Digital Twin for Liquid-Cooled Electric Vehicle Battery Packs with Prismatic Lithium Iron Phosphate Cells: A Combined Numerical-Experimental Hierarchical Approach

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CORE CONCEPTS

Digital twins are real-time digital replicas of physical systems that enable predictive maintenance, performance optimization, and lifecycle management.

Finite element analyses (FEA) are accurate but computationally prohibitive for real-time digital twins of large systems.

Reduced-order models (ROMs) balance computational efficiency and predictive accuracy.

MOTIVATION

Eclectic vehicle (EV) battery packs with large prismatic cells might exhibit significant inter- and intra-cell spatio-temporal temperature gradients, accelerating battery degradation.

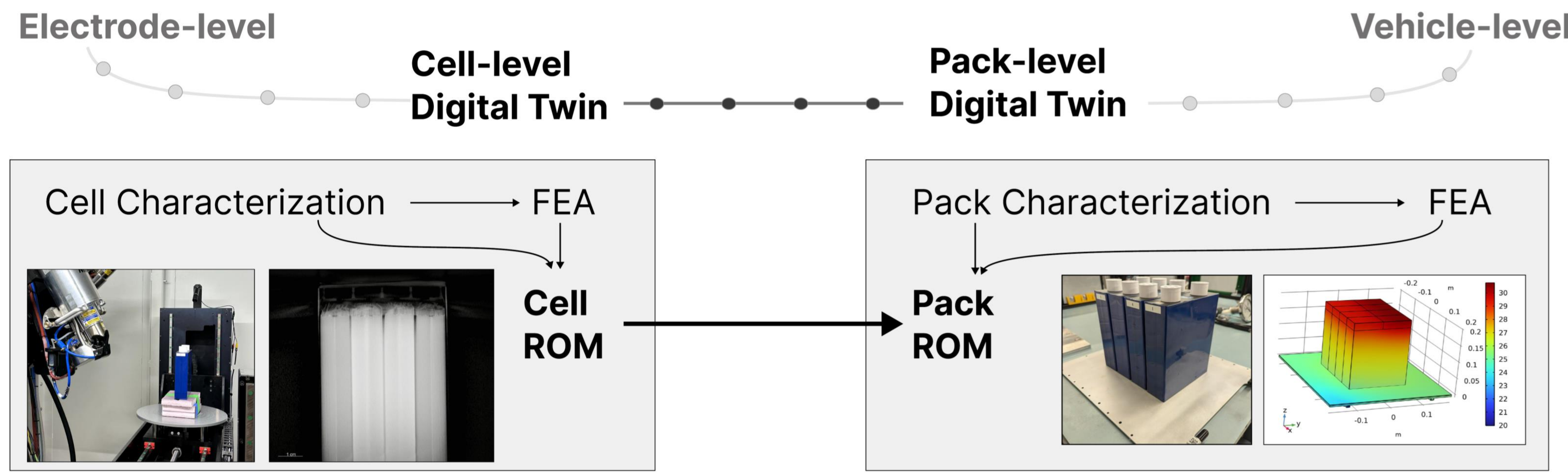
Effective digital twins of EV battery packs are paramount for real-time predictions and optimal thermal and electrical performance.

GOAL

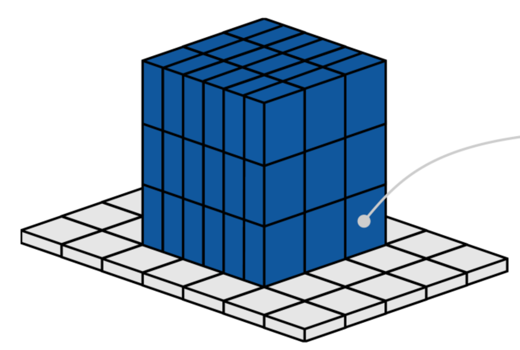
This work proposes a novel approach to modelling the thermo-electrical performance of liquid-cooled EV battery packs with prismatic cells using a **hierarchical ROM framework**.

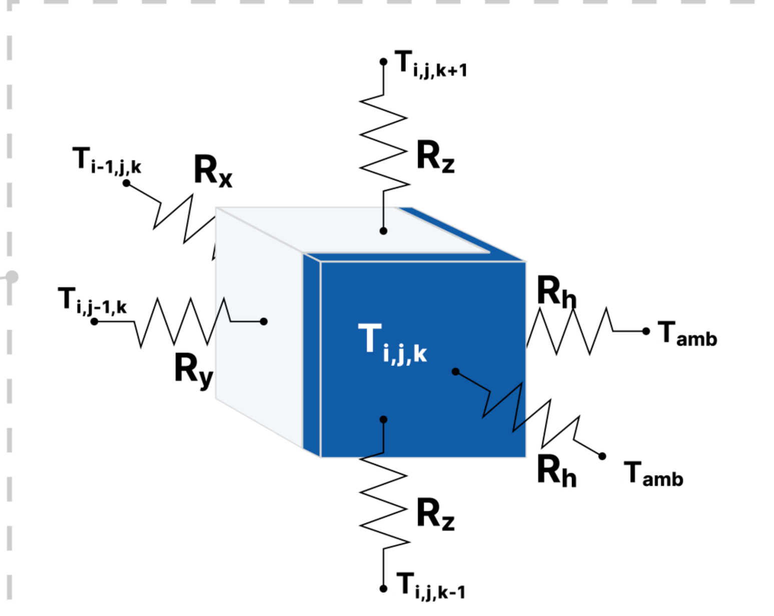
The framework is highly iterative, with experiments and results at lower levels of the hierarchy informing design and modelling decisions at higher levels.

HIERARCHICHAL METHODOLOGY



REDUCED-ORDER NUMERICAL MODELLING





Energy Equation Per Element

$$mC_p\frac{T^{t+\Delta t}-T^t}{\Delta t}=\sum_{i=x,y,z}\left(\frac{T_{i+}-T}{R_{i+}}+\frac{T_{i-}-T}{R_{i-}}\right)+\dot{q}\mathrm{Vol}+C_f\dot{m}(T_{i-}-T)$$

Thermal Resistance

$$R_i=\frac{L_i}{k_i\cdot A_i}\quad \text{for } i=x,y,z$$

Thermal Conductivity

$$k_{\parallel}=\frac{\sum_i d_i k_i}{\sum_i d_i}$$

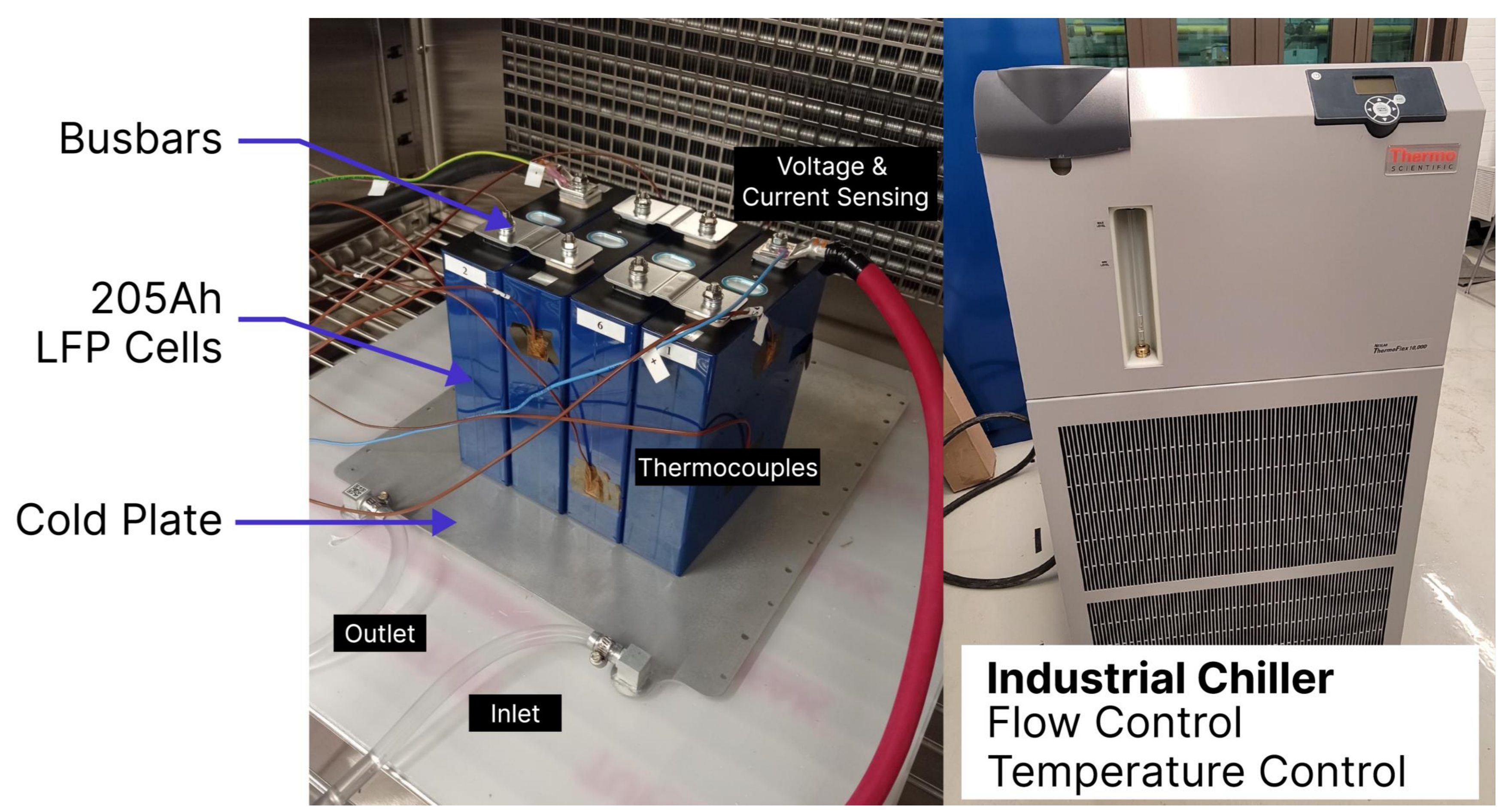
Heat Capacity

$$\rho c_p=\frac{\sum_i \rho_i c_{p,i} d_i}{\sum_i d_i}$$

Equation For Thermal Network

$$\mathbf{T}(t+\Delta t)=\mathbf{T}(t)+\frac{\Delta t}{mC_p}(\mathbf{K}\mathbf{T}(t)+\mathbf{Q})$$

EXPERIMENTAL SETUP



Baseline battery module with 4 prismatic cells, a cold plate, and cooling fluid.

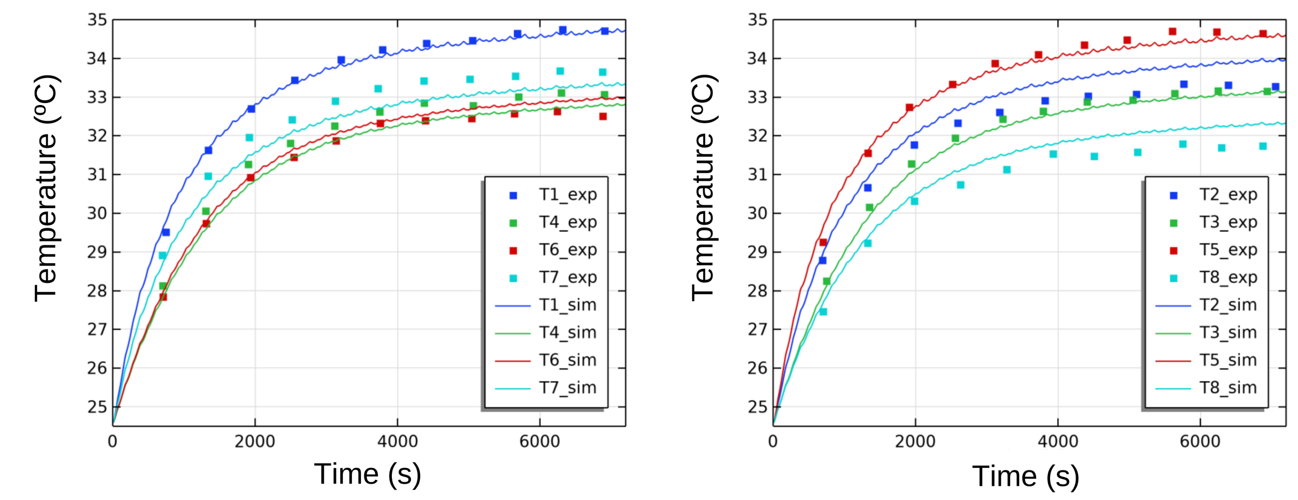
Heat generation is calculated from the input current and voltage data.

$$Q_{gen}(t)=|I(t)\cdot(V_t(t)-V_{oc}(SOC))|$$

Transient temperature data is collected to validate models.

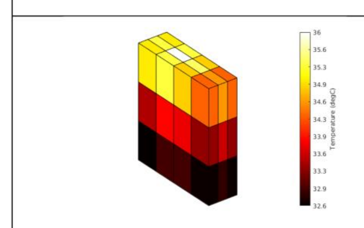
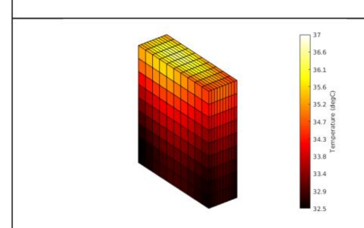
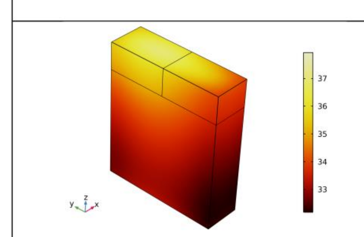
RESULTS & DISCUSSION

Characterization Results



Property	Fitted Value
Specific Heat Capacity (C_p)	1151 [J/(kg*K)]
Thermal Conductivity in x (k_x)	1.29 [W/(m*K)]
Thermal Conductivity in y (k_y)	2.15 [W/(m*K)]
Thermal Conductivity in z (k_z)	12.06 [W/(m*K)]
Geometric Factor (gf)	5
Concentration Factor 1 (cf1)	0.17
Concentration Factor 2 (cf2)	0.25

Computational Efficiency

Temperature gradient	Model	Degrees of freedom	Time to compute for $T_{sim}=7200$ seconds
	Thermal network	3x4x3 isothermal elements (36 total)	0.4 seconds
	Thermal network	10x10x9 isothermal elements (900 total)	1.7 seconds
	FEA model	6943 finite elements	221 seconds

ROM predictions closely match experimental results and are significantly faster than FEA-based models.

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