A simulation-based platform to design high-performance buildings that use phase change materials

Dr. Facundo Bre[1,2]
Prof. Eduardus Koenders[1]

[1] *Institut für Werkstoffe im Bauwesen, Technische Universität Darmstadt, Darmstadt, Deutschland*
E-Mail: bre@wib.tu-darmstadt.de

[2] *Centro de Investigación de Métodos Computacionales (CIMEC), UNL, CONICET, Predio Dr. Alberto Cassano, Colectora Ruta Nacional 168, Paraje El Pozo, Argentina*
E-Mail: facubre@cimec.santafe-conicet.gov.ar

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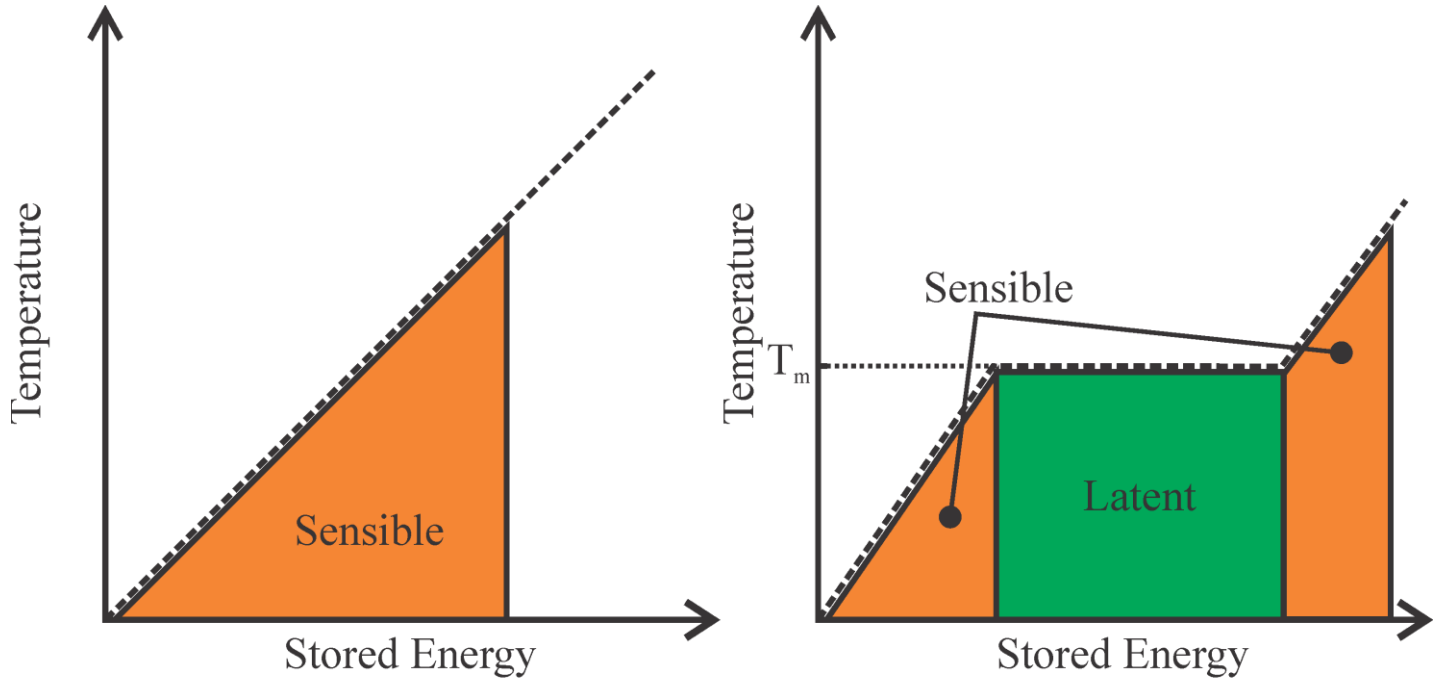
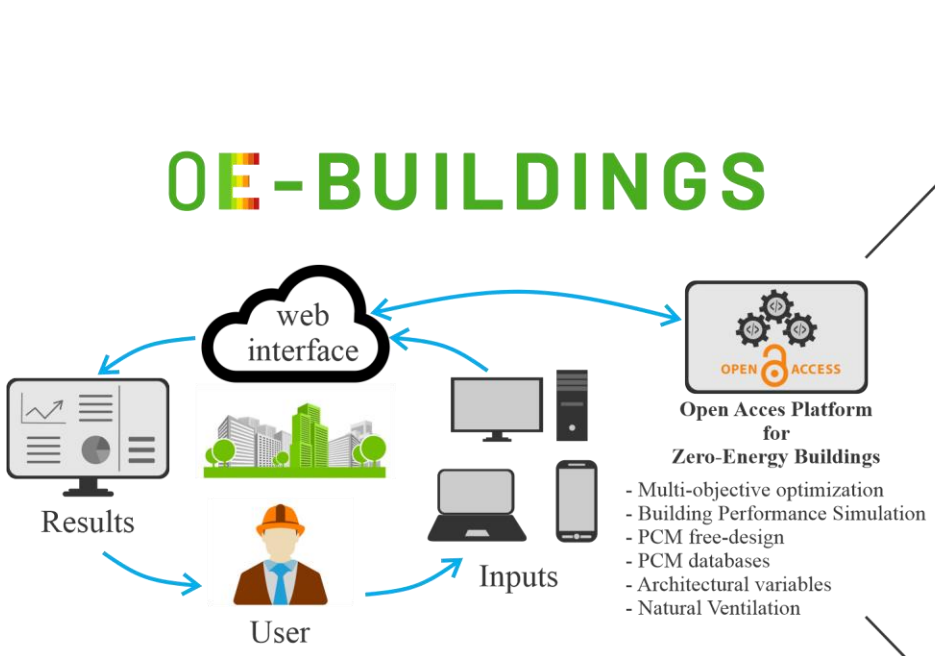
Phase change materials

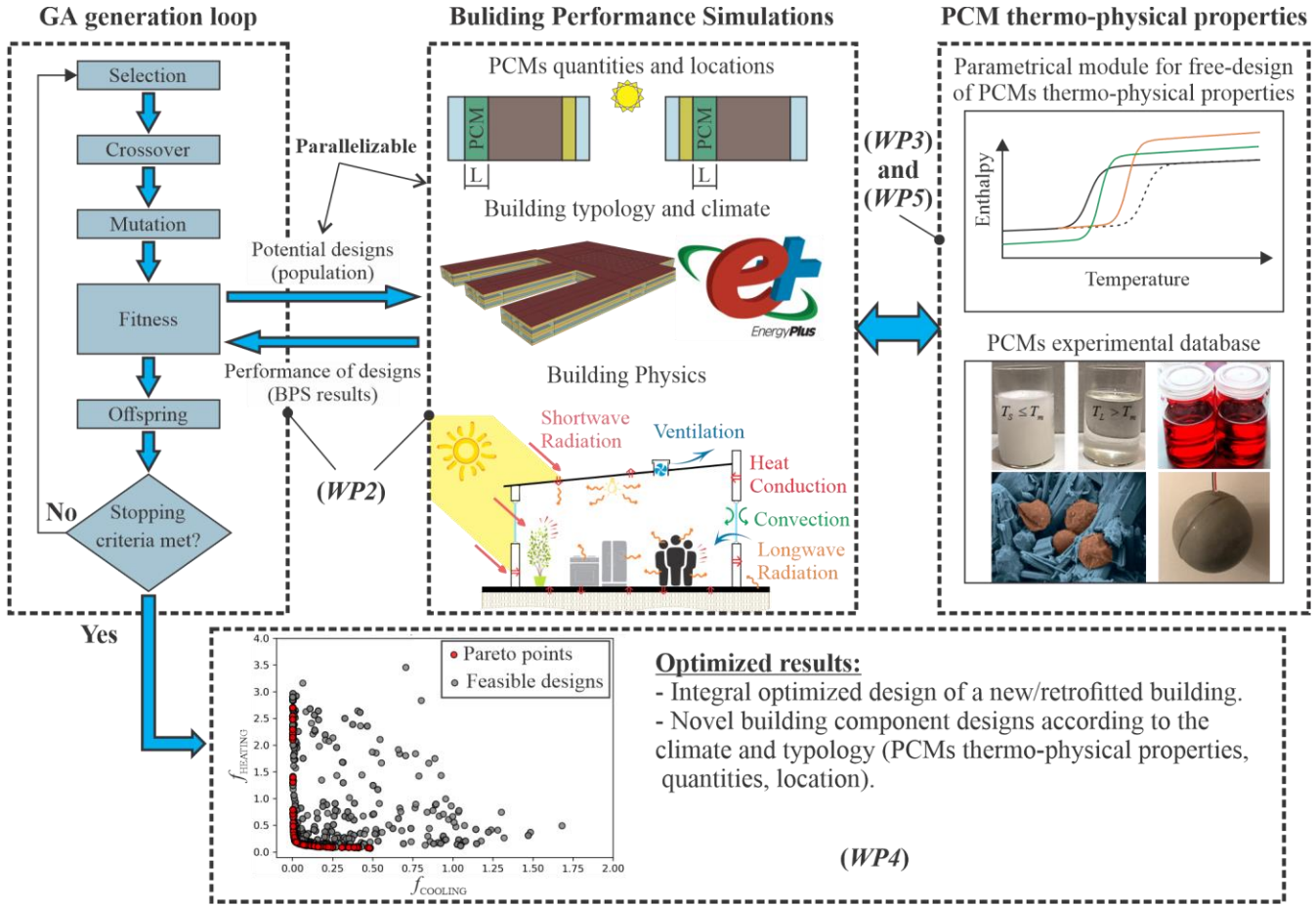
Phase change materials (PCMs) are substances that can absorb/release large amounts of heat during the phase transition.



(a) Material without phase change (b) Material with phase change

The OE-BUILDINGS project (MSCA-IF)





https://cordis.europa.eu/project/id/101024627

PCM modeling in buildings

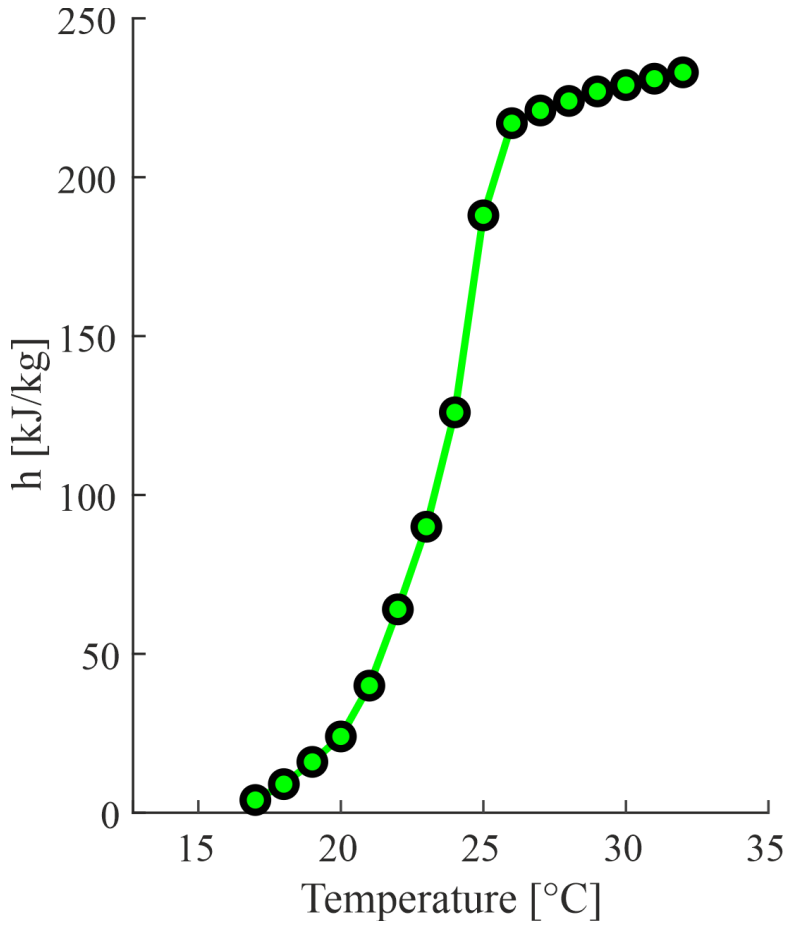
EnergyPlus

The thermal capacity of PCMs is iteratively calculated at each time step as:

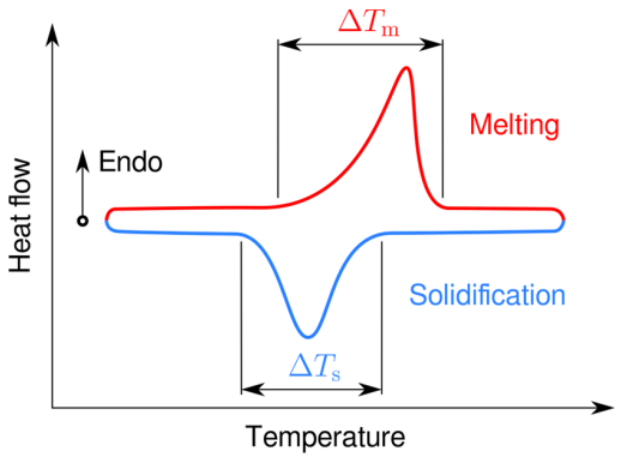
$$c_p(T) = \frac{h_i^j - h_i^{j-1}}{T_i^j - T_i^{j-1}},$$

where h is the enthalpy (J/kg), *T* is the temperature (°C), *i* indicates the material node, and *j* and *j-1* indicate the current and previous time steps, respectively.

Single curve - *MaterialProperty:PhaseChange*



Phase change hysteresis of PCMs



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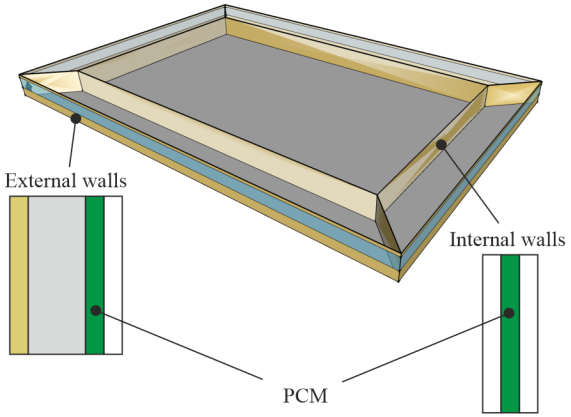
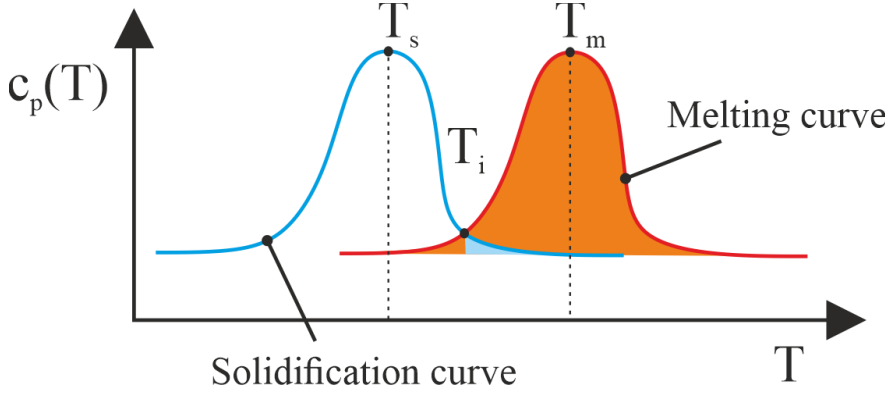
Phase change hysteresis

- Hysteresis in PCMs introduces a temperature delay between melting and solidification, complicating their behavior and modeling.

Dual curve - *MaterialProperty:PhaseChangeHysteresis*





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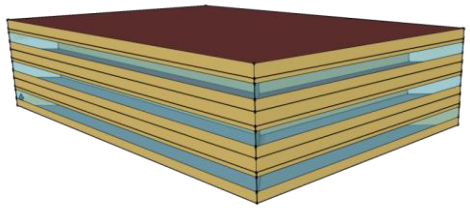
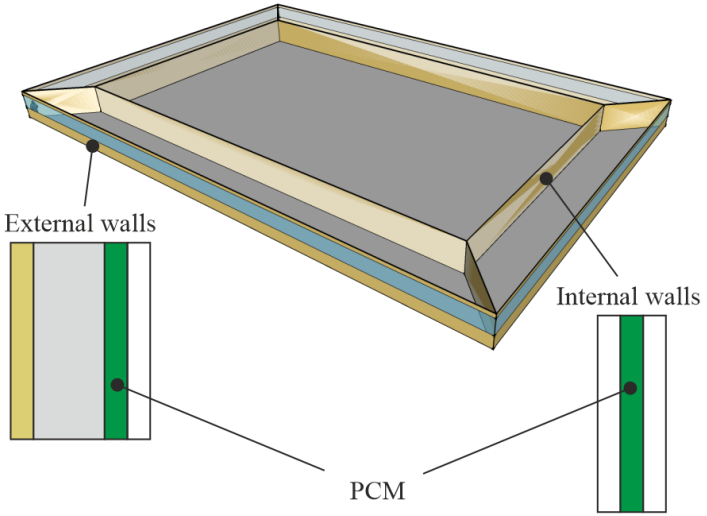
- A “numerical energy” is generated because of the modeling approach when incomplete cycles occur.
- The model is not energy-conservative because of the switching approach between curves.
- Large heating/cooling load reductions can be wrong-predicted (5 times higher than PCMs without hysteresis).

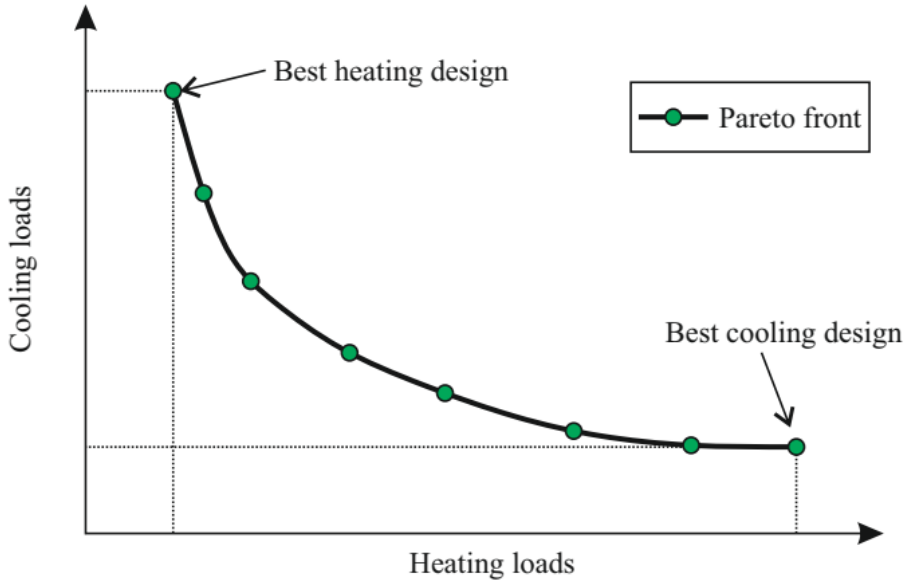
Design of PCMs in buildings

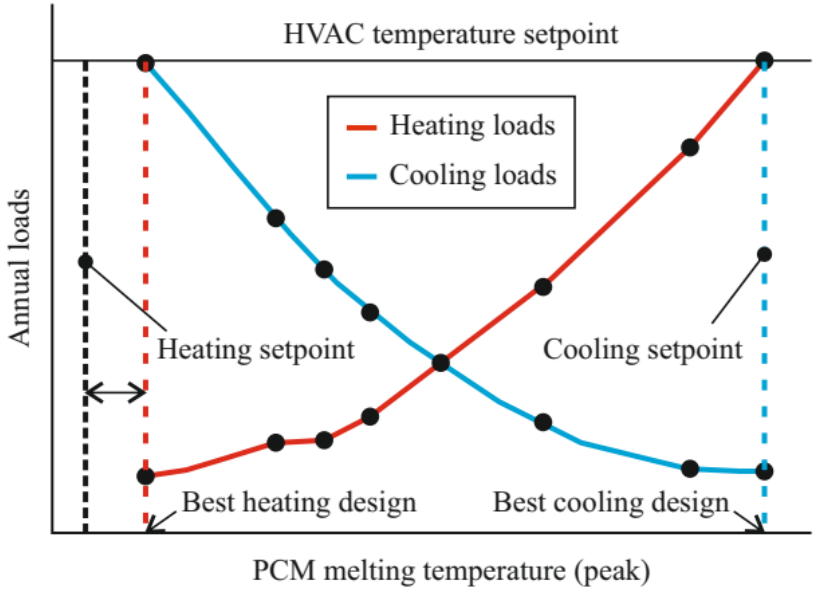
PCM design parameters:

- **Melting temperature.**
- **Location.**
- **Amount.**
- Thermal conductivity.
- Thermal capacity.
- Others.

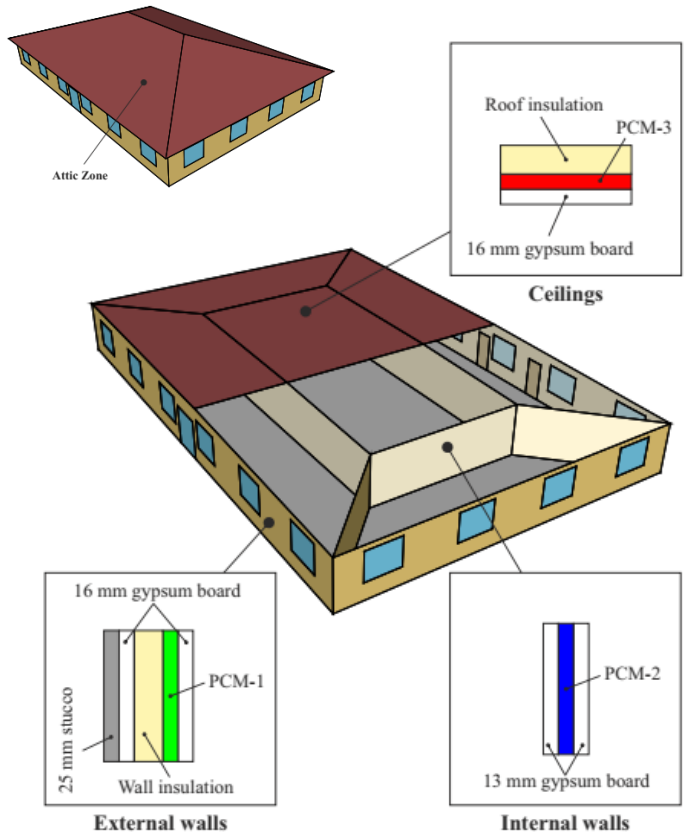








Use and optimization of PCMs with different melting temperatures in buildings



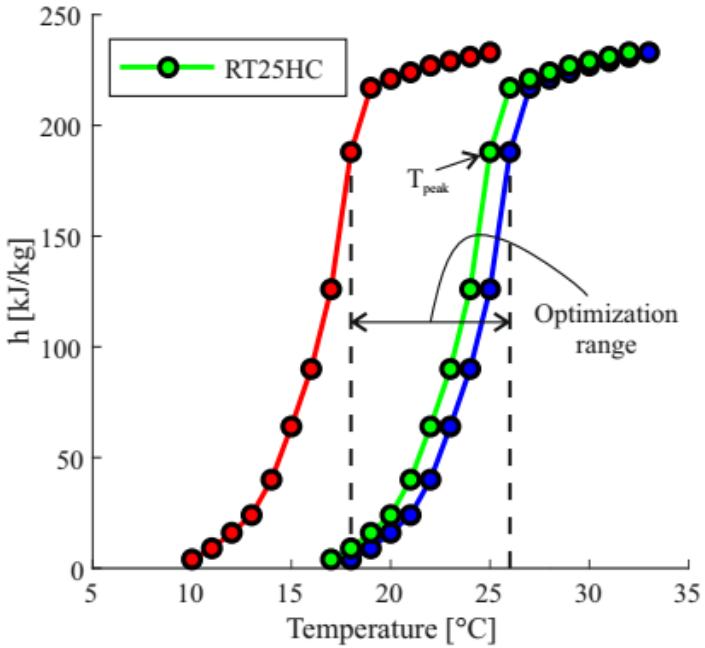
$$\min_{\mathbf{x}\in\mathcal{V}} \quad [f_1(\mathbf{x}), f_2(\mathbf{x})]$$

subject to :

$$x_i^L \leq x_i \leq x_i^U, \; i = 1, \ldots, n;$$

The objective functions *f1*(x) and *f2*(x) are annual heating and cooling loads, which are obtained from the results for each EnergyPlus simulation.

Design variable	x^L	x^U
T_{peak} PCM-1 [°C]	18	26
T_{peak} PCM-2 [°C]	18	26
T_{peak} PCM-3 [°C]	18	26
Thickness PCM-1 [m]	0.001	0.025
Thickness PCM-2 [m]	0.001	0.025
Thickness PCM-3 [m]	0.001	0.025



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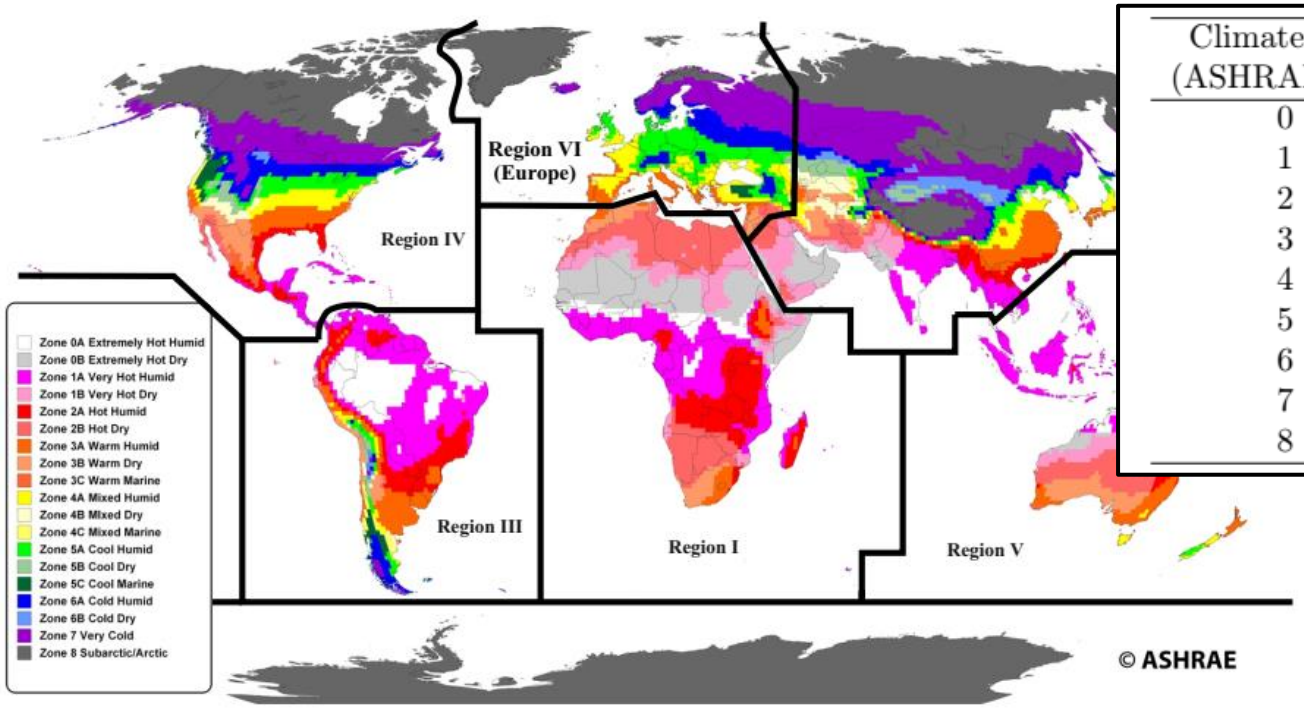
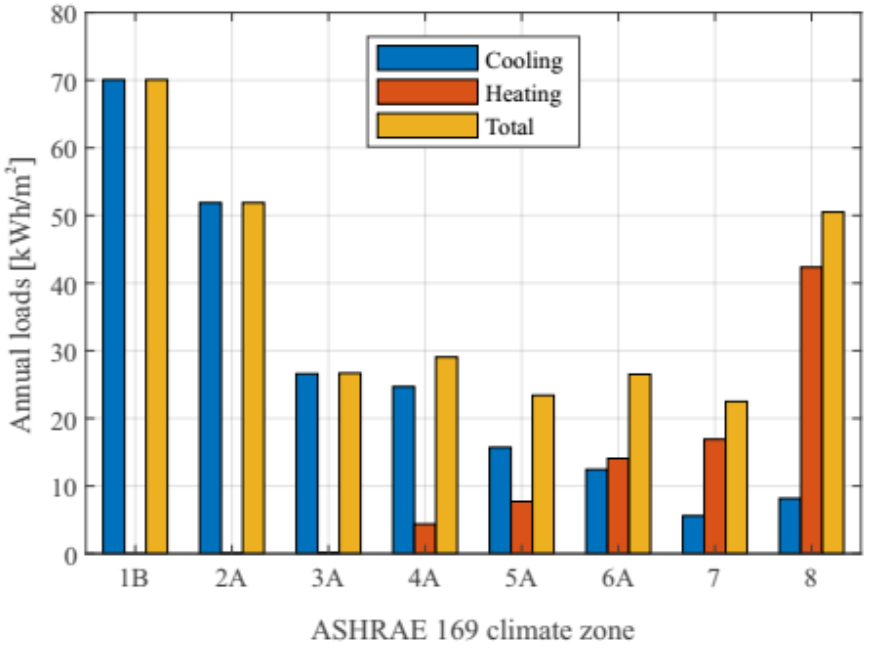
Climate-representative locations (ASHRAE-169) in the WMO-Region VI (Europe)



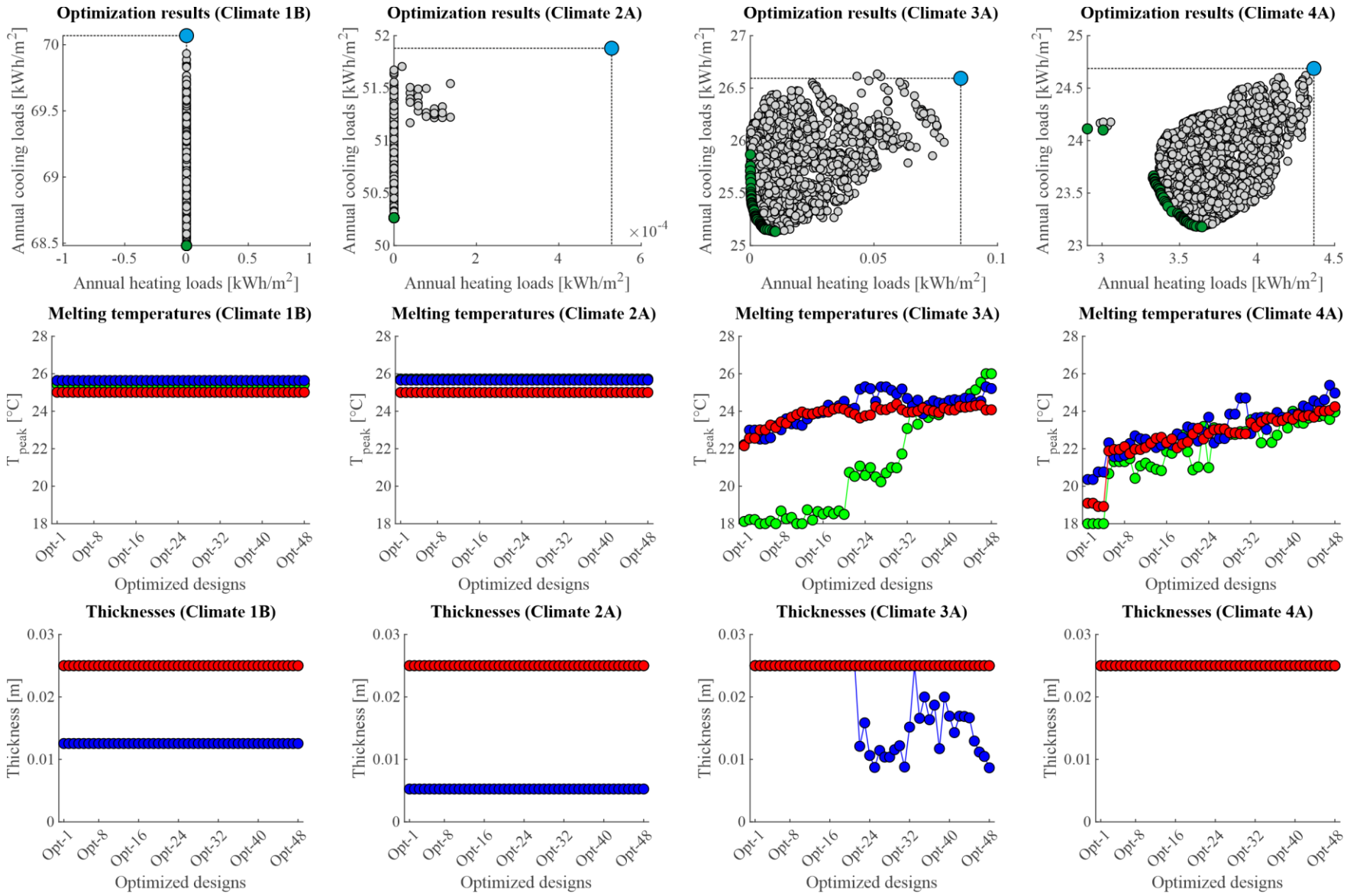
Climate zone (ASHRAE 169)	Climate description	Criteria - CDD10 [°C], HDD18 [°C]
0	Extremely Hot	6000 < CDD10
1	Very Hot	5000 < CDD10 <= 6000
2	Hot	3500 < CDD10 <= 5000
3	Warm	CDD10 <= 3500 & HDD18 <= 2000
4	Mixed	CDD10 <= 3500 & 2000 < HDD18 < 3000
5	Cool	CDD10 <= 3500 & 3000 < HDD18 < 4000
6	Cool	4000 < HDD18 <= 5000
7	Very Cold	5000 < HDD18 <= 7000
8	Subarctic/Arctic	7000 < HDD18

Climate zone (ASHRAE 169)	Selected location	Latitude	Longitude	Elevation [m]	WMO ID	CDD10 [°C]	HDD18 [°C]
1B	Aqaba (Jordan)	N 29° 36.72'	E 35° 1.08'	53	403400	5597	162
2A	Beirut (Lebanon)	N 33° 49.26'	E 35° 29.28'	27	401000	4217	319
3A	Capo Pertusato (France)	N 41° 22.48'	E 9° 10.70'	116	77700	2464	1116
4A	Osijek (Croatia)	N 45° 27.78'	E 18° 48.60'	88	142840	1964	2502
5A	Torun (Poland)	N 53° 3.00'	E 18° 34.98'	72	122500	1027	3499
6A	Kongsvinger (Norway)	N 60° 11.42'	E 12° 0.40'	148	14680	614	4498
7	Hovden (Norway)	N 59° 34.60'	E 7° 23.38'	836	14410	127	6005
8	Qaanaaq (Greenland)	N 77° 29.10'	W 69° 22.38'	16	42050	7	9676



https://climate.onebuilding.org/

Optimization results



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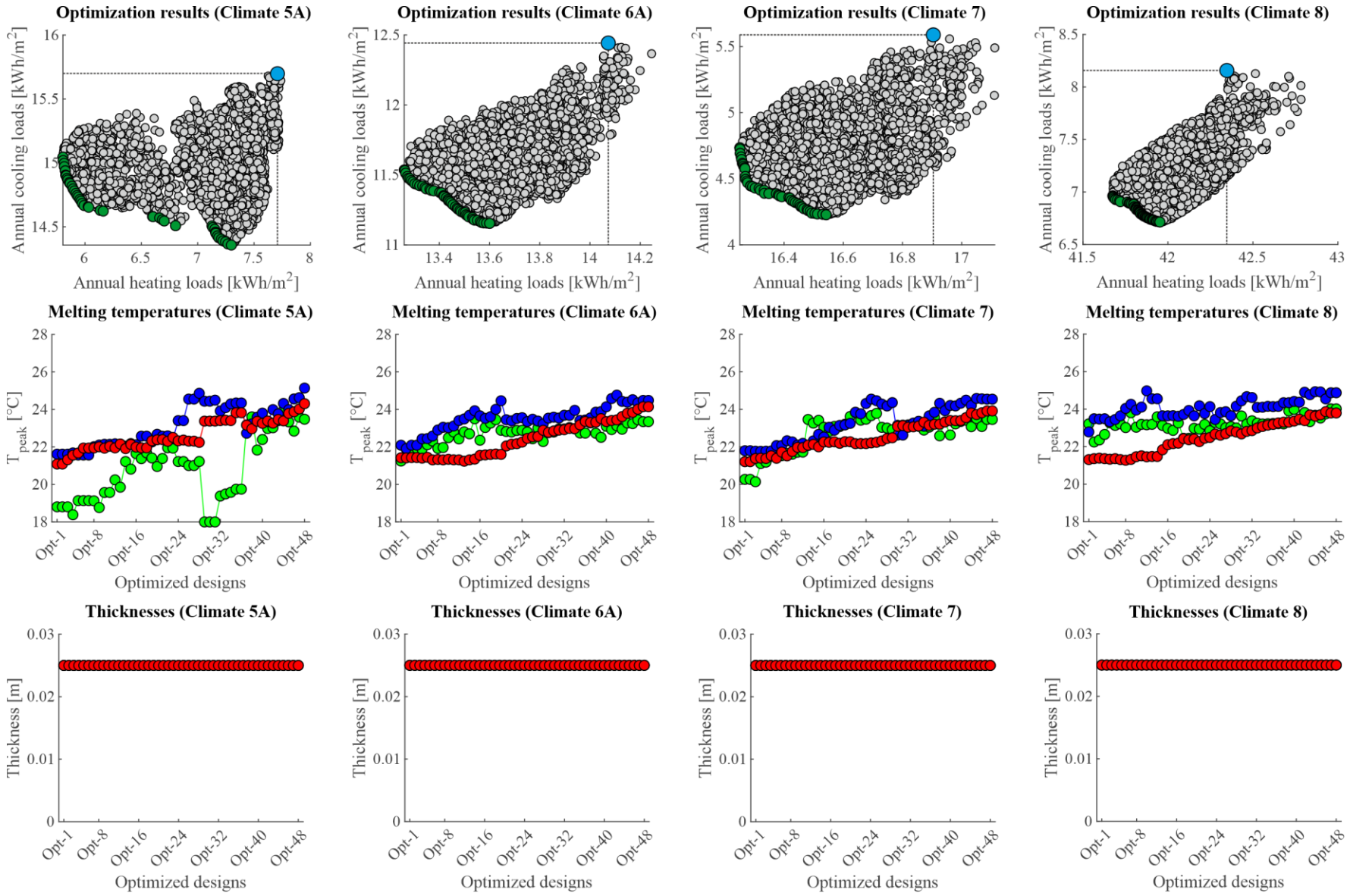
Optimization results



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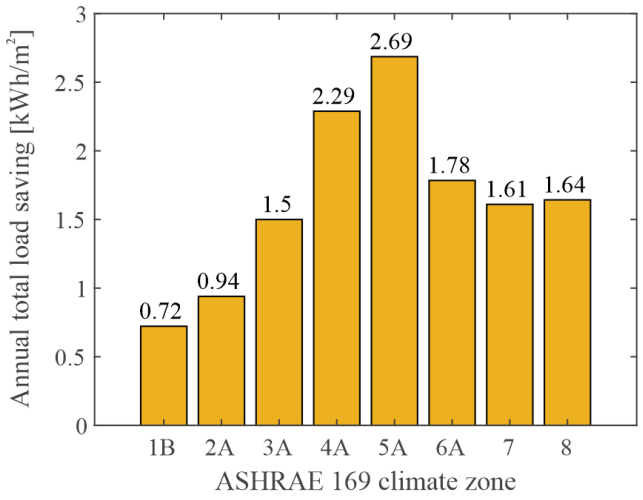
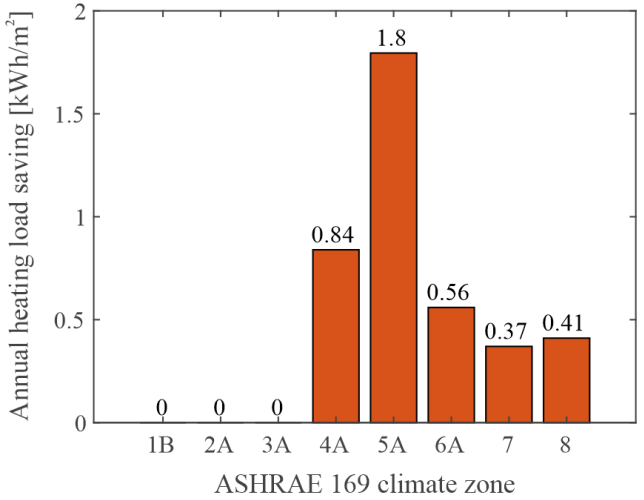
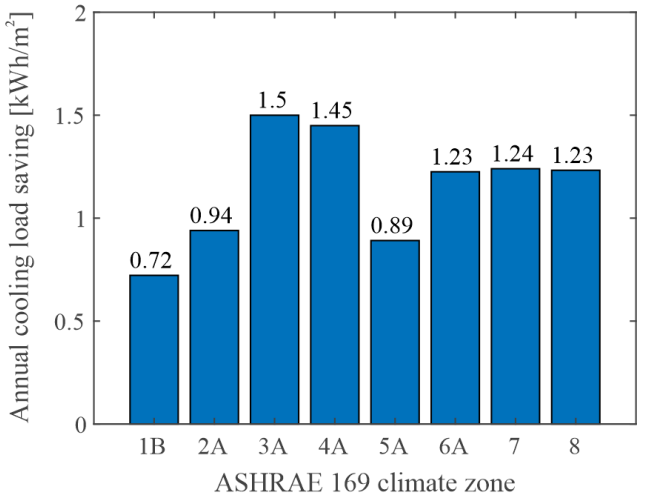
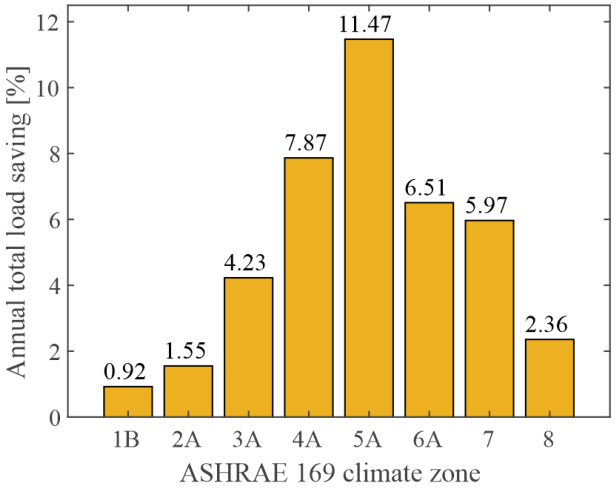
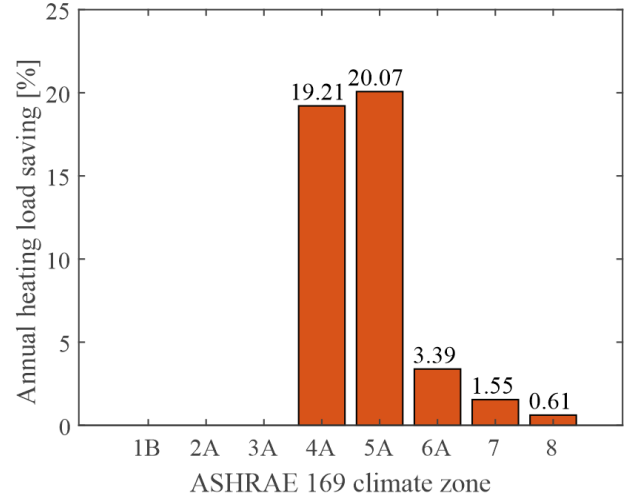
Optimization results: load reductions

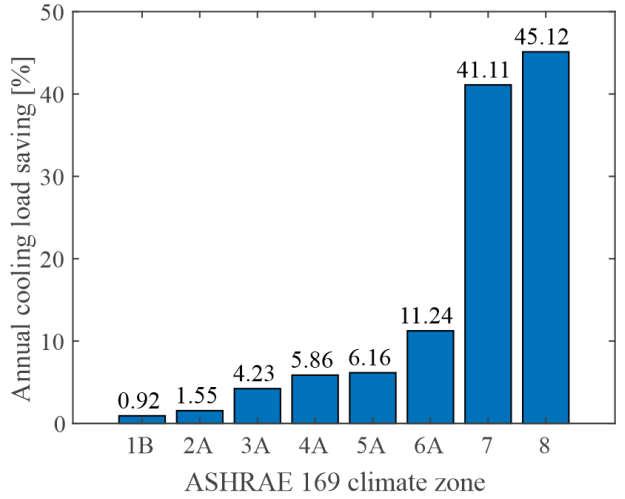












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Effectiveness Indicators for PCMs

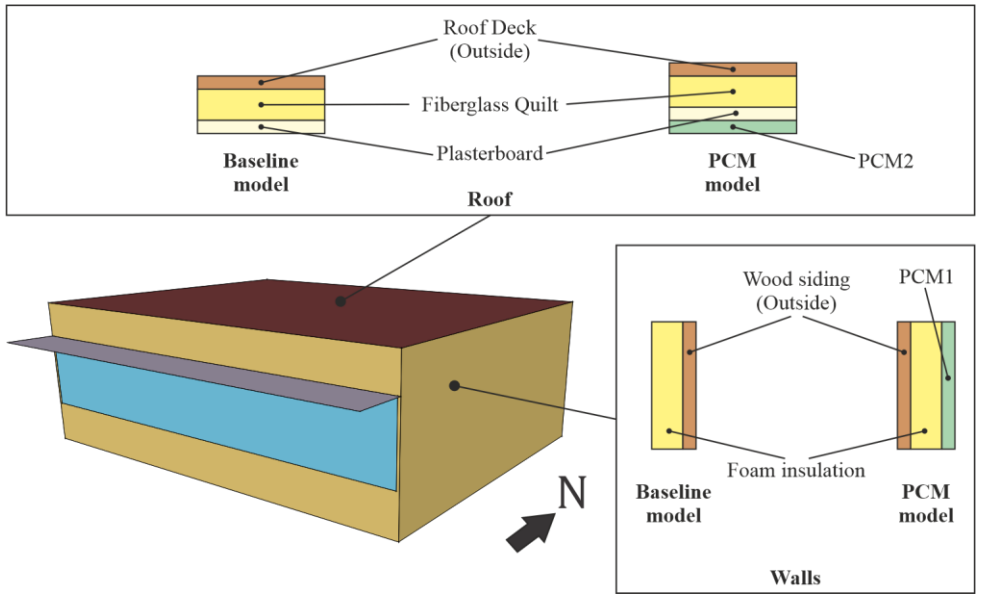
$$\mathrm{PCMEI} = \frac{\mathrm{ALS}}{\mathrm{LSC}}$$

- **ALS** is the annual load saved (kJ) by the incorporation of PCMs into the building.

$$\mathrm{ALS} = \mathrm{AL}_{\mathrm{Baseline}} - \mathrm{AL}_{\mathrm{PCM}}$$

- **LSC** is the latent heat storage capacity (kJ) installed in the building using PCMs.

$$\mathrm{LSC} = \sum_{i=1}^{N} m_{\mathrm{PCM_i}} \Delta h_{\mathrm{PCM_i}}$$



Sensitivity analysis using the Morris method.

#	Design variable	ID	Unity	Level 1	Level 2	Level 3	Level 4
1	Thickness of PCM1 (walls)	$\mathrm{THK_{PCM1}}$	m	0.005	0.020	0.035	0.050
2	Thickness of PCM2 (roof)	$\mathrm{THK_{PCM2}}$	m	0.005	0.020	0.035	0.050
3	Peak melting temperature of PCM1 (walls)	$\mathrm{Tpeak_{PCM1}}$	°C	20.5	22.5	24.5	26.5
4	Peak melting temperature of PCM2 (roof)	$\mathrm{Tpeak_{PCM2}}$	°C	20.5	22.5	24.5	26.5
5	Thickness of insulation in the walls	$\mathrm{THK_{INSUL}}$	m	0.050	0.083	0.117	0.150
6	Window-to-wall ratio	WWR	%	30	50	70	90
7	External shading length ratio	ESR	%	1	34	67	100

Effectiveness Indicators for PCMs

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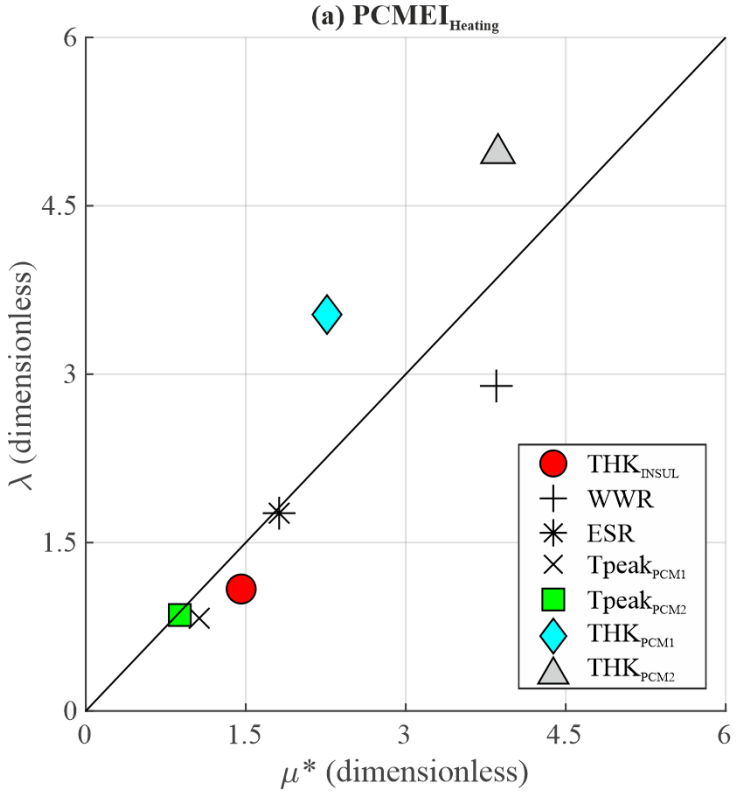
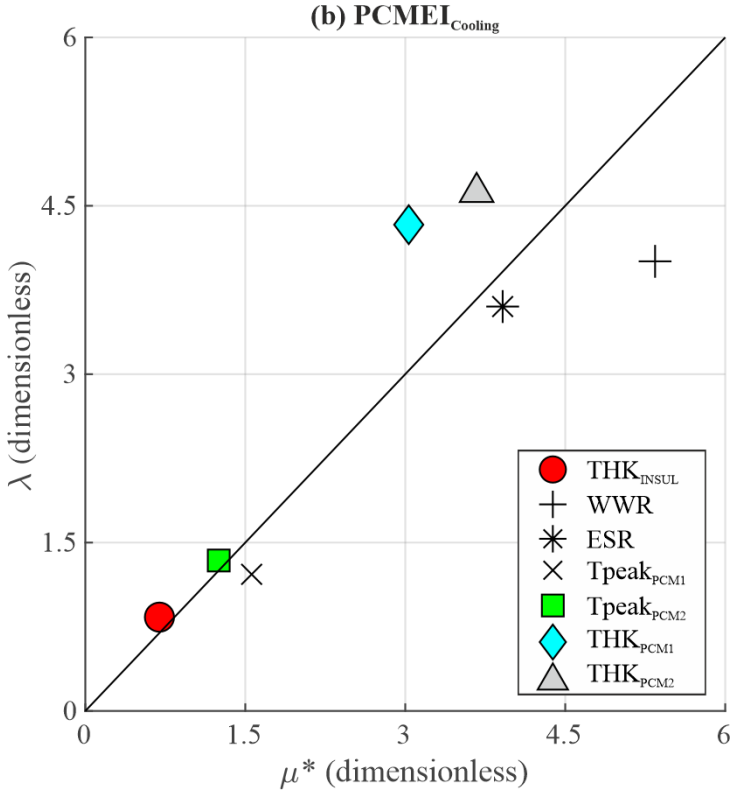
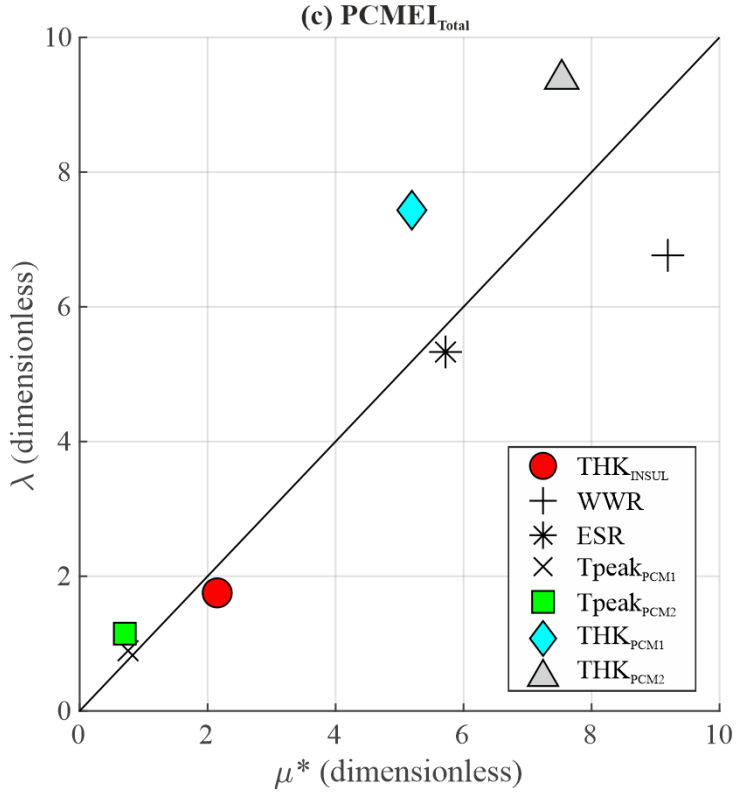
Sensitivity analysis results







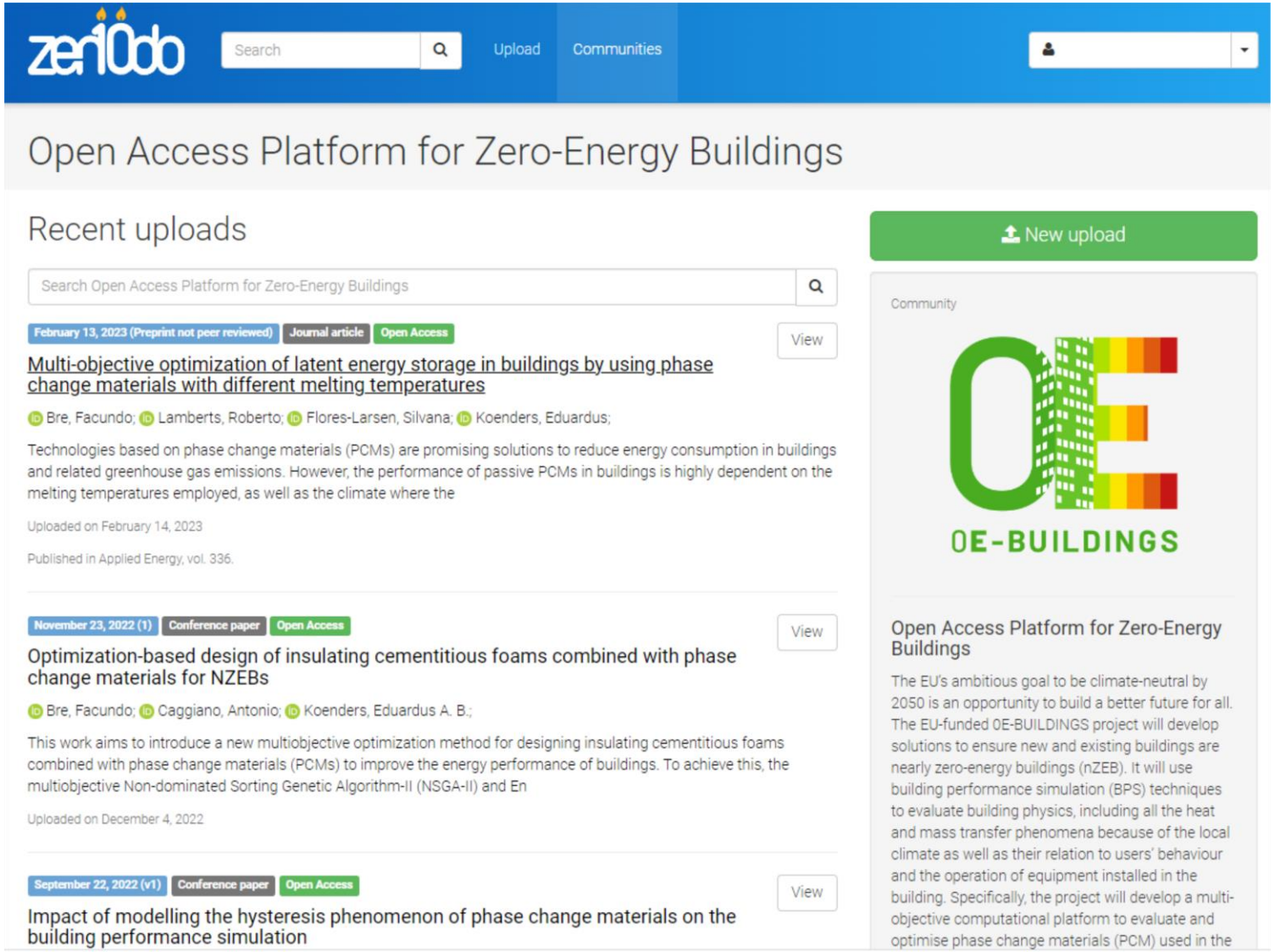
To conclude

- The performance of PCMs in buildings is complex and their proper design requires the use of **whole-building performance simulation**.
- The **melting temperature**, **amount**, and **location** of PCMs should be carefully designed to maximize their performance.
- Using **PCMs with different melting temperatures** is preferred, especially in climate zones and case studies **with both heating and cooling loads**.
- **Building design variables** (e.g., window-to-wall ratio) have a significantly higher impact on the **effectiveness of PCMs** than typically employed **PCM design variables** (e.g., melting temperatures).
- In some climates, the performance of **passive PCMs** can be limited, and their design should be combined with other **passive strategies** and **architectural variables**, preferably at the early design stage.

Future works

- An automatic optimization procedure that characterizes all the knowledge got during the project is under development (to be published in the Open Research Europe (ORE) - SI of Sustainable Places 2023).
- A simple web interface of the platform will be developed to give access to any building designers.

Research data – Zenodo repository



https://zenodo.org/communities/0e-buildings/

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Thank you for your attention!

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