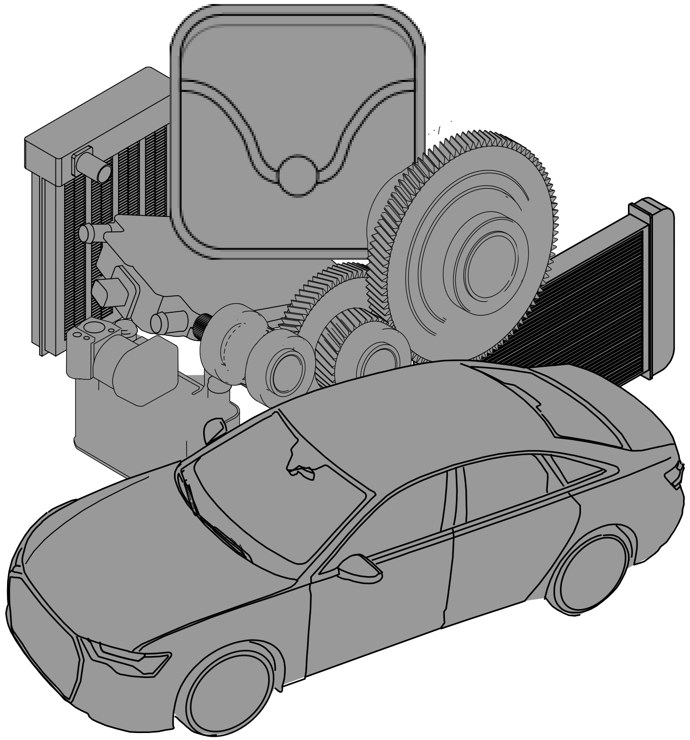
Simulate & Analyze

Optimize

Use the BEV model to **understand your design**

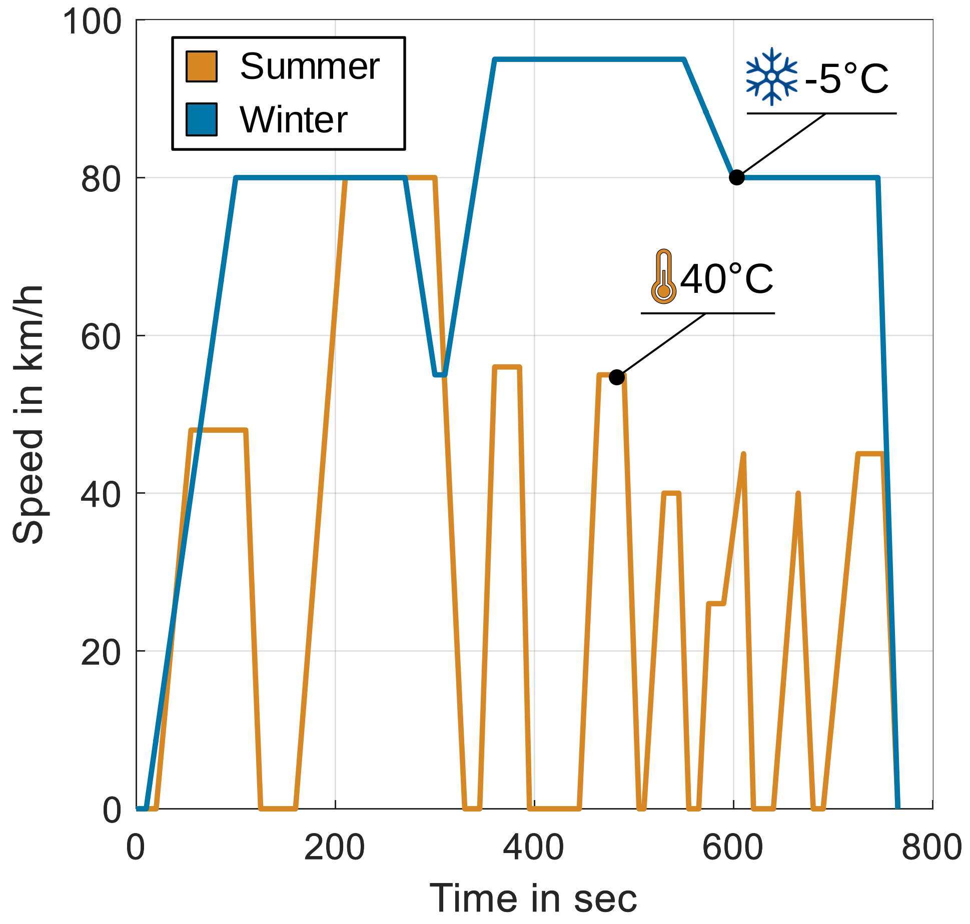


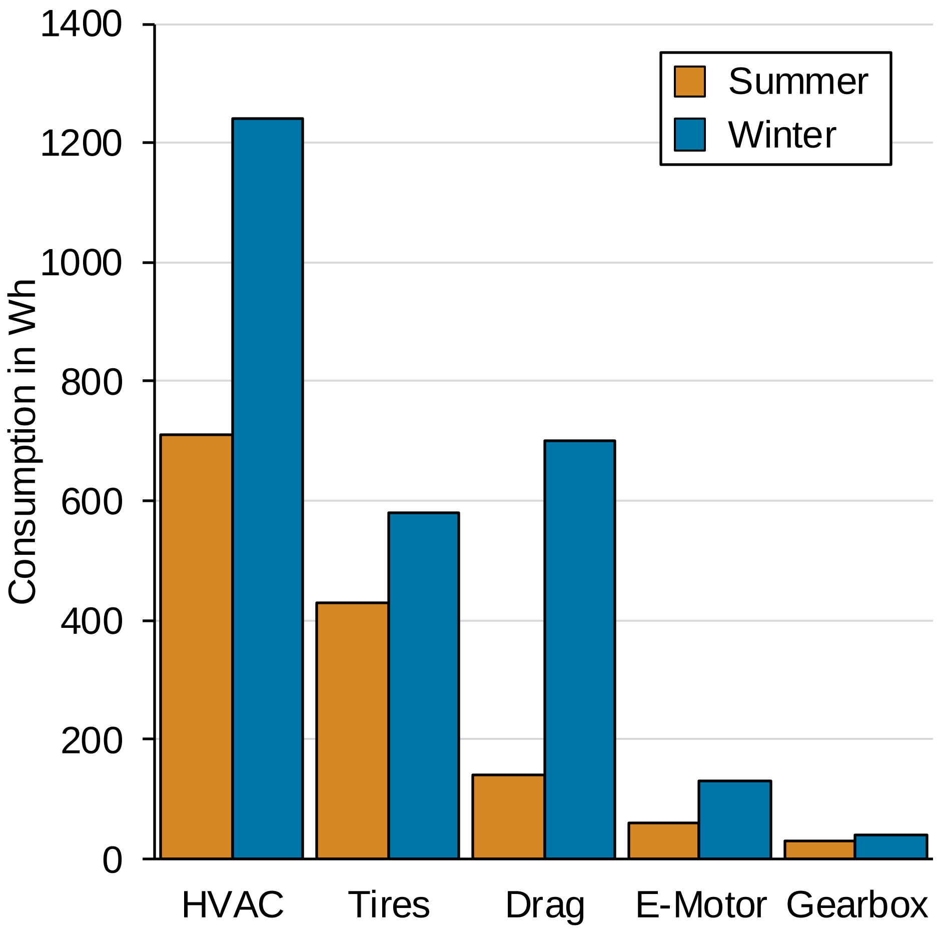




Build Holistic BEV Model | **Simulate & Analyze** | **Optimize**

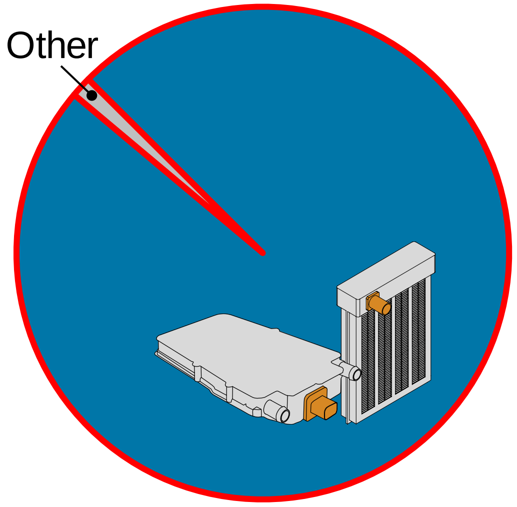
Drive style and weather **influence vehicle consumption**

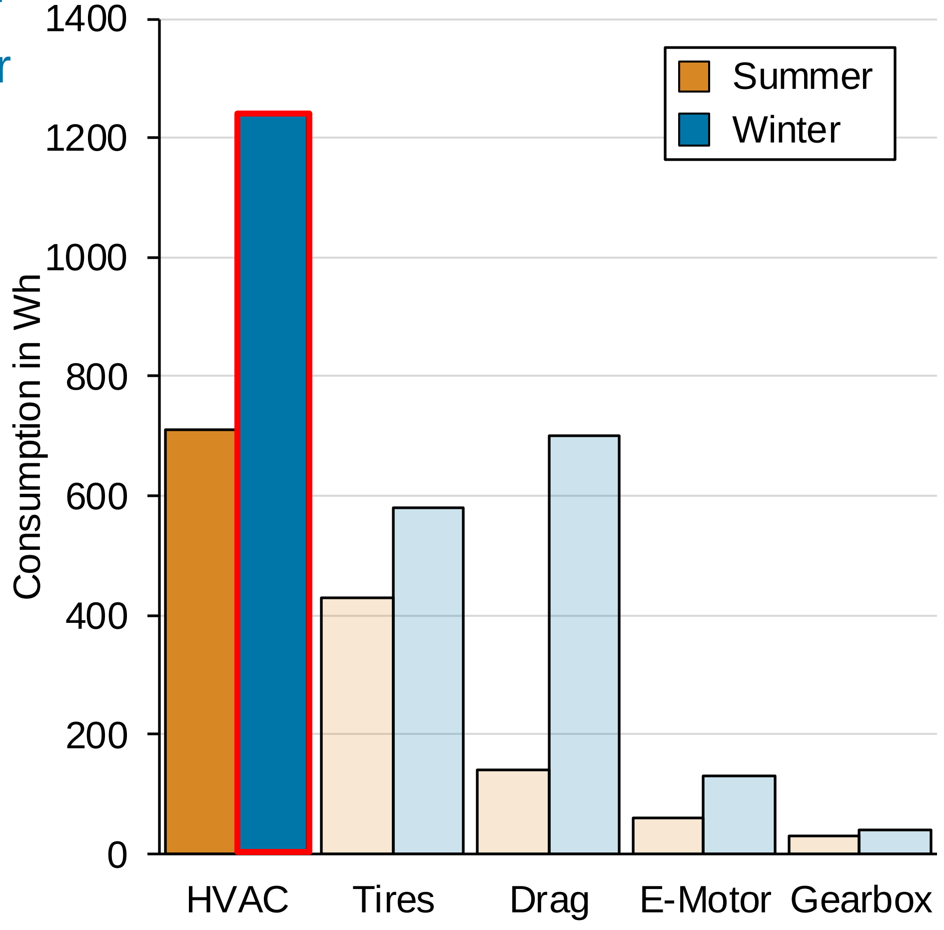




The weather conditions determine which thermal management components **need to be active**

The heaters account for **98%** of the HVAC consumption in winter





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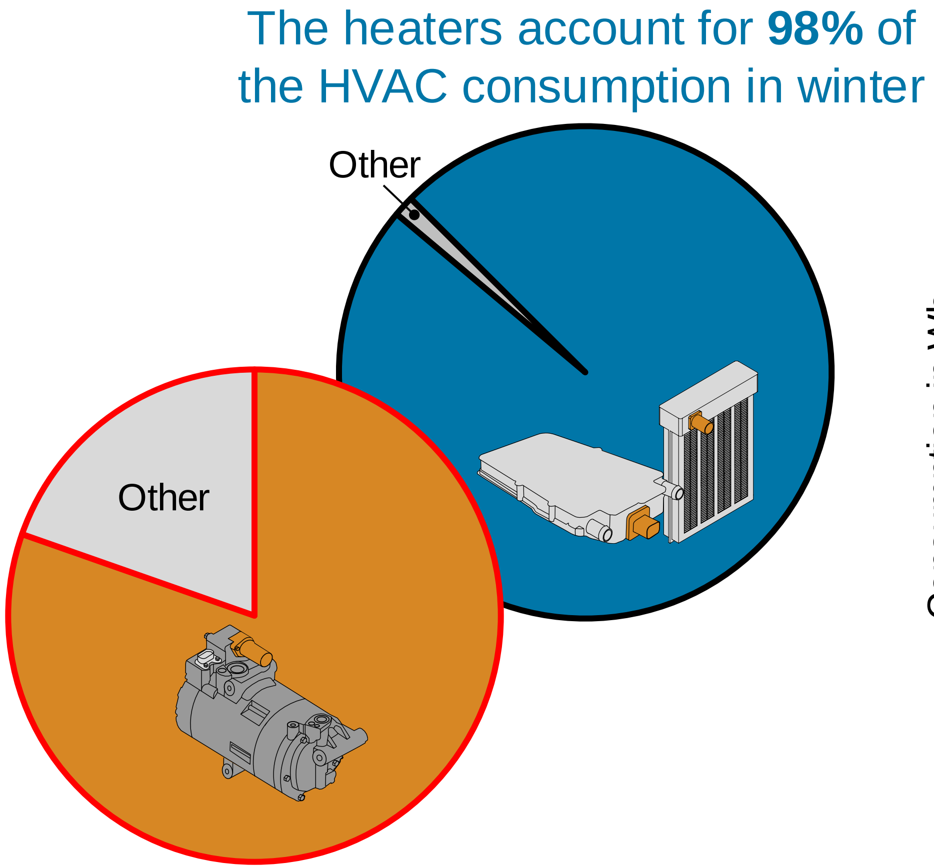
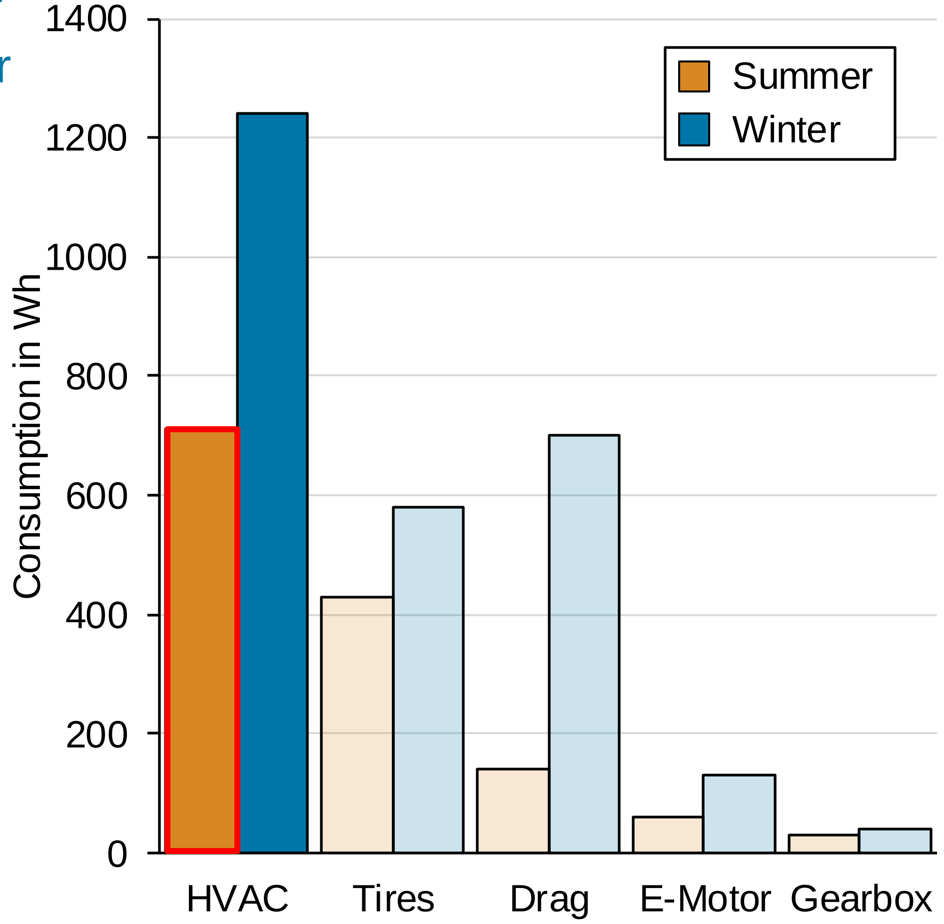
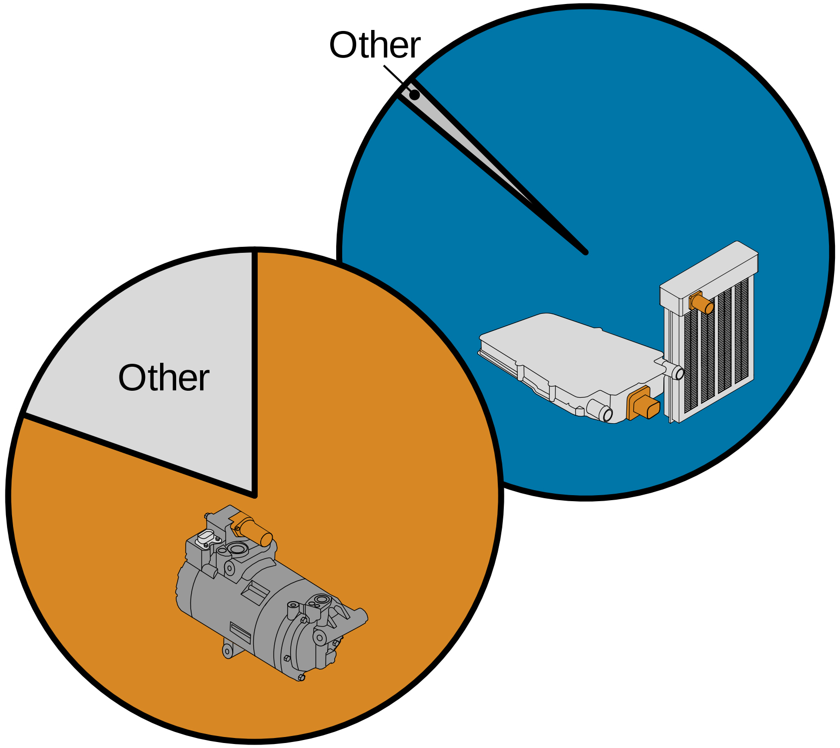


The compressor accounts for **80%** of the HVAC consumption in summer



The active thermal management components influence the **thermal management performance**

The heaters account for **98%** of the HVAC consumption in winter



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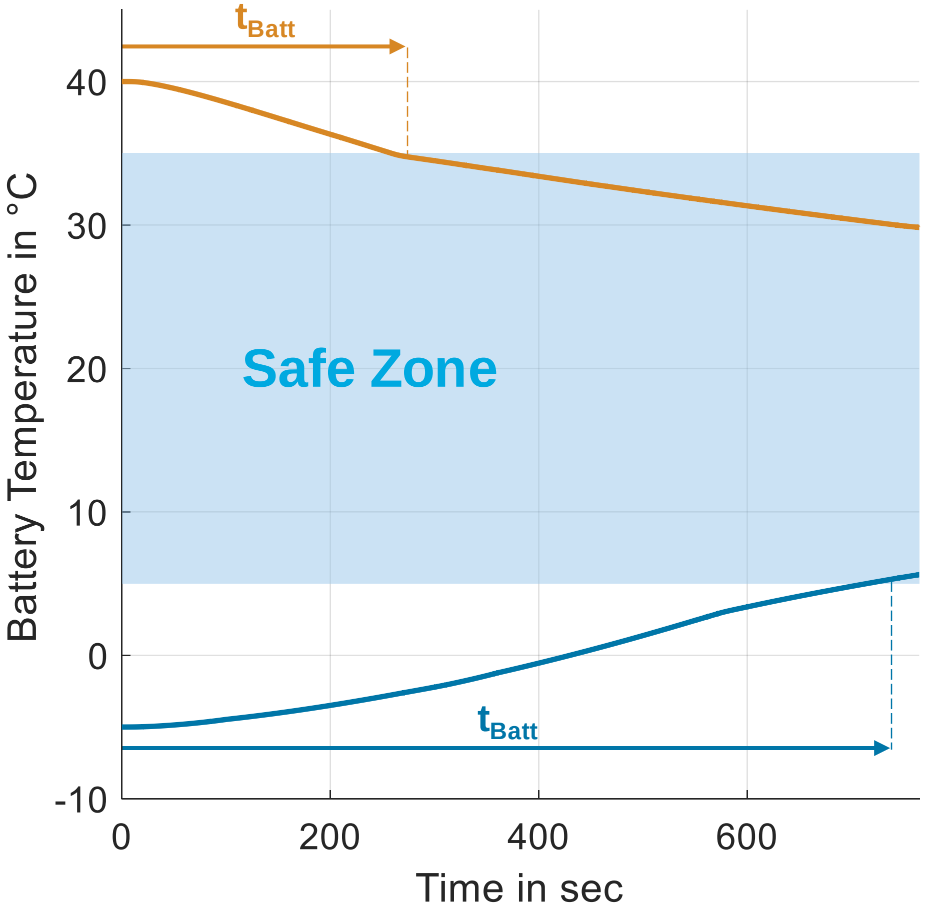
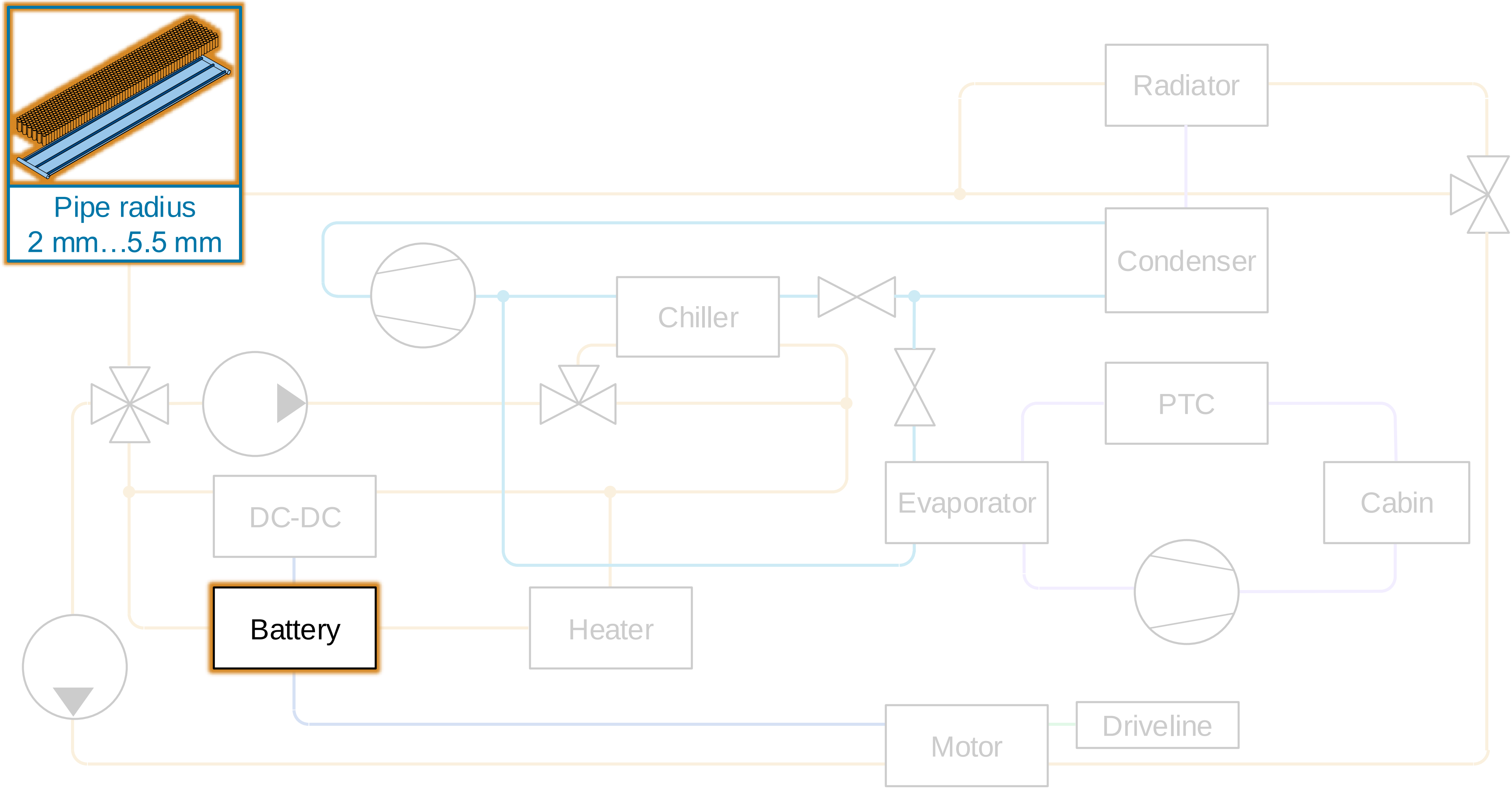


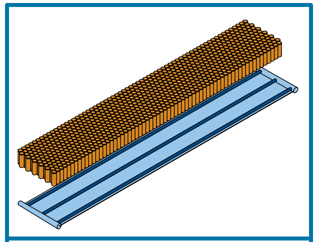
A sensitivity can help **quantifying the influence** of different parameters on consumption and perfomance

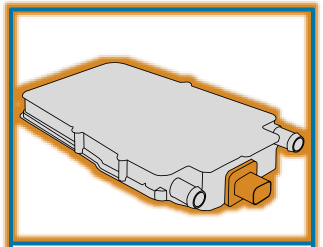
- In summary, drive style and weather conditions determine:
  - The **consumption** of the vehicle
  - The thermal management active components
  - The thermal management performance $\mathbf{t_{Batt}}$
- Due to the complexity of the system, identifying which parameters to tune for improving vehicle design is a **challenging task**
- We will use a sensitivity analysis to understand how parameter tuning impacts the vehicle **consumption** and $\mathbf{t_{Batt}}$

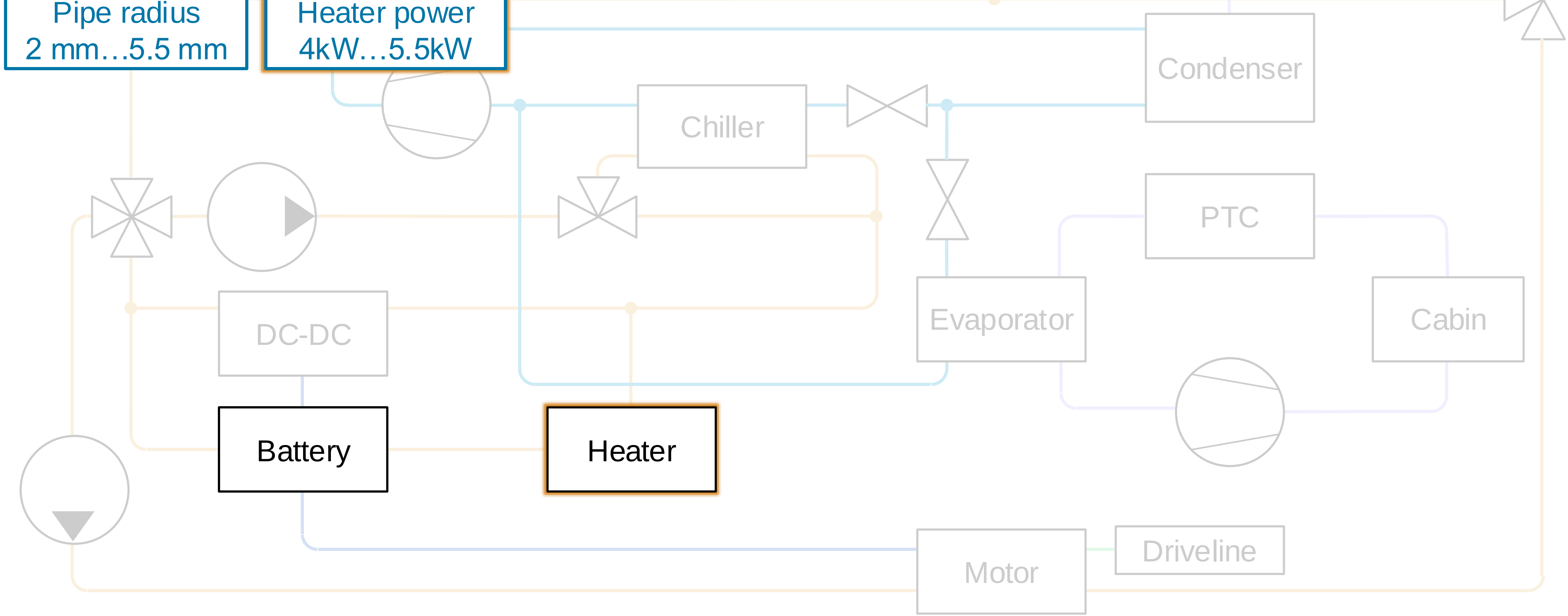
1st Parameter: Cooling pipe radius impacts on pressure losses and heat exchange with the battery



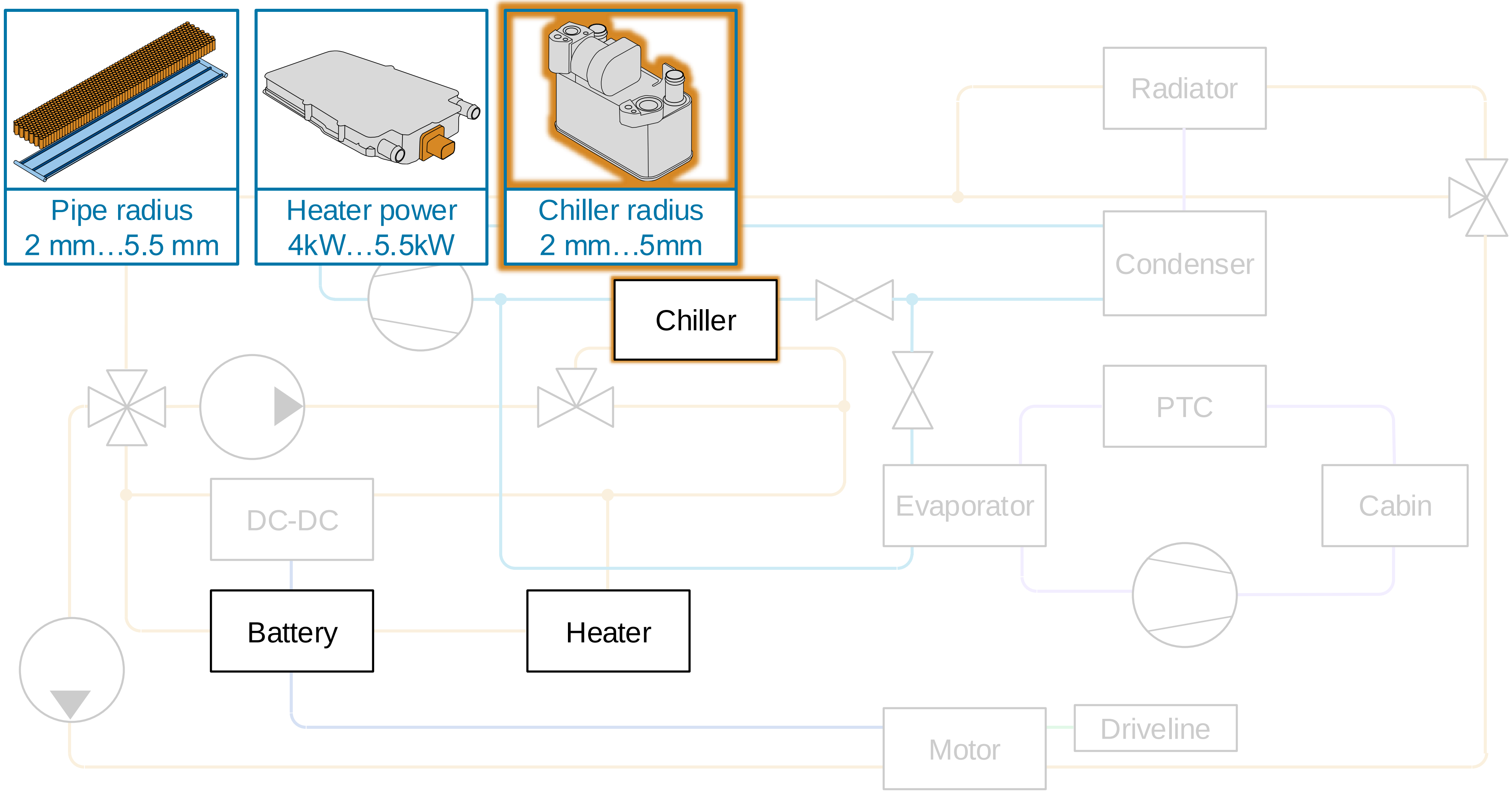
2nd Parameter: Heater power influences battery temperature in winter and impacts overall consumption



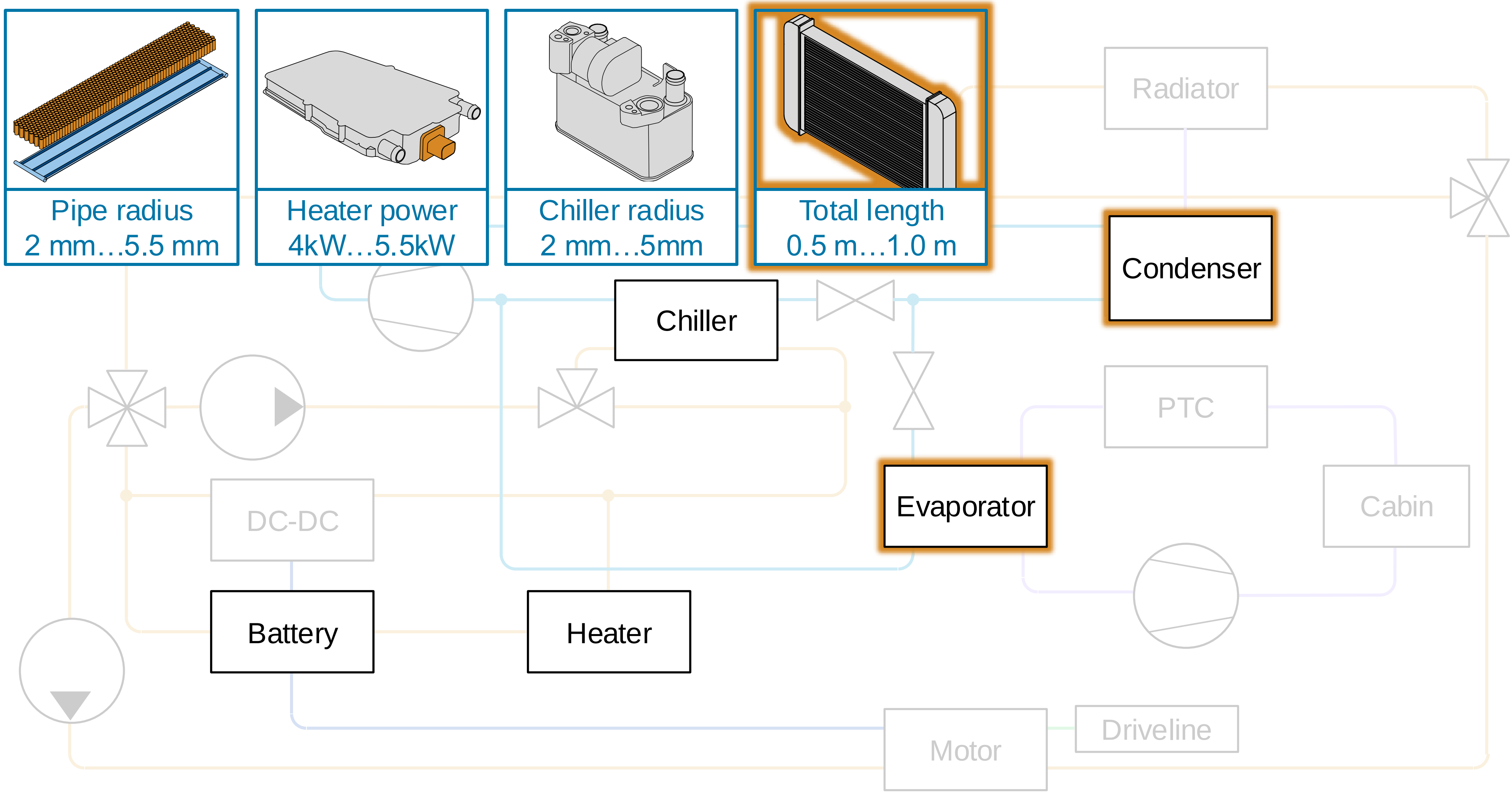




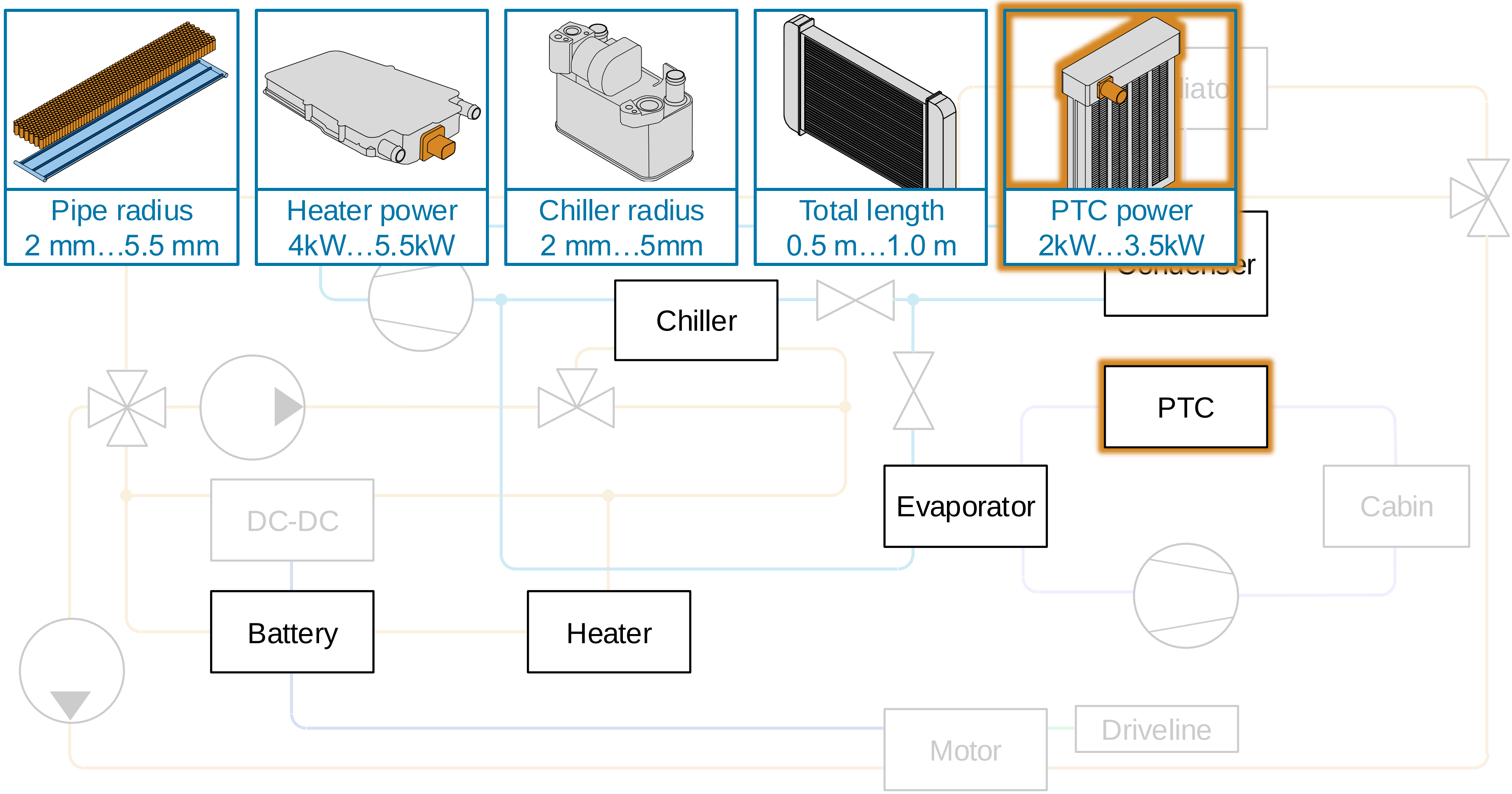
3rd Parameter: Chiller radius impacts on heat exchange and pressure losses



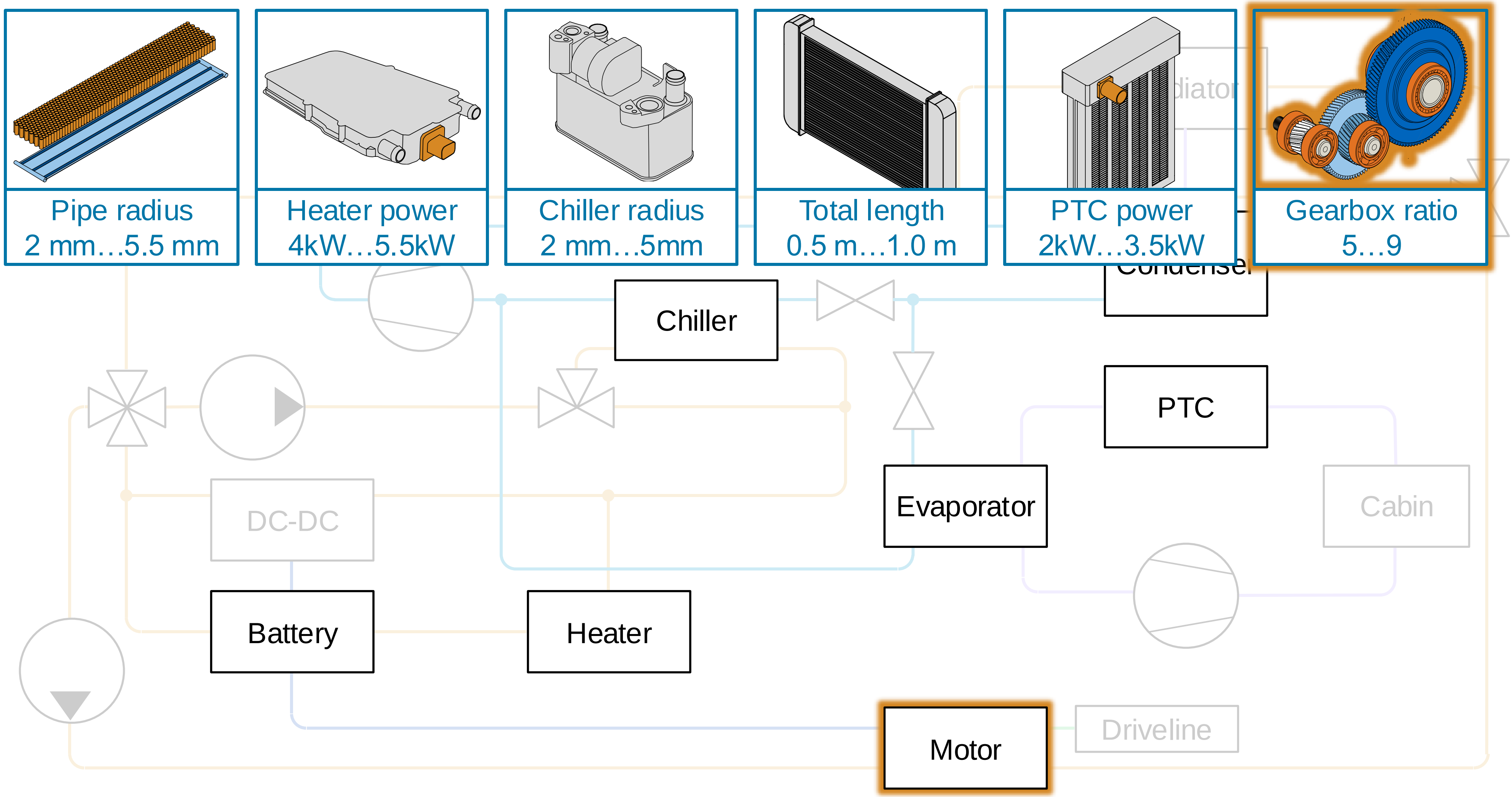
4th Parameter: The lengths of evaporator and condenser impact pressure losses and heat exchange



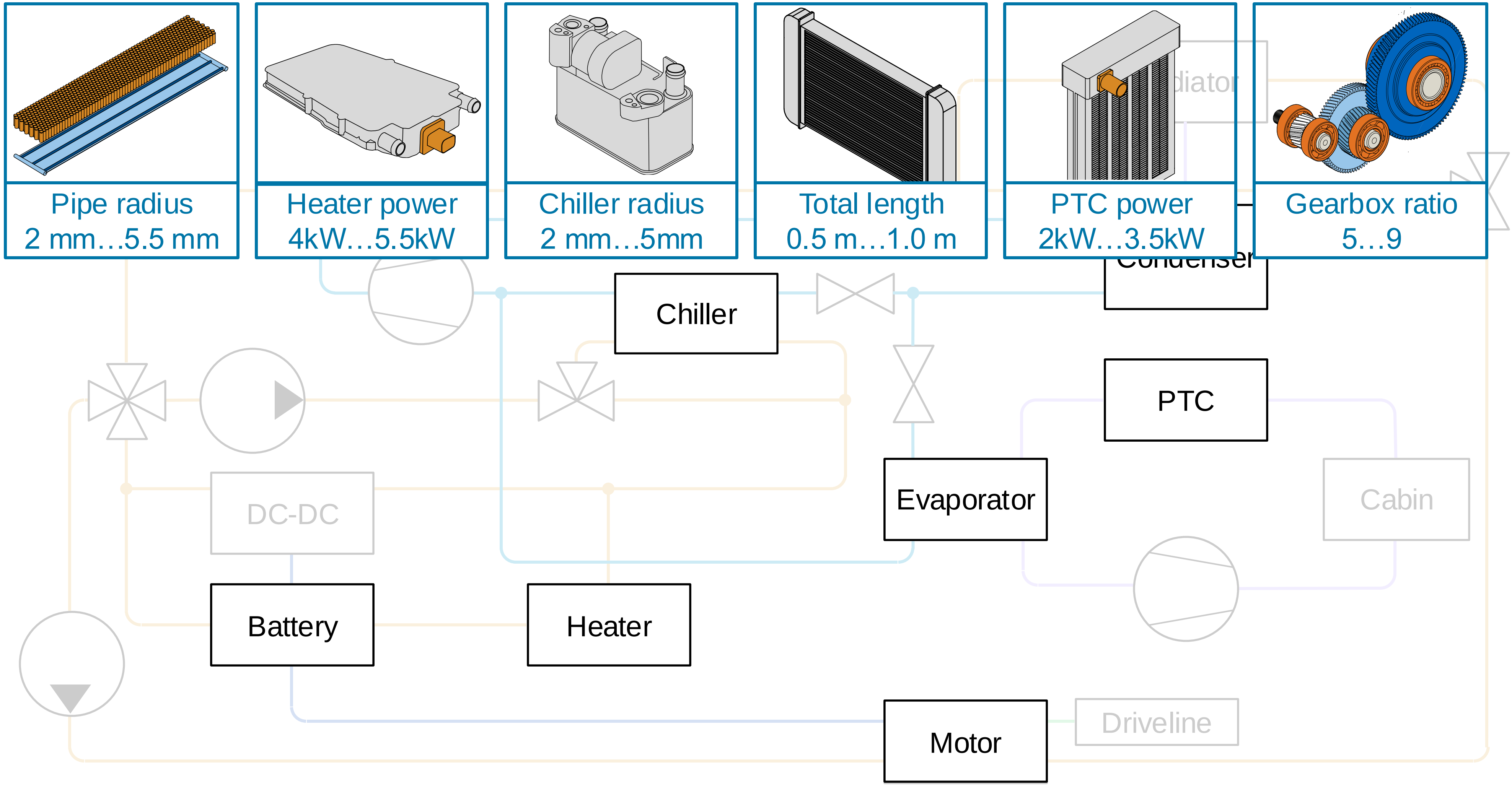
5th Parameter: PTC power influences cabin temperature in winter and impacts overall consumption



6th Parameter: Gearbox ratio determines load points of the electric machine during the drive cycle



Once the objective and the parameters are chosen, we can set up the sensitivity analysis



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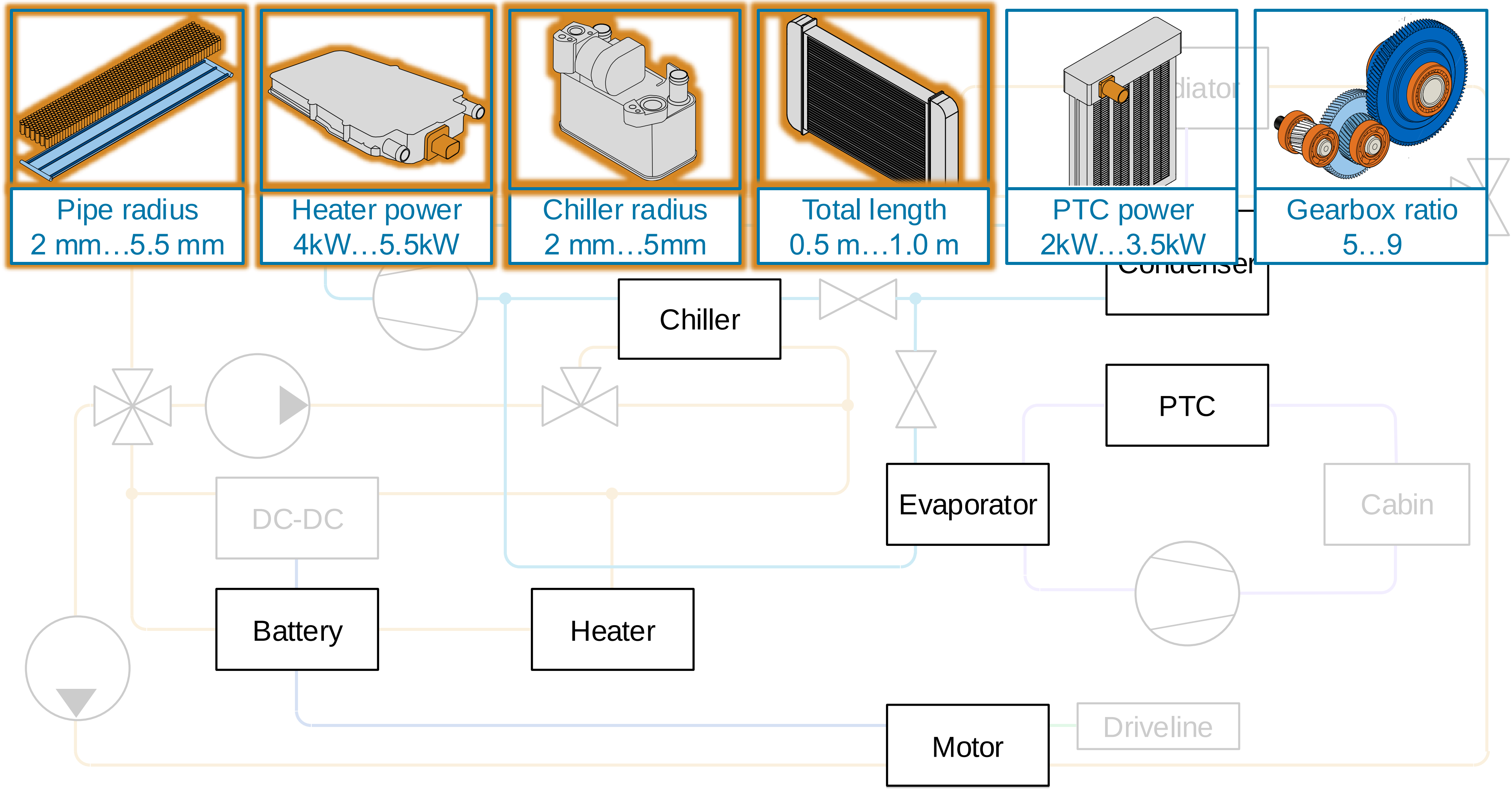
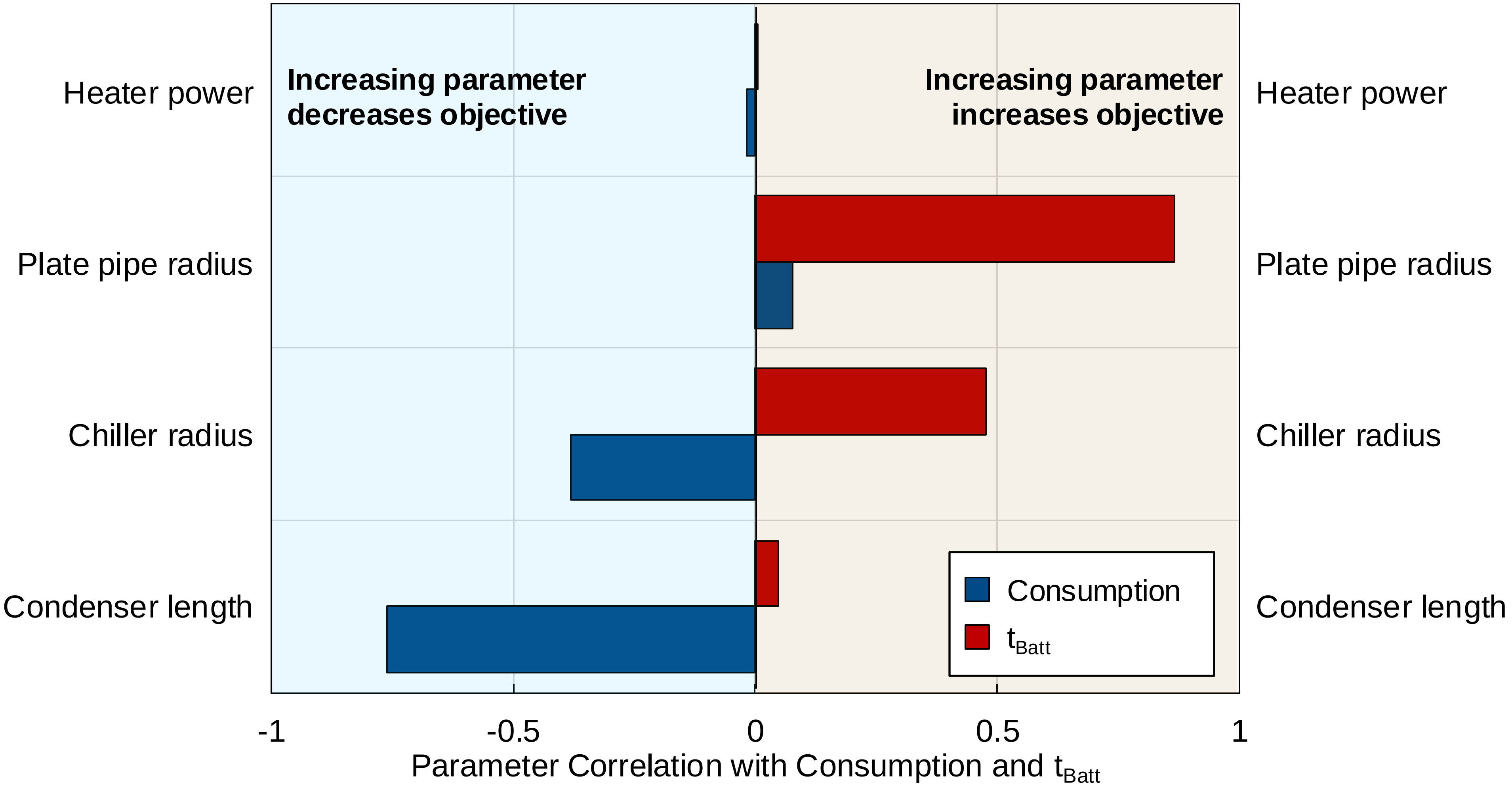
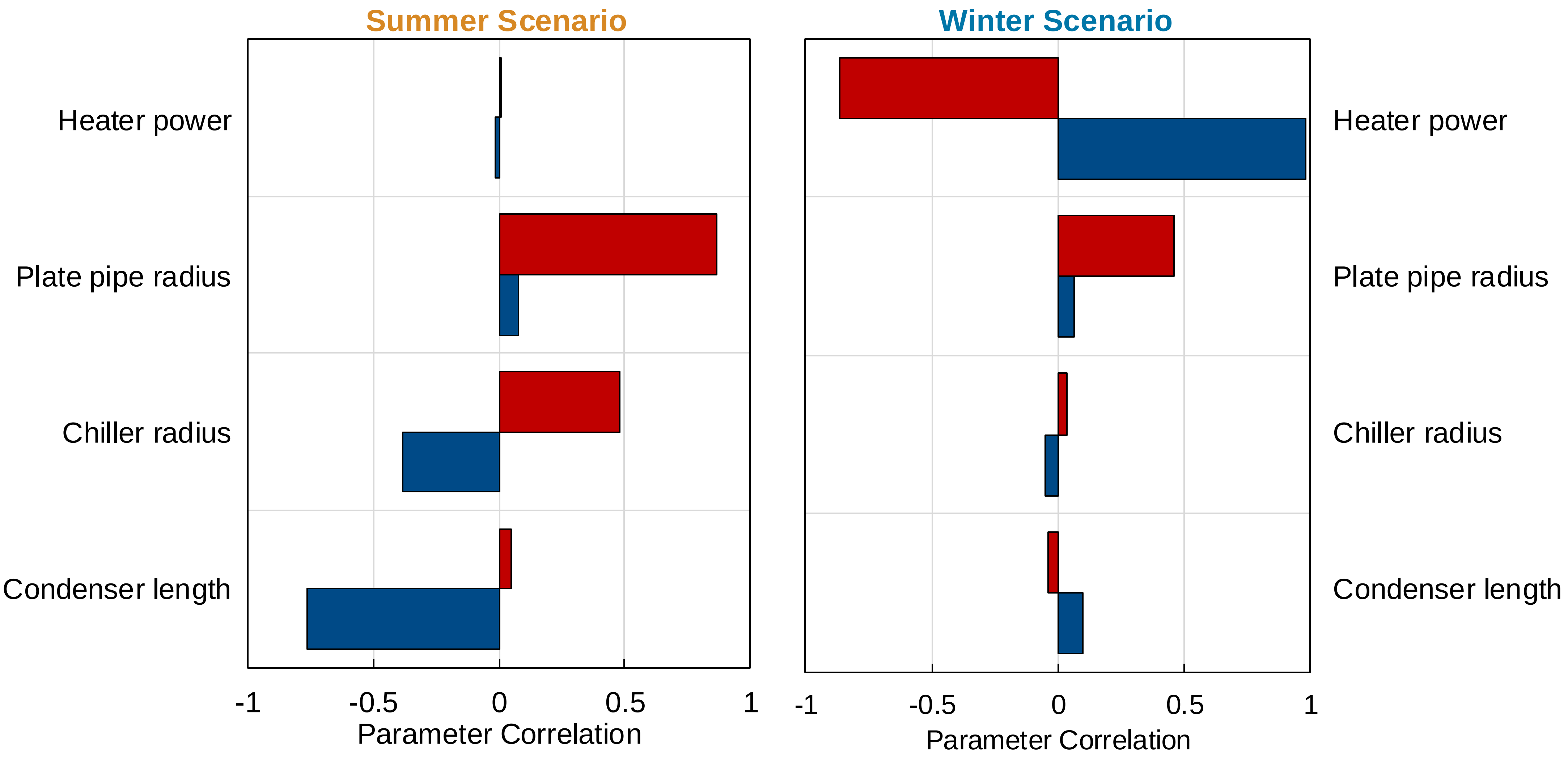


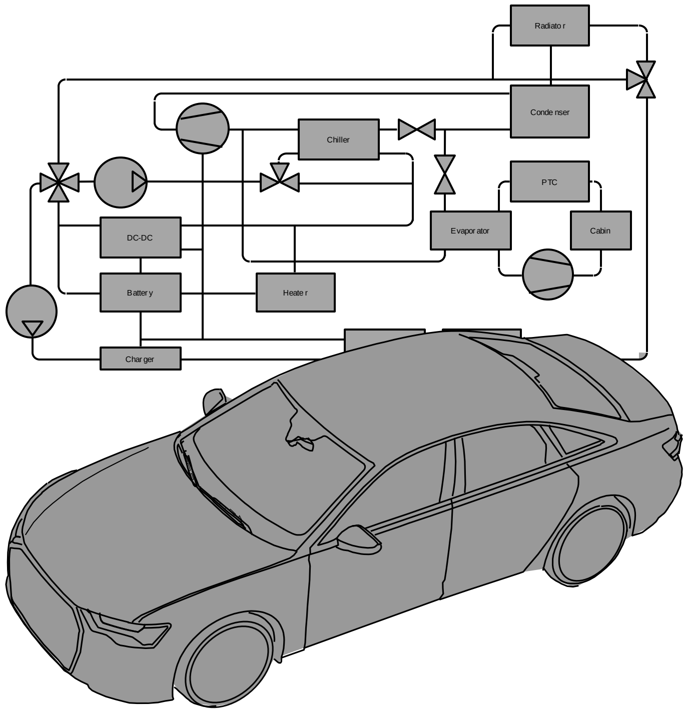
Summer Scenario: The tornado plot highlights the type of correlation between parameters and objectives

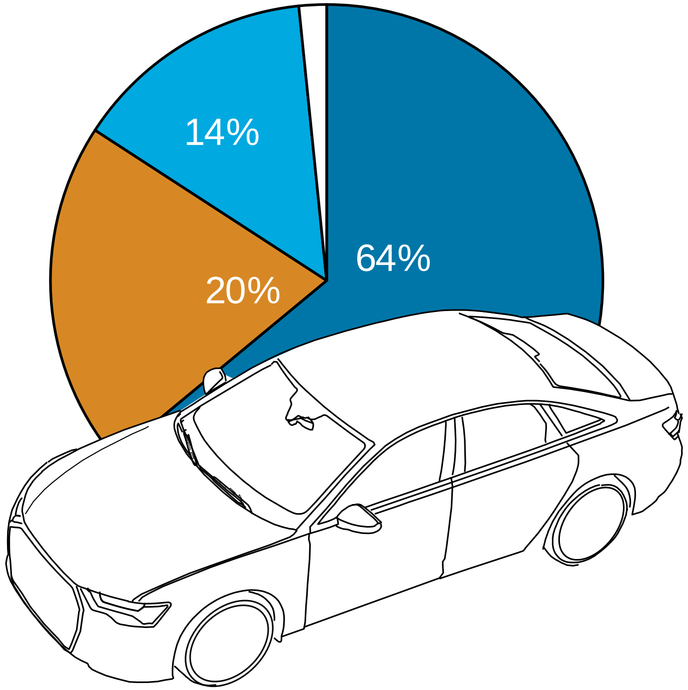


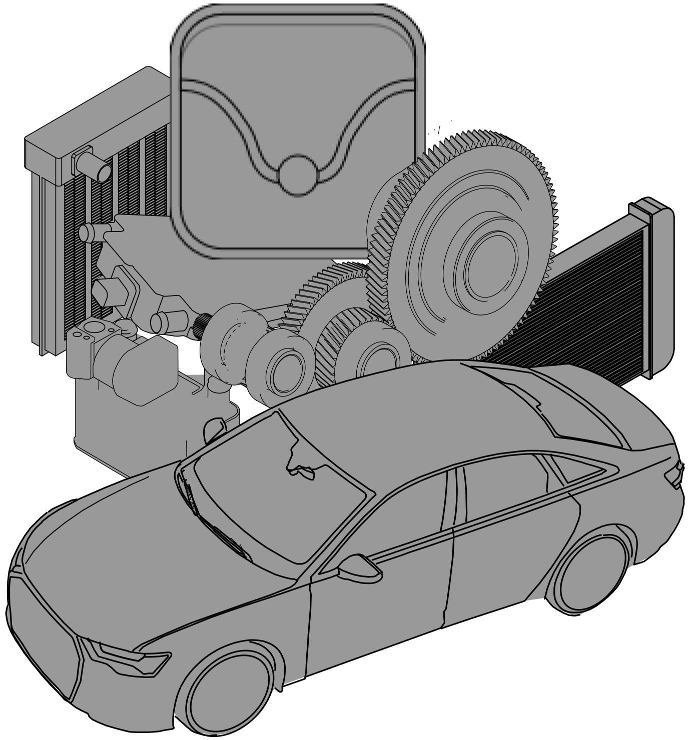
Comparison between winter and summer scenario highlights **completely different sensitivities**



Use the BEV model to **understand your design**

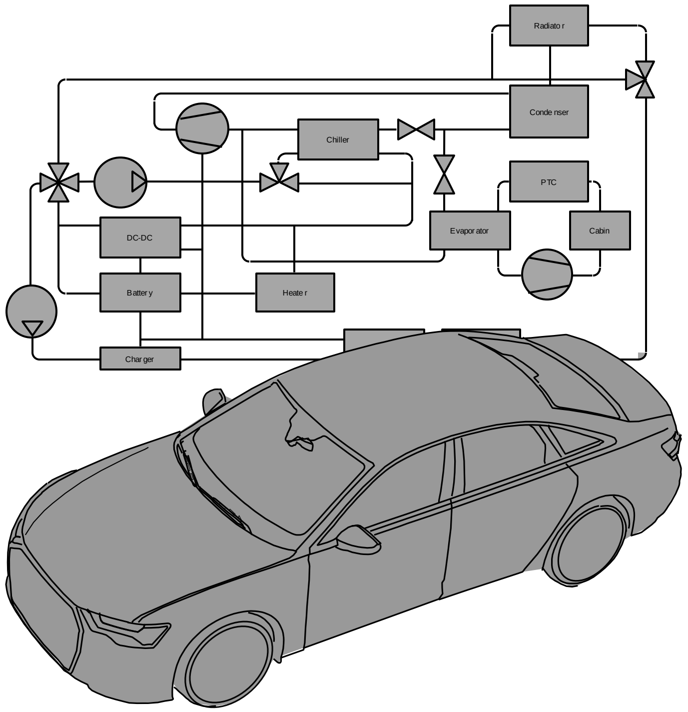


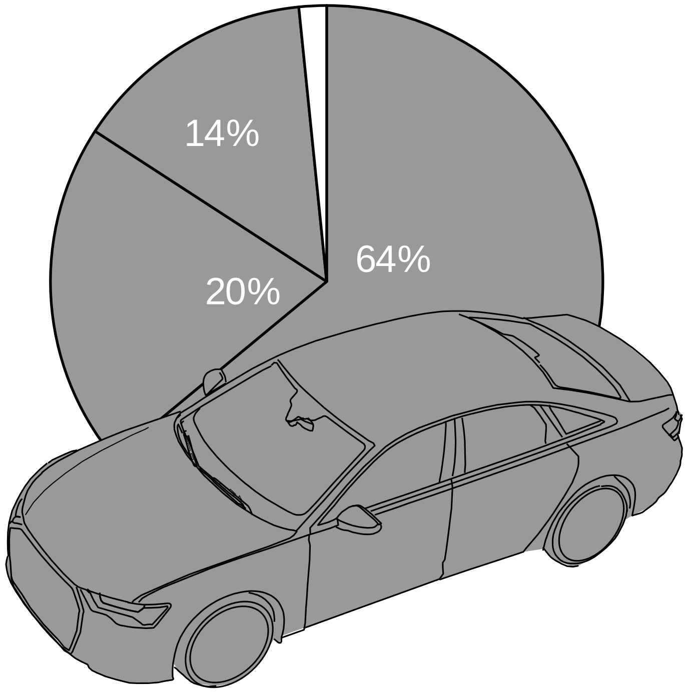


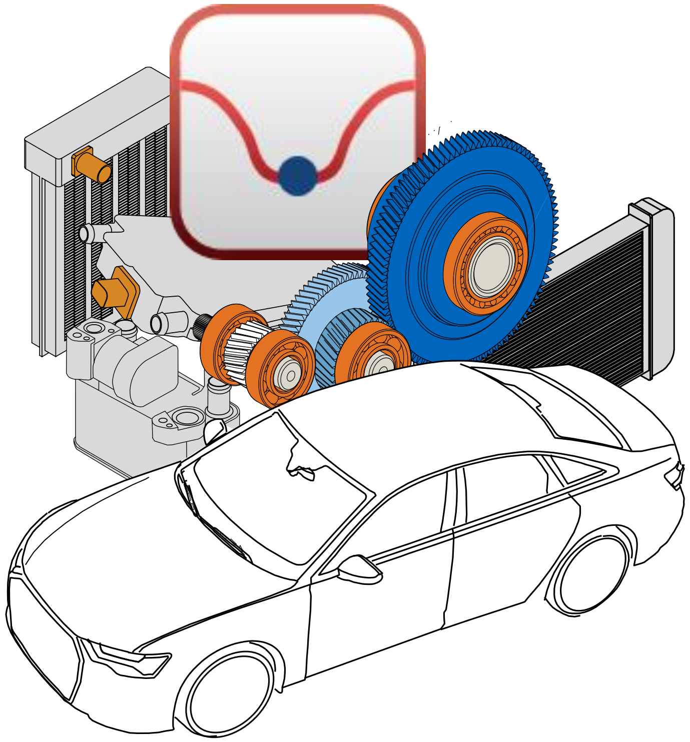


Build Holistic BEV Model **Simulate & Analyze** **Optimize**

Use the BEV model to **optimize your design**







Build Holistic BEV Model **Simulate & Analyze** **Optimize**

The objective is to reduce consumption while ensuring acceptable thermal management performance

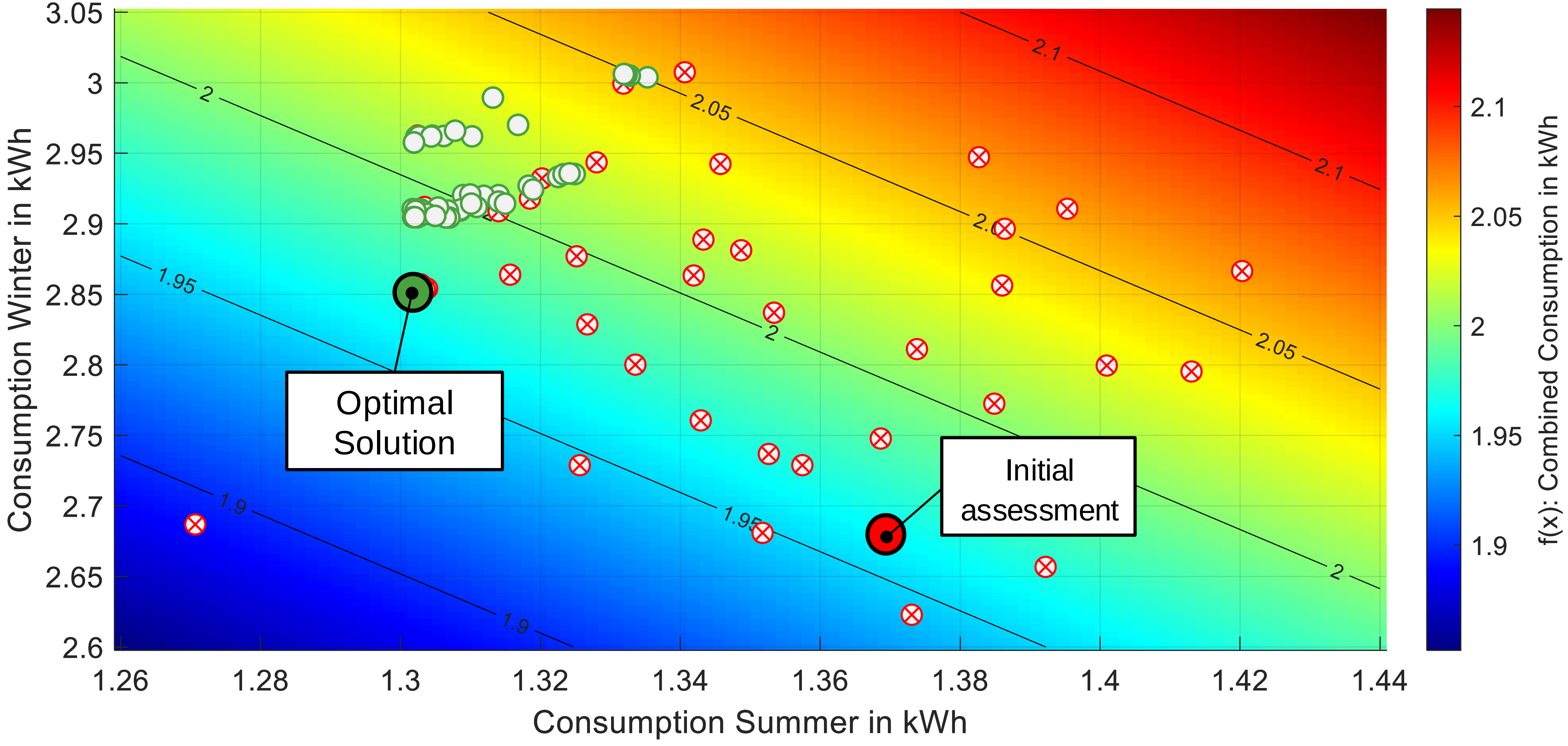
- **Goal:** Minimize combined consumption

$$f(x) = s_{Summer} \times \mathbf{Consumption}_{Summer} + s_{Winter} \times \mathbf{Consumption}_{Winter}$$

- **Constraint:** Battery & cabin reach target temperature quickly
  1. $t_{Battery} \leq 600$ sec
  2. $t_{Cabin} \leq 720$ sec
- **Design Parameters:** Same as for sensitivity analysis
  1. Continuous: Plate and chiller radius, condenser and evaporator length, trans. ratio
  2. Discrete: heater and PTC Power
- **Algorithm:** Global optimizer `surrogateopt`
  – Can handle inequality constraints
  – Can handle discrete design parameters

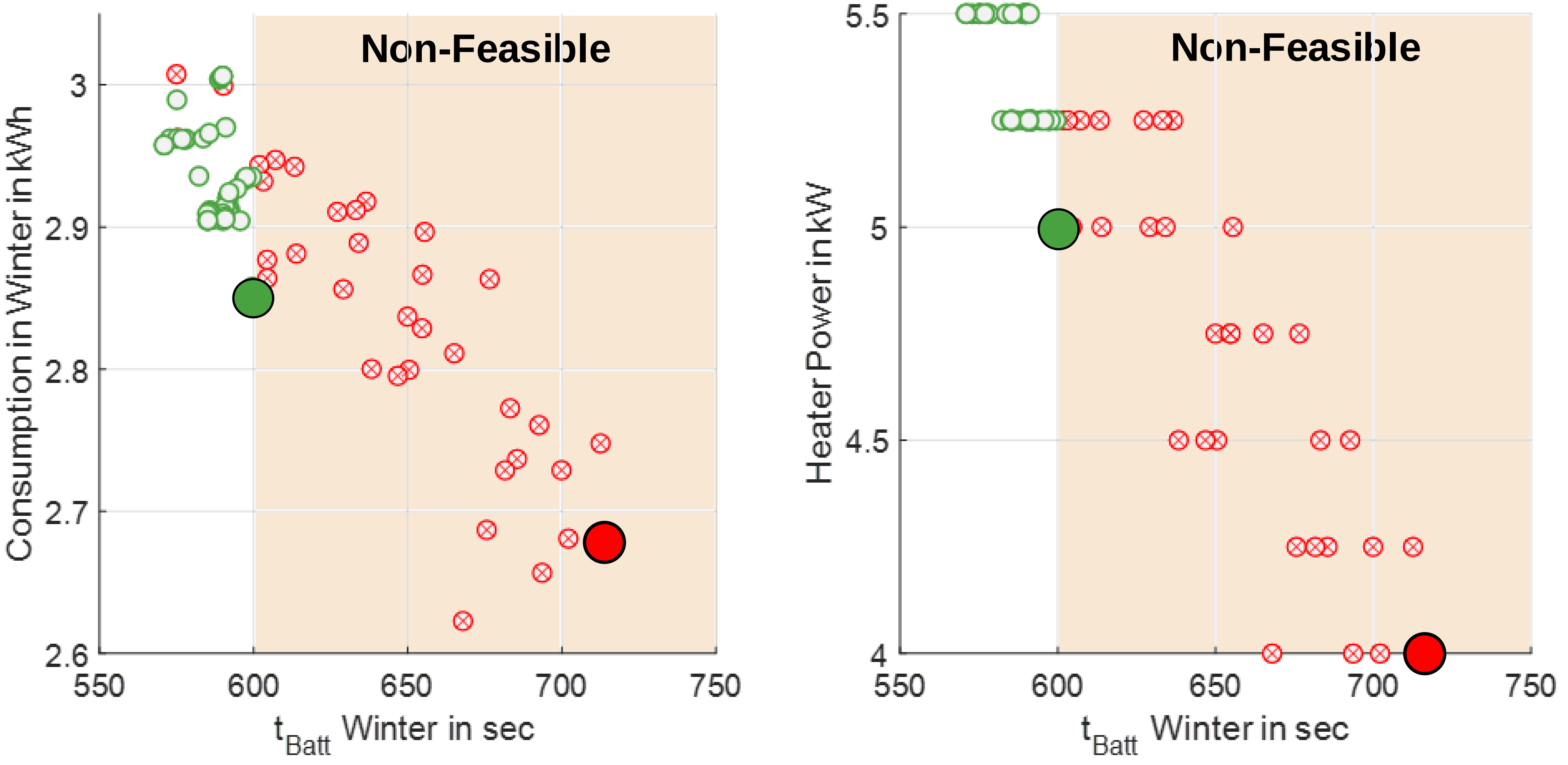
[1] s_{Summer} and s_{Winter} are scaling factor

`surrogateopt` finds a feasible solution **within 1 hour**

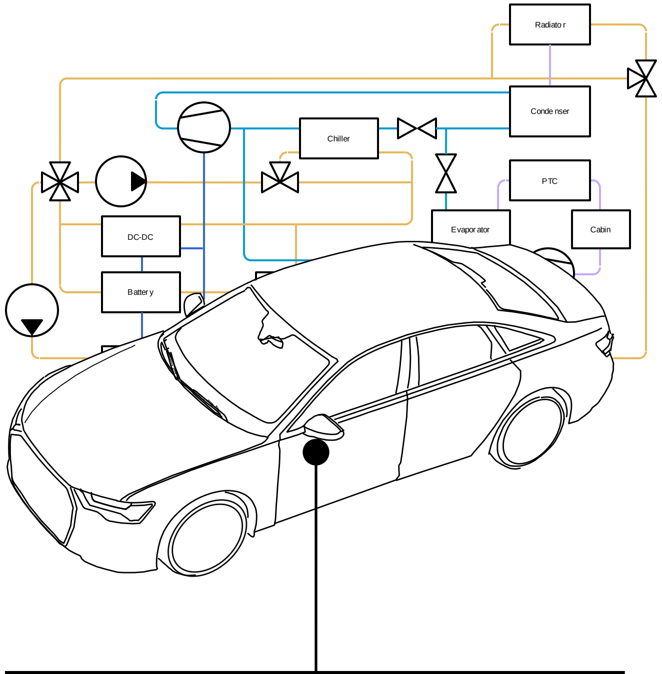


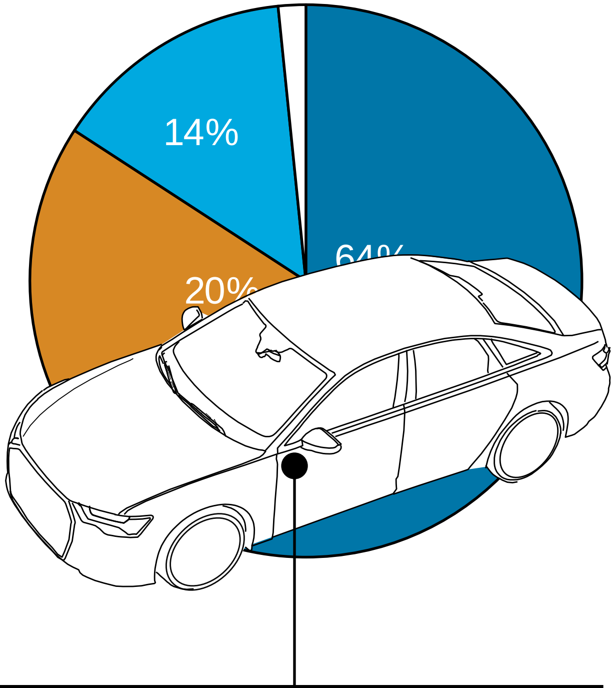
*Optimization lasted ~1h on a laptop with these specs: 13th Gen Intel® Core™ i7-1365U, 32GB RAM, in parallel with 6 cores

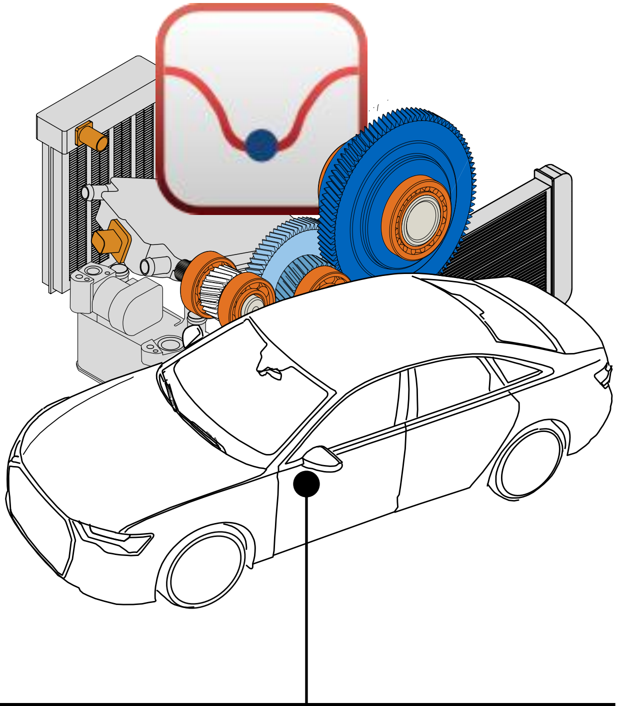
The constraint for heating the battery in less than 600 sec is fulfilled at the cost of a slight increase in consumption



In summary, MathWorks enables smooth workflows for building, analyzing, and optimizing your design







Key Takeaway I
Model complex multi-domain physical systems with Simscape

Key Takeaway II
Easily and quickly set-up a sensitivity analysis with Simulink Design Optimization

Key Takeaway III
Easily optimize designs with multiple variables and constraints with surrogateopt