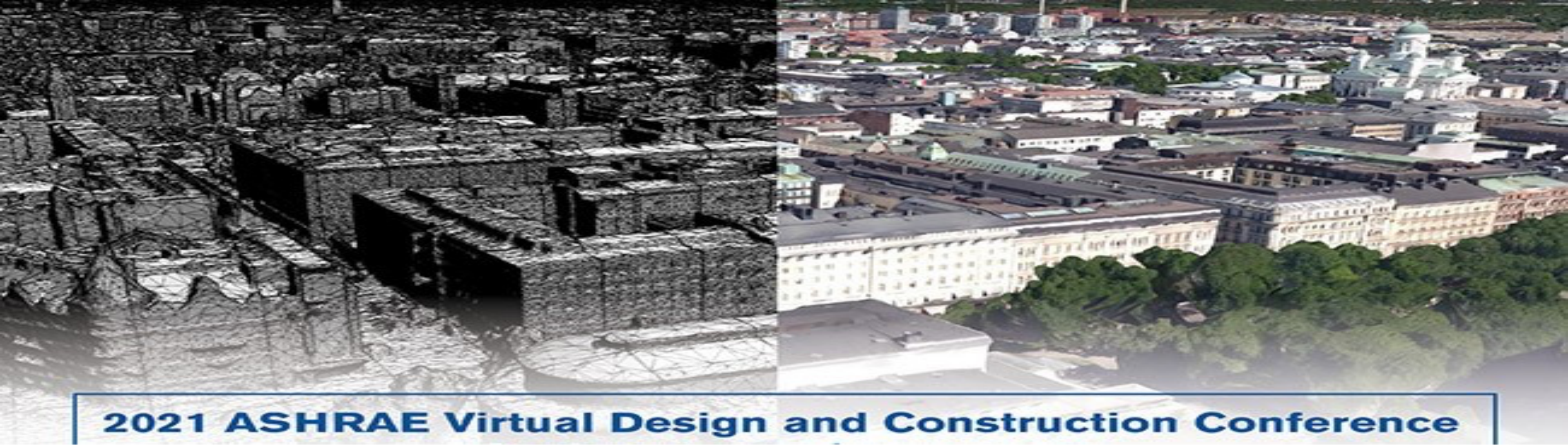


Case Study 104

Youngjin Hwang
Rensselaer Polytechnic Institute
Center for Architecture, Science and Ecology (CASE)
hwangy3@rpi.edu

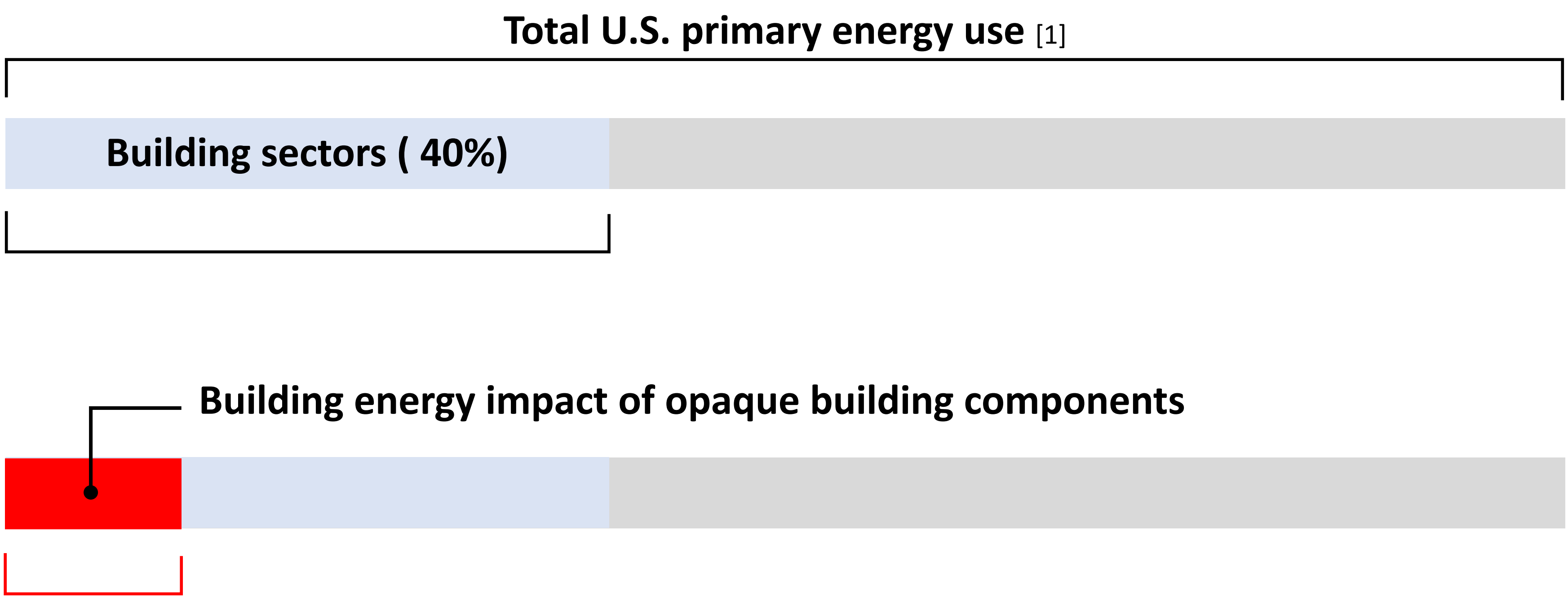
Rensselaer
case Center for Architecture Science and Ecology

Modeling and Simulation of a Structurally Integrated Building Energy Module

Learning Objectives

- Novel building envelope technology: Climate adaptive opaque building envelope
- Challenges & limitations in current building energy modeling & simulation (BEMS) techniques.
- State-of-the-art BEMS techniques for climate adaptive opaque building envelopes.
- The Modelica language-based modeling & simulation approach with case study.

Impacts of Opaque Building Components on Energy Use



10% of total U.S. primary energy use &
25% of energy use in building sectors [2]

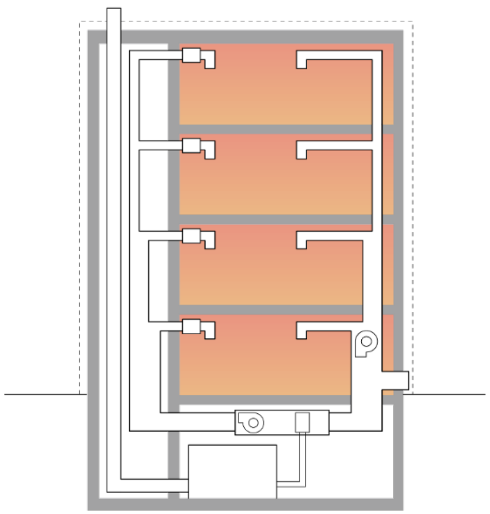
[1] U.S. Energy Information Administration, "Annual Energy Outlook, 2018," Washington, D.C, 2018.
[2] J. Langevin, C.B. Harris, and J.L Renya, "Assessing the Potential to Reduce U.S. Building CO2 Emission 80% by 2050," *Joule*, 2019; vol.3 (10); 2403-2424.

The role of a Building Envelope

Conventional Building

Heat Source
Energy from Grid

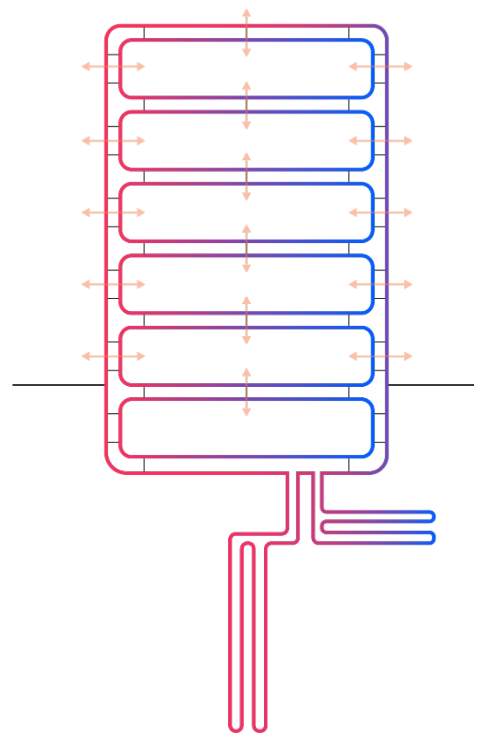
Envelope
Thermal Barrier



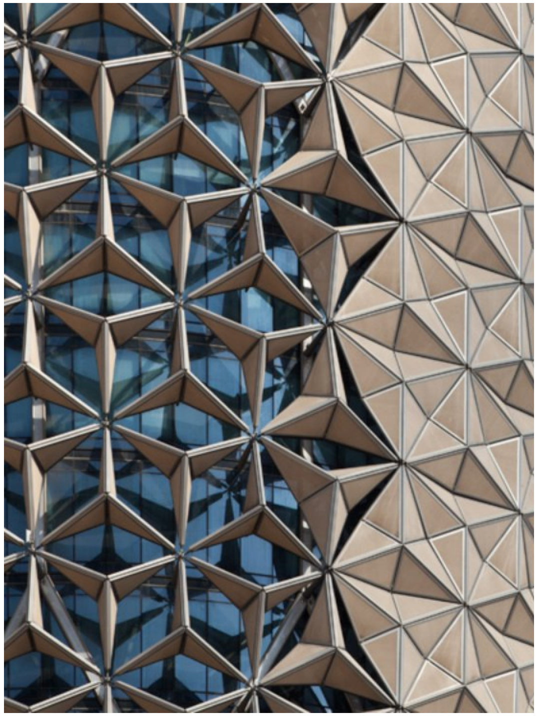
Climate Adaptive Building

Heat Source
Energy from ambient environment

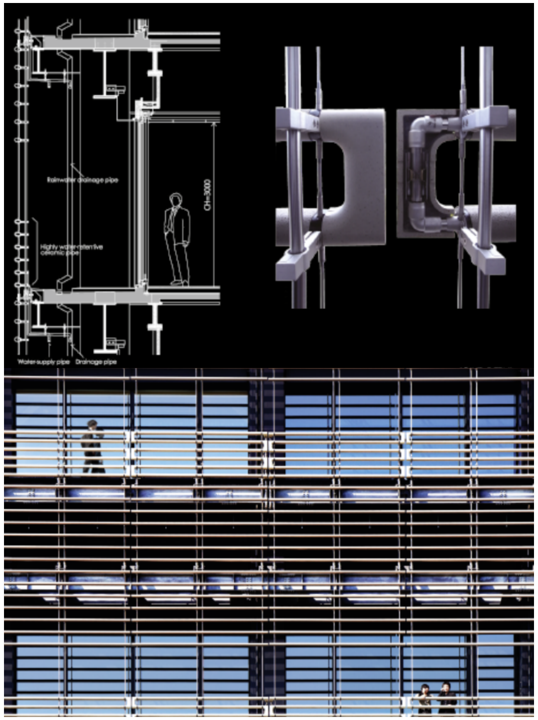
Envelope
Thermal Mediator



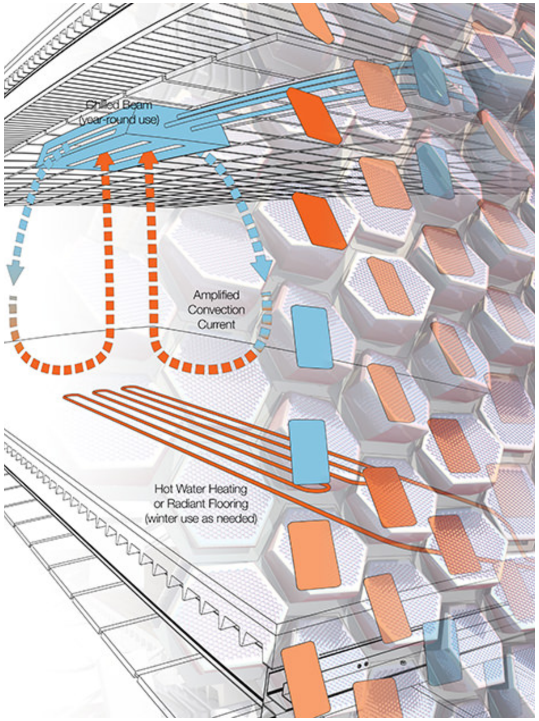
Climate Adaptive Building Envelopes



Al Bahar Towers, Aedas, 2012 [1]
Dynamic Shading device



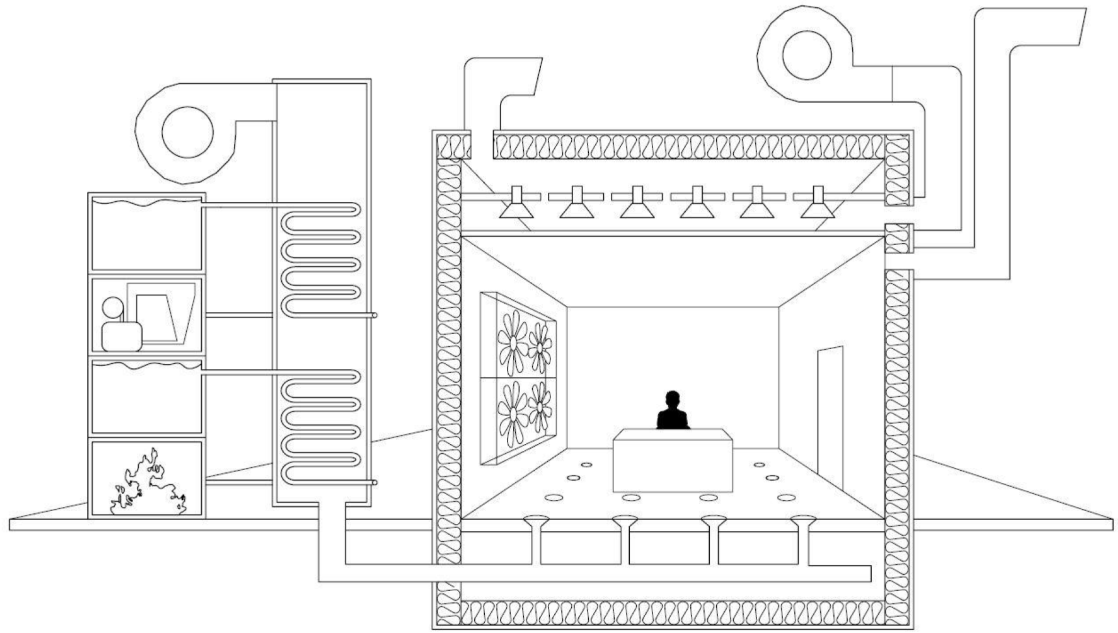
Sony Osaki Building, Nikken Sekkei, 2011 [2]
Active Evaporative Cooling Systems

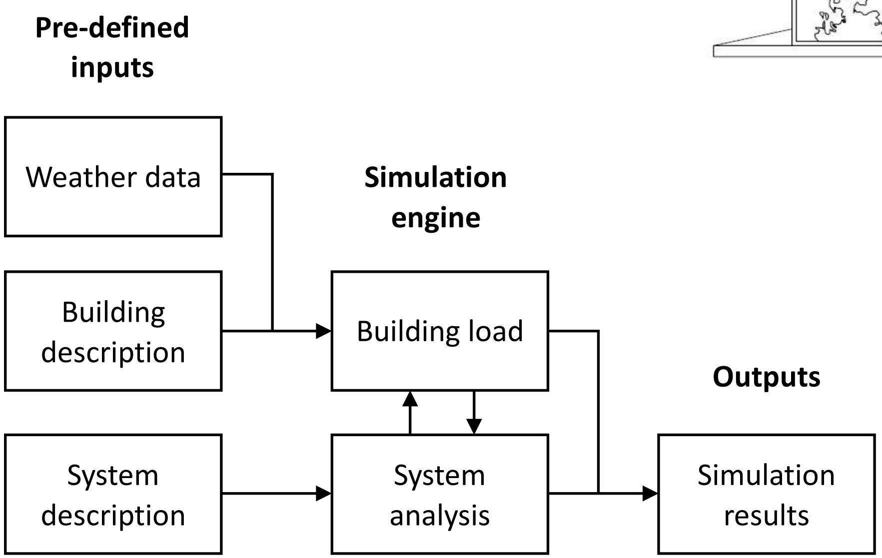


EcoCeramic, CASE [3]
Masonry Active Building Envelope

[1] https://igsmag.com/market-trends/super-tall-buildings/the-al-bahar-towers-shading-the-real-envelope/
[2] T. Yamanashi, T. Hatori, Y. Ishihara, N. Kawashima, and K. Niwa, “Bio Skin Urban Cooling Façade,” Architectural Design 2011; 08.
[3] https://www.case.rpi.edu/research/advanced-ecoceramic-envelope-systems

Challenges & Limitations in Modeling & Simulation of a Climate Adaptive Building Envelope





Conventional building energy modeling & simulation based on

fixed building construction properties & pre-defined building energy system

Image from C. Mackey, “Pan Climatic Humans,” MS Thesis, Dept. Arch, MIT, Cambridge, MA, USA, 2015, p.12.

Challenges & Limitations in Modeling & Simulation of a Climate Adaptive Building Envelope

Modeling Features of a Climate Adaptive Building Envelope in Modern BEMS tools

BEMS software	Built-in features*	Advanced modeling features	Code access & modification
EnergyPlus	DS, TW, GR, GW, MI, TC, PCM	Limited (EMS)	X
ESP-r	DS, TW, GR, GW, PCM	Limited	X
IDA ICE	DS, TW, MI, PCM	Limited	X
IES-VE	DS, TW, GR	Limited	X
TRNSYS	DS, TW, GR, GW, PCM	Limited	X

*DS: Double Skin Façade, TW: Trombe Wall, GR: Green Roof, GW: Green Wall, MI: Movable Insulation, TC: Thermo-collect, PCM: Phase Change Material

[1] F. Favoino, M. Doya, R.C.G.M. Loonen, F. Goia, C. Bendon, and F. Babich, Eds., *Building performance simulation and characterization of adaptive facades-adaptive façade network*, Delft, Netherlands: TU Delft Open, 2018.

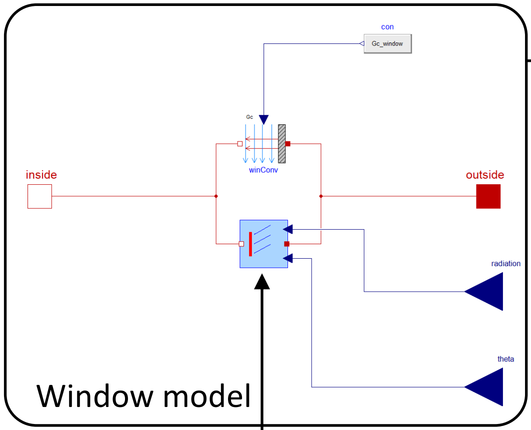
State-of-the-art
Climate Adaptive Opaque Building Envelope Technologies

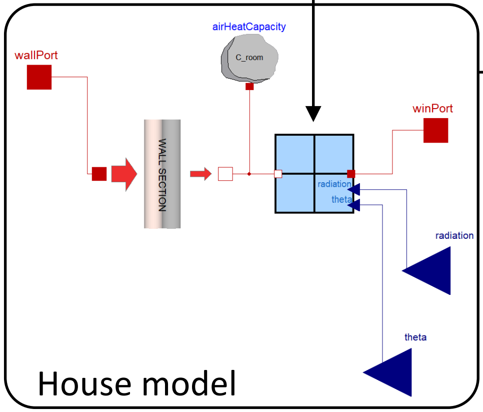
Control Type	Key Working Principle	Adaptation Technology	Evaluation Methods	Modularity	Market Available	Retrofit ability
Passive (Intrinsic)	Conduction	Phase change material	AM [1] & BEMS [2]	Y	Y	Y
		Thermal diode wall	AM [3]	Y	N	Y
	Convection	Shape memory alloy	AM [4]	Y	N	Y
		Solar thermal collector	AM & PM [5]	N	Y	N
Active (Extrinsic)	Conduction	Active vacuum	AM [6]	Y	N	Y
		Mechanical contact	AM [7]	Y	N	Y
	Convection	Fluidic-system Embedded technology	AM [8]	Y	Y	Y

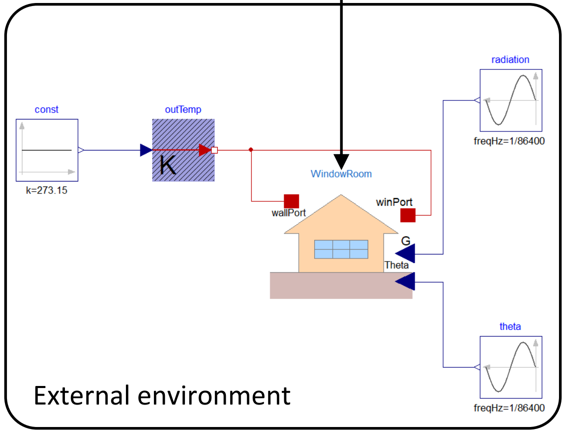
*AM: Analytical Model (Equation-based model), BEMS: Building Energy Modeling & Simulation Software, PM: Physical Test Model

[1] K. Biswas, Y. Shukla, A. Desjarlais, R. Rawal, “Thermal characterization of full-scale PCM products and numerical simulation, including hysteresis, to evaluate energy impacts in an envelope application,” *Applied Thermal Engineering*, 2018; 138; 501-512. [2] P.C. Tabares-Velasco, C. Christensen, and M. Bianchi, “Verification and validation of EnergyPlus phase change material model for opaque wall assemblies,” *Building and Environment*, 2012; 54; 186-196. [3] Z. Zhang, Z. Sun, and C. Duan, “A new type of passive solar energy utilization technology – The wall implanted with heat pipes,” *Energy and Buildings*, 2014 84; 111-116. [4] M. Formentini and S. Lenci, “An innovative building envelope (kinetic facade) with Shape Memory Alloys used as actuators and sensor,” *Automation in Construction*, 2018; 85; 220-231. [5] M. Ibrahim, E. Wurtz, J. Anger, and O. Ibrahim, “Experimental and numerical study on a novel low temperature solar thermal collector to decrease the heating demands: A south-north pipe-embedded closed-water-loop system,” Solar Energy, 2017; 147; 22-36 [6] A. Berge, C.E. Hagentoft, P. Wahlgren, and B. Adl-Zarrabi, “Effect from a variable u-value in adaptive building components with controlled internal air pressure,” *Energy Procedia*, 2015; 78; 376-381. [7] M. Kimber, W.W. Clark, and L.Schaefer, “Conceptual analysis and design of a partitioned multifunctional smart insulation,” *Applied Energy*, 2014; 114; 310-319. [8] Y. Yu, F. Niu, H.A. Guo, and D. Woradechjumroen, “A thermo-activated wall for load reduction and supplementary cooling with free to low-cost thermal water,” *Energy*, 2016; 99; 250-265.

New Alternative: The Modelica Language





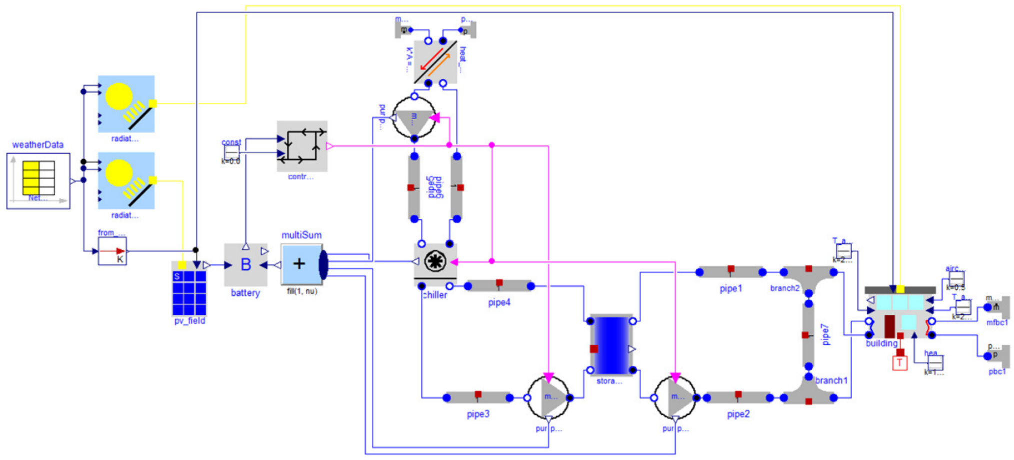



```
model Pane "window pane that lets in radiant and convection heat"
  parameter Real a0=0.75;
  parameter Real a1=4.4;
  parameter Real a2=0.004;
  parameter Modelica.SIunits.Area A;
  Real eff "Collector efficiency";
  Real F;
  Real G_aux "Variable used to avoid G=0";

equation
  port_a.Q_flow = -port_b.Q_flow;
  port_b.Q_flow = -eff*A*G "Heat Flow Generation";
  G_aux = if abs(G)<Modelica.Constants.eps then Modelica.Constants.eps else G;
  eff = F*(a0 - a1*(port_b.T - port_a.T)/G_aux - a2*(port_b.T - port_a.T)^2/G_aux);
  F = if theta>84.4 then 0.0 else 1-0.108*(1/cos(theta/360*2*Modelica.Constants.pi)-1);

end Pane;
```

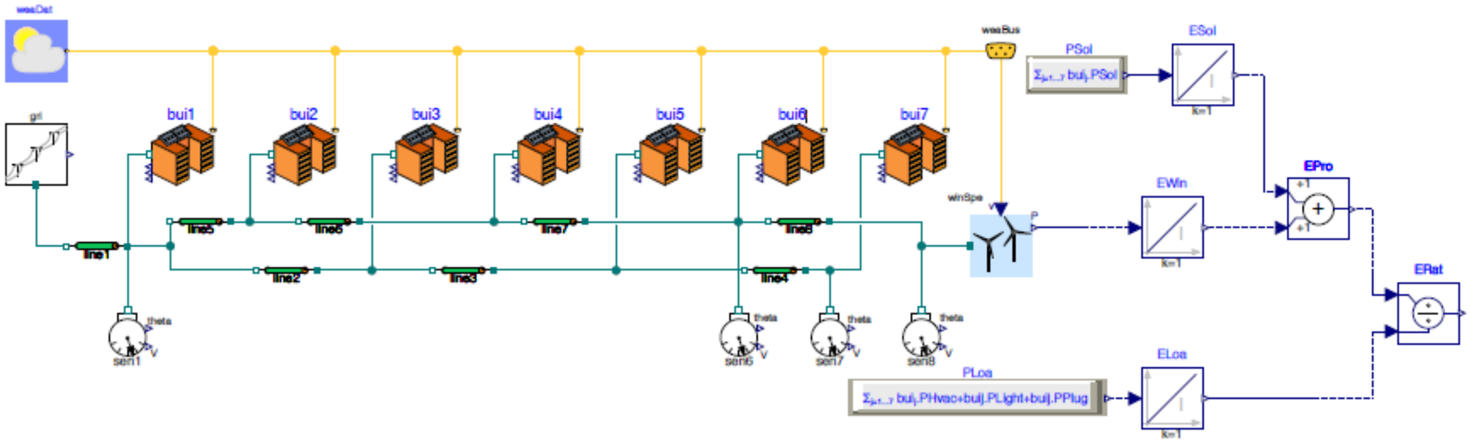
Modelica Language **:An Equation-based Object-oriented System Modeling Language**

Building System Modeling Cases Using Modelica

Design of Building Energy Systems



Design of District Energy Systems



[1] International Energy Agency, *ANNEX 60 Final Report: New Generation Computational Tools for Building & Community Energy Systems*, September 2017.

Co-simulation Technique Using the FMI Standard

Modelica-based Tools

Advanced System Modeling
Dynamic Controls

Co-Simulation

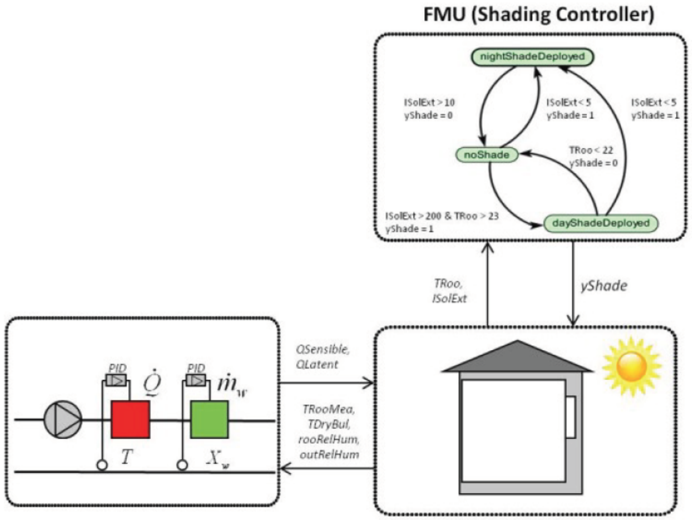
Mature BEMS Tools

Well-established Building
Modeling Engine

State-of-the-art Co-Simulation Technique for BEMS

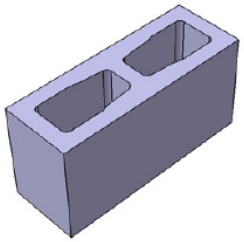
Dynamic System Control [1]

Modelica < > EnergyPlus

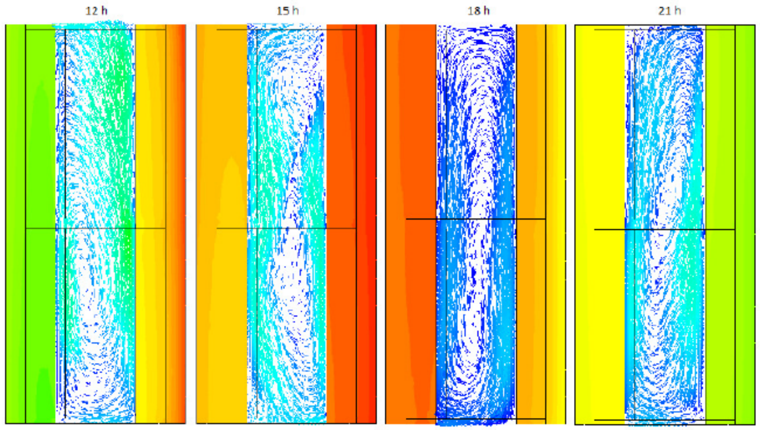


High Accuracy & Calibration [2]

Modelica & EnergyPlus < > ANSYS-CFX (CFD)



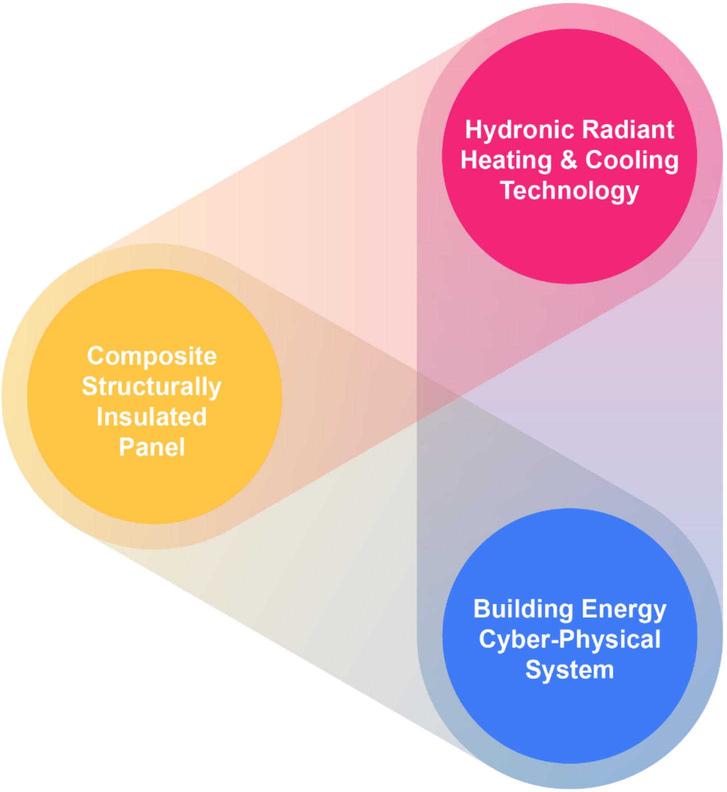
(b)

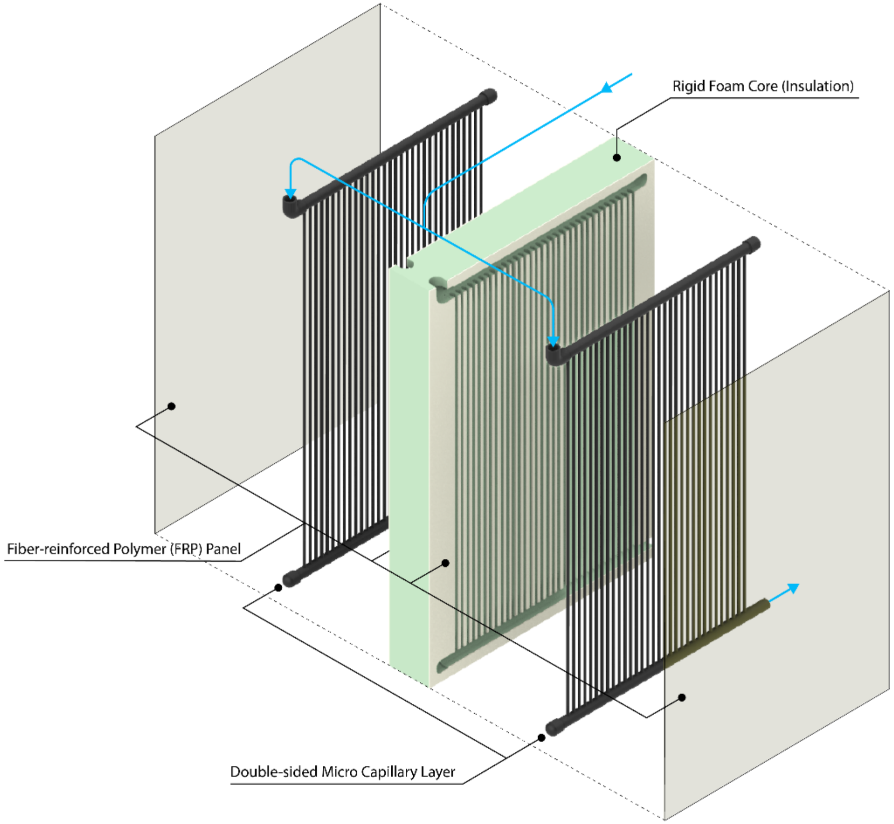


(c)

[1] T.S. Nouidui, M. Wetter, and W. Zuo, "Functional Mock-up Unit Import in EnergyPlus for Co-simulation," in *Proceedings of BS2013 13th Conference of International Building Performance Simulation Association*, Chamber, France.
[2] International Energy Agency, *ANNEX 60 Final Report: New Generation Computational Tools for Building & Community Energy Systems*, September 2017.

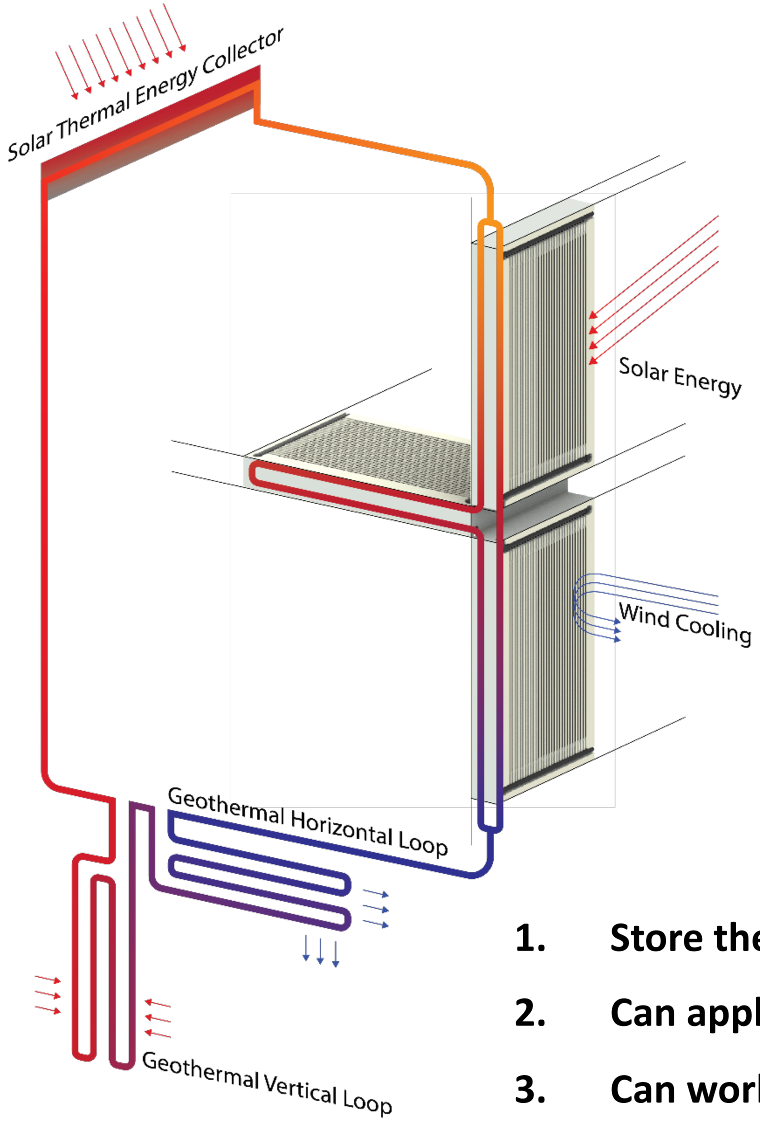
Case Study: Structurally Integrated Building Energy Module





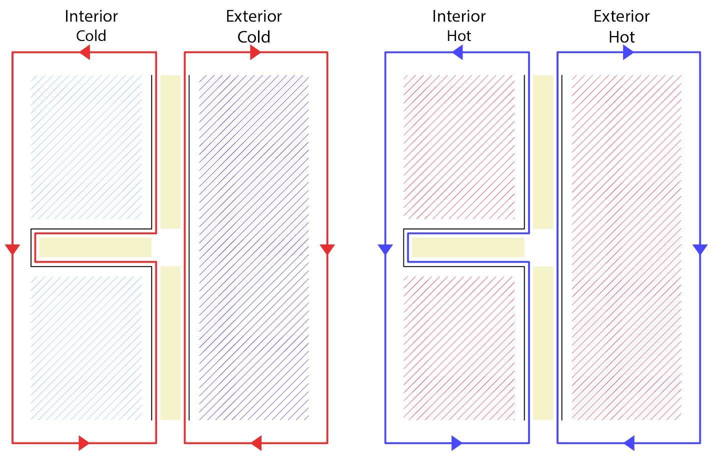
FROG: Structurally Integrated Building Energy Module

Case Study: Structurally Integrated Building Energy Module

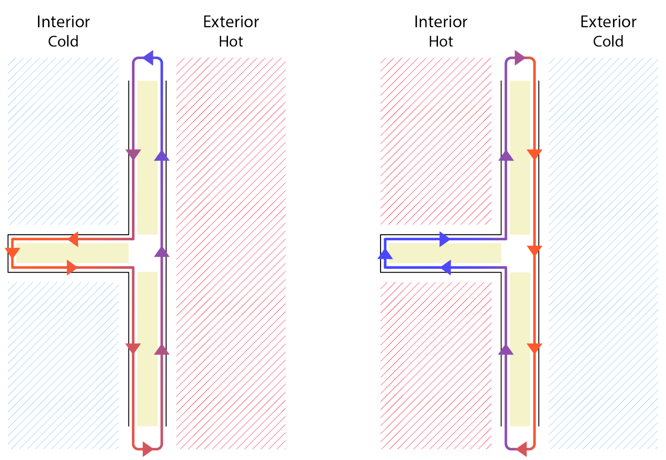


1. **Store thermal energy and manage thermal resistance simultaneously.**
2. **Can apply to various opaque building elements.**
3. **Can work in conjunction with multiple renewable energy systems.**

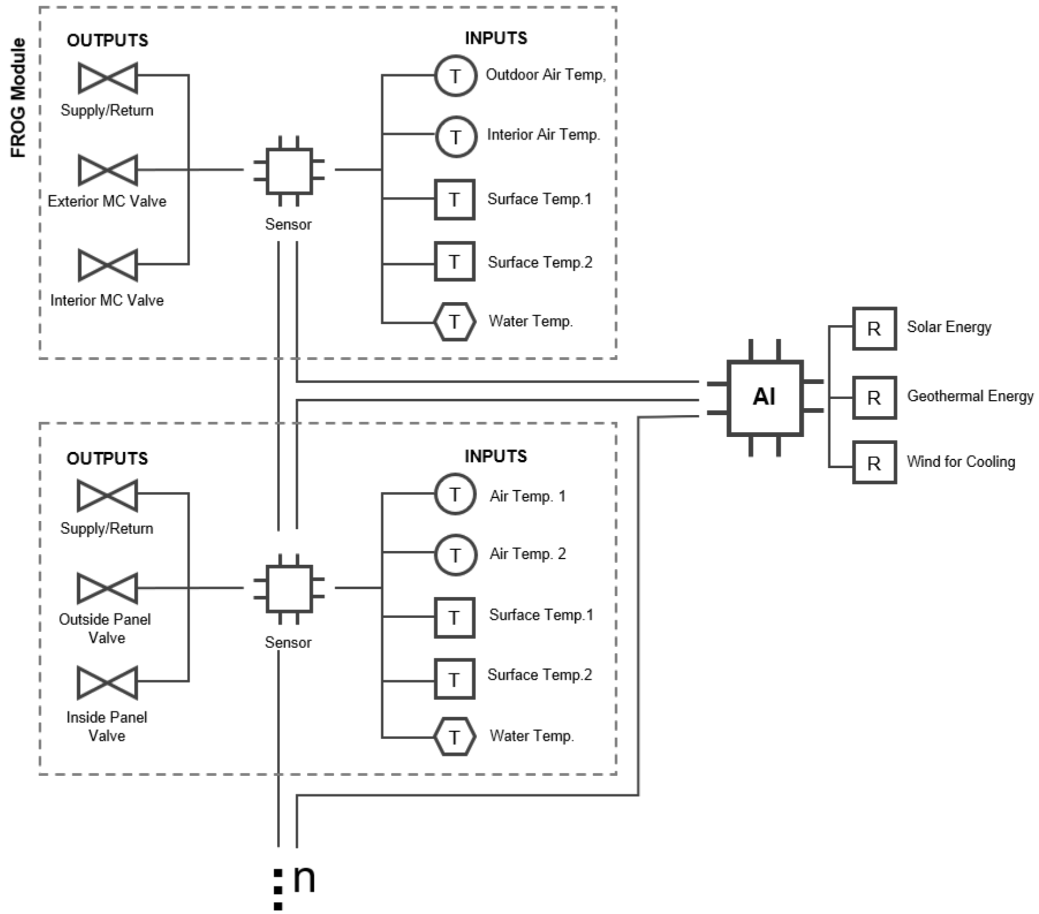
Dynamic Thermal Behaviors of the FROG System



Isolating (Insulating) Mode
Open Loop

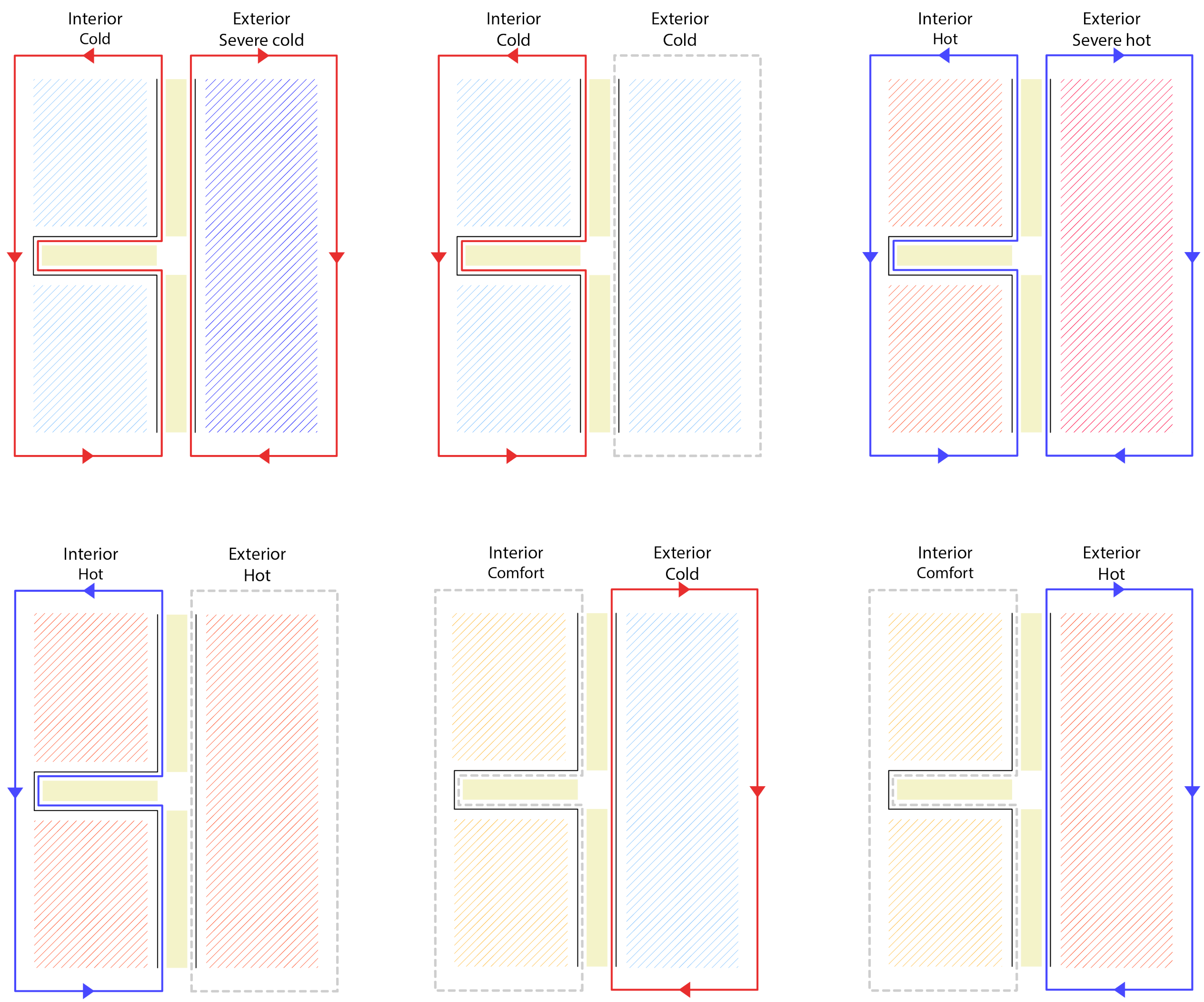


Heat Exchange Mode
Closed Loop

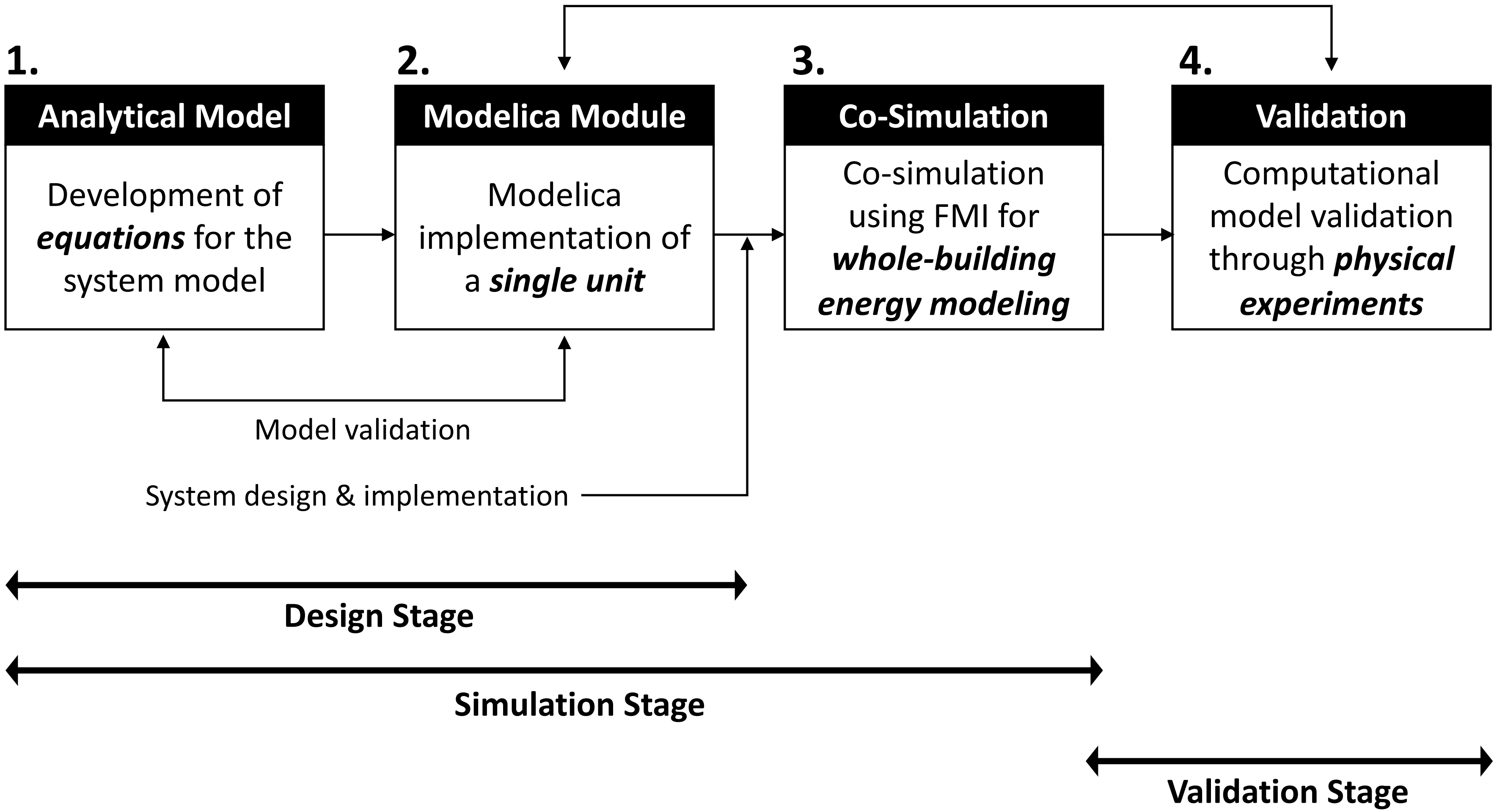


Dynamic Thermal Behaviors of the FROG System

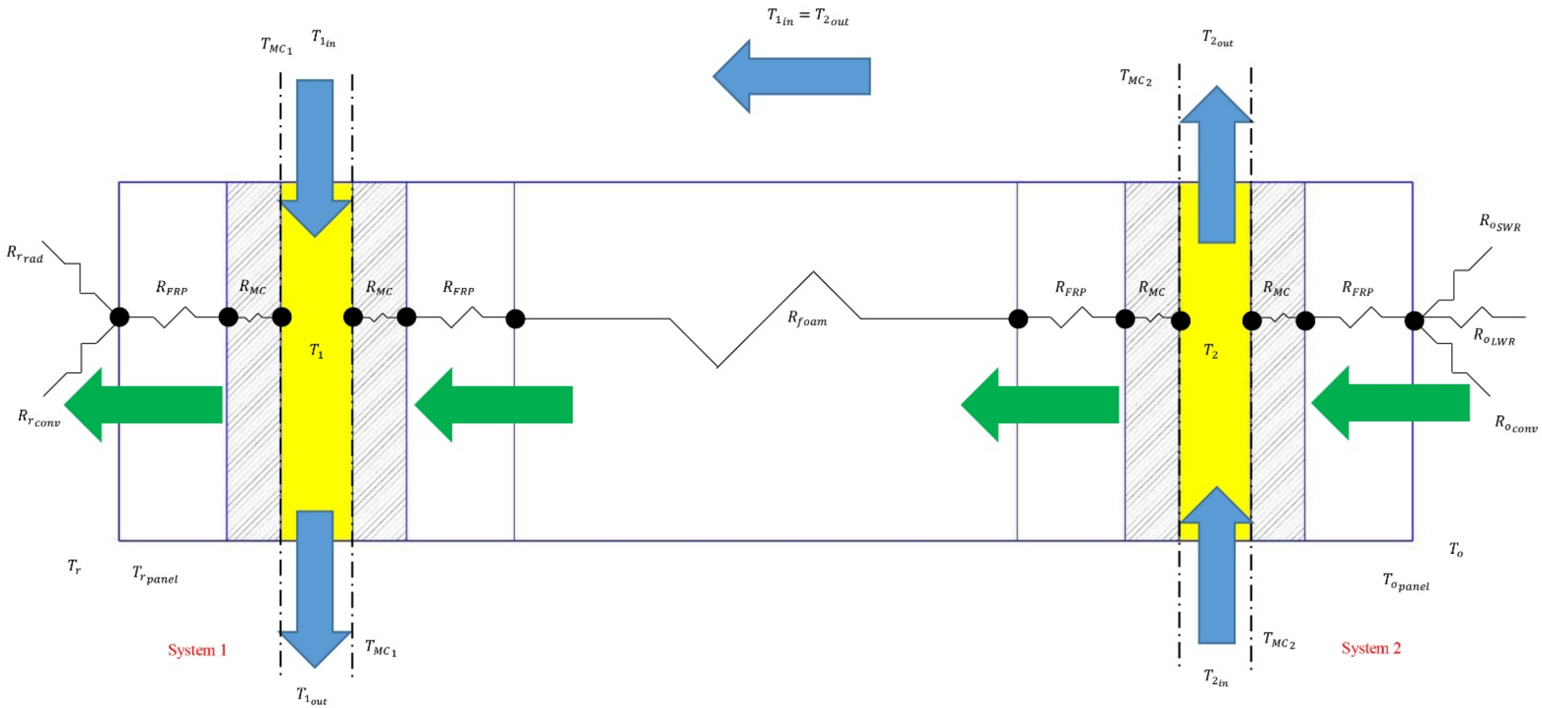
Climate adaptive isolating modes
Open Loop



Design, Testing, and Validation of the FROG System



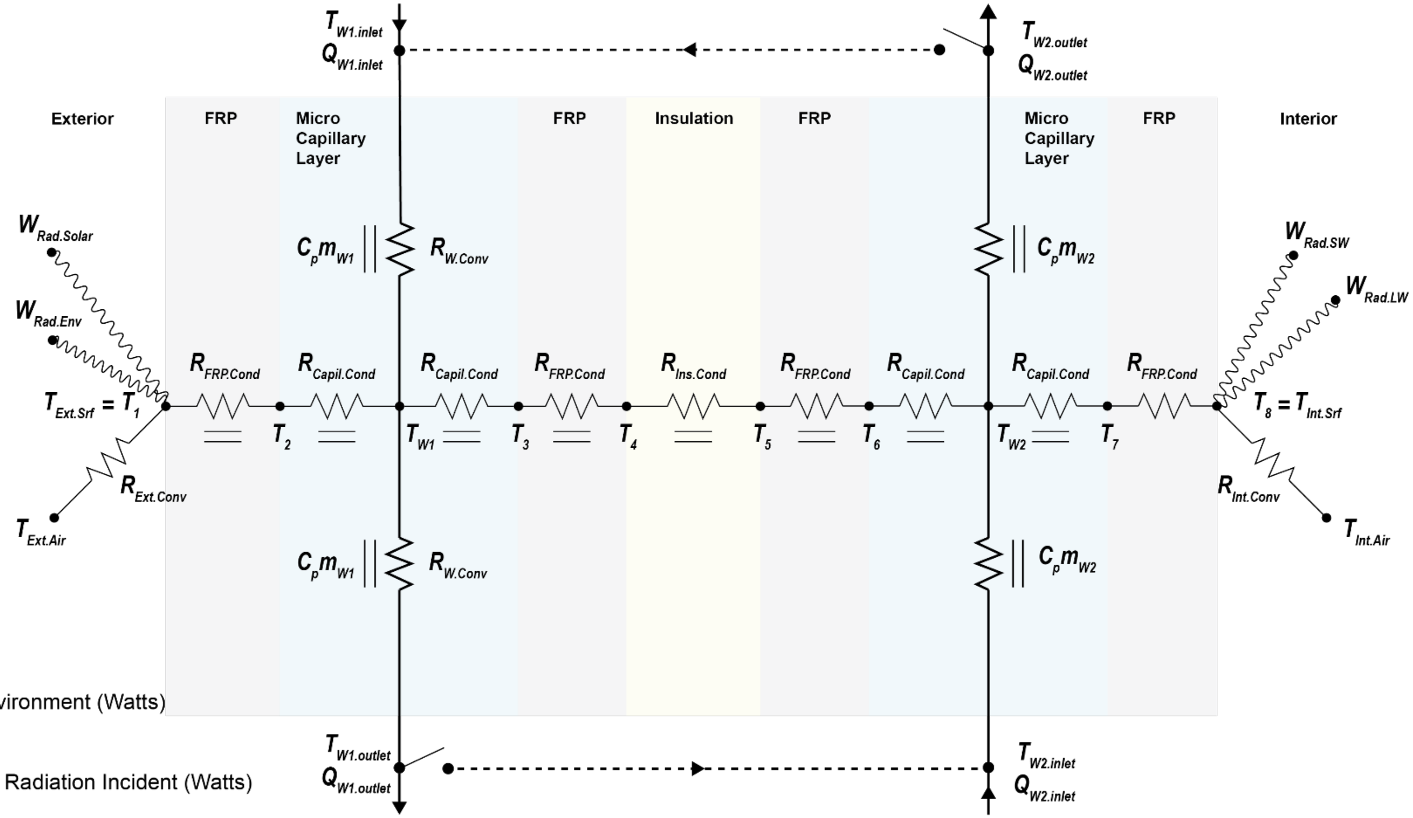
1. Analytical Model Development



$$T_{MC_1} = \frac{T_{1in} - T_{1out} exp\left(\frac{h_1 A_{MC_{wall}}}{\dot{m}_1 c_{p_1}}\right)}{1 - exp\left(\frac{h_1 A_{MC_{wall}}}{\dot{m}_1 c_{p_1}}\right)}$$

$$T_{MC_2} = \frac{T_{2in} - T_{2out} exp\left(\frac{h_2 A_{MC_{wall}}}{\dot{m}_2 c_{p_2}}\right)}{1 - exp\left(\frac{h_2 A_{MC_{wall}}}{\dot{m}_2 c_{p_2}}\right)}$$

2-1. A Digital Twin Model of the FROG Module by using the Modelica Language



$W_{Rad.Env}$ = Radiation Incident from Environment (Watts)

$W_{Rad.Solar}$ = Radiation Incident (Watts)

W_{Rad} = Inteior Short or Long Wave Radiation Incident (Watts)

Q_W = Volumetric Flowrate (m^3/s)

$C_p m_W$ = Specific Heat (J/g) and Mass (g) of water

R_{Cond} = Conduction Resistance (mK/W)

R_{Conv} = Convection Resistance (m^2K/W)

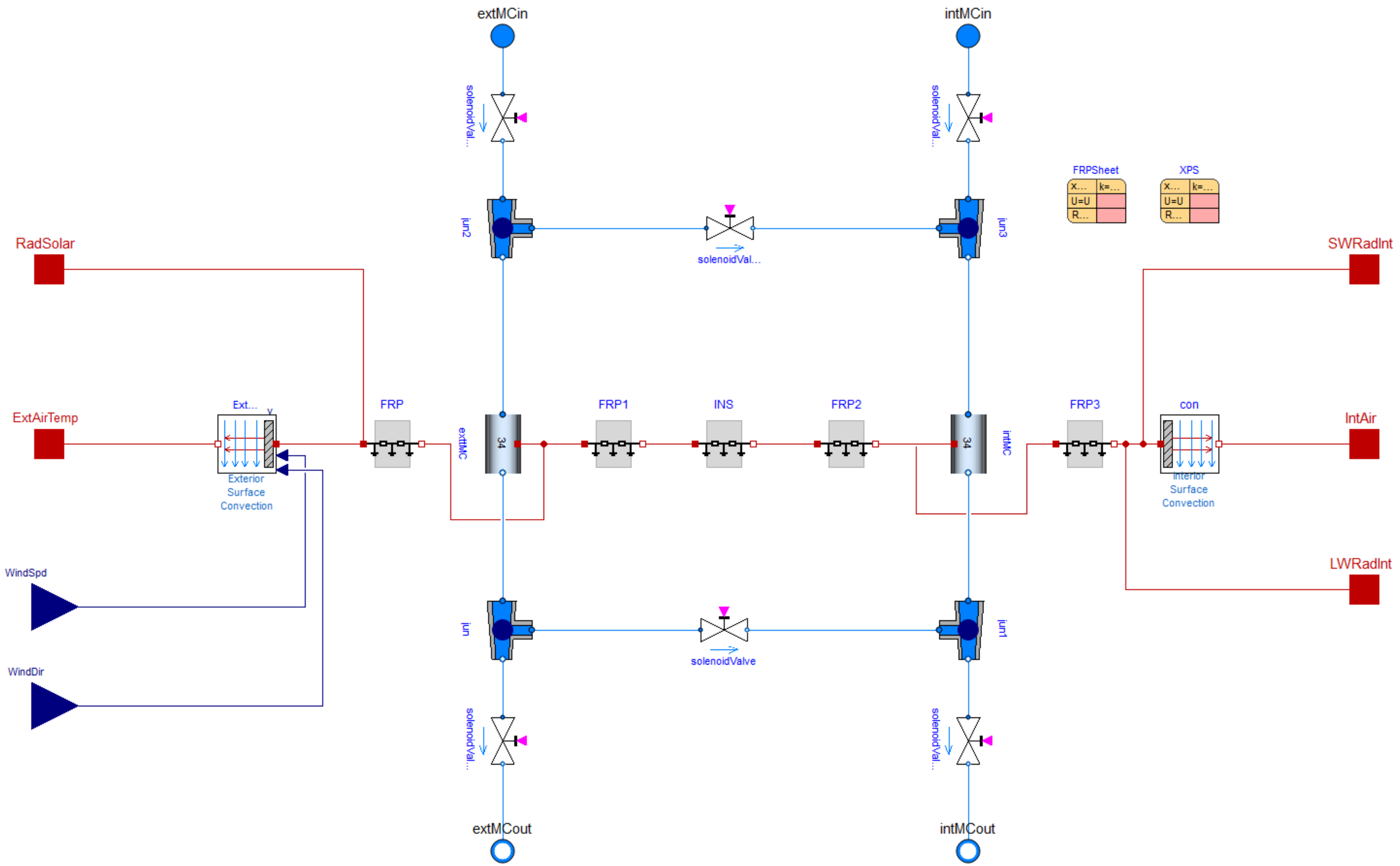
T_n = Temperature of the n^{th} interface

T_W = Temperature of the Water in The Micro Capillary Layer

$T_{Ext.Air}$ = Temperature of the Exterior Air

$T_{Int.Air}$ = Temperature of the Interior Air

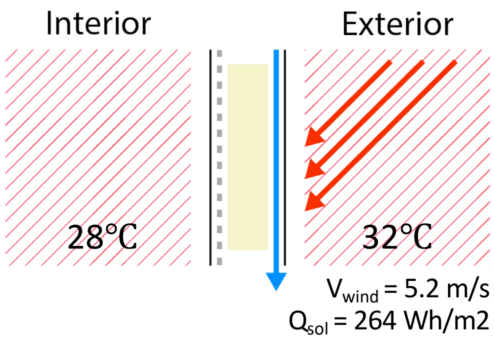
2-1. A Digital Twin Model of the FROG Module by using the Modelica Language

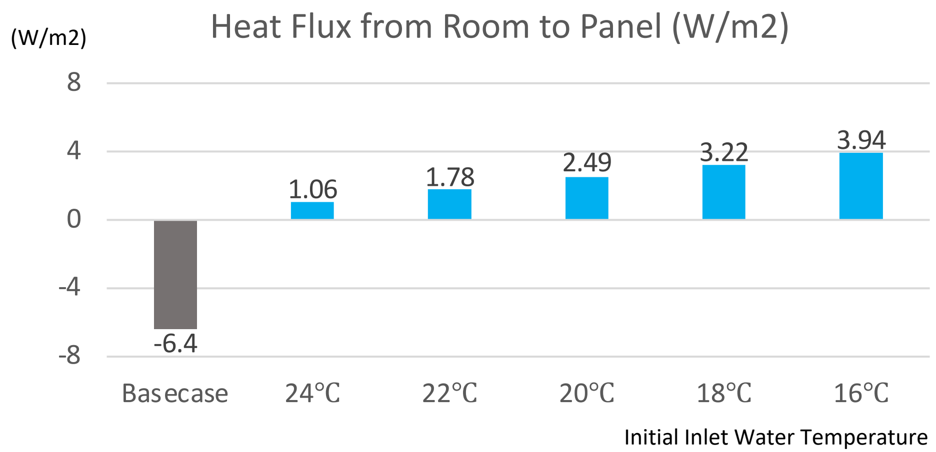


Simulation Results: Cooling Modes

1.

$T_{out} > T_{in}$
$Q_{sol} > 0$

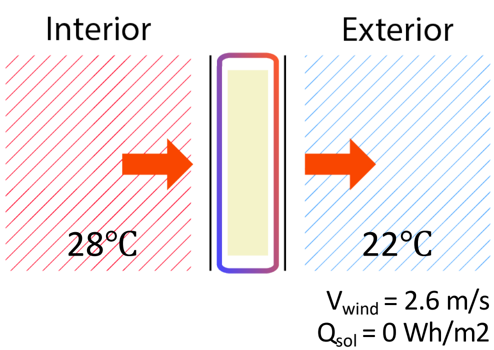


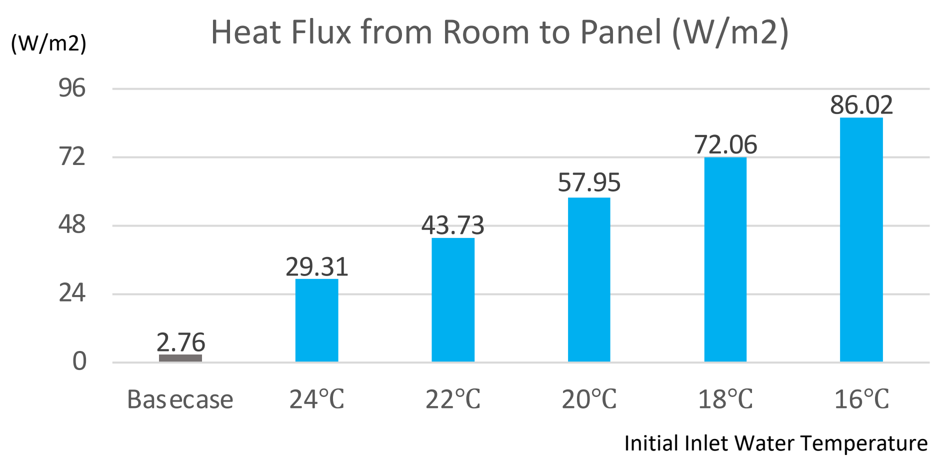


5.2 m/s

2.

$T_{out} < T_{in}$
$Q_{sol} = 0$



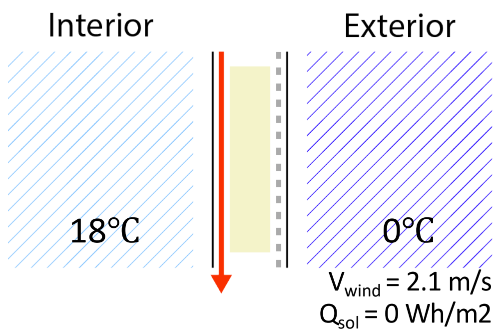


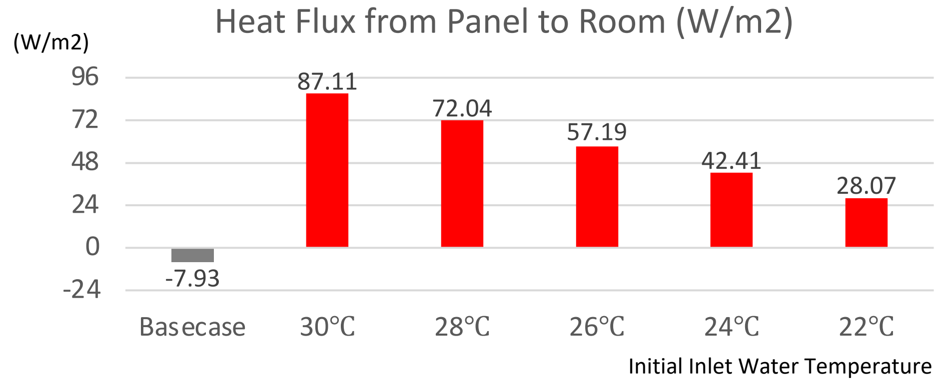
Simulation Results: Heating Modes

1.

$T_{out} < T_{in}$

$Q_{sol} = 0$

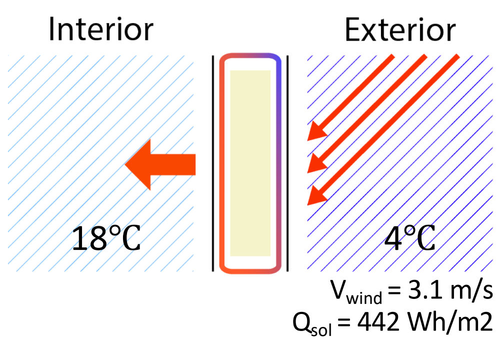


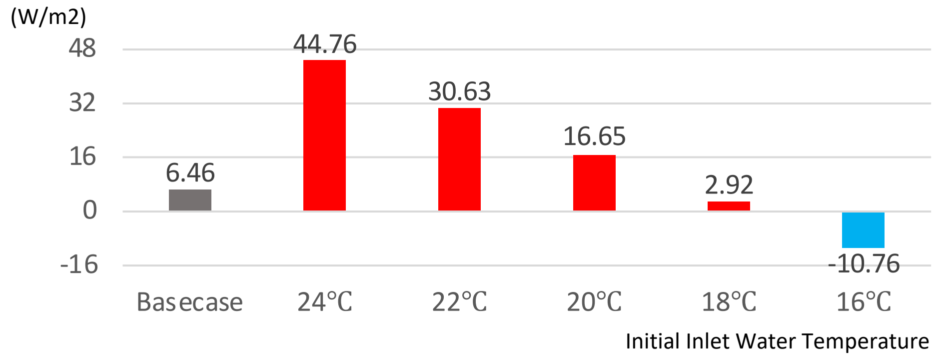


2.

$T_{out} > T_{in}$

$Q_{sol} > 0$

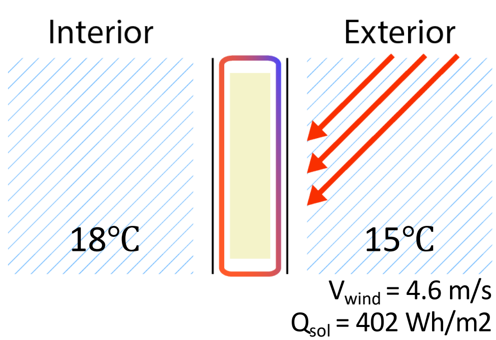


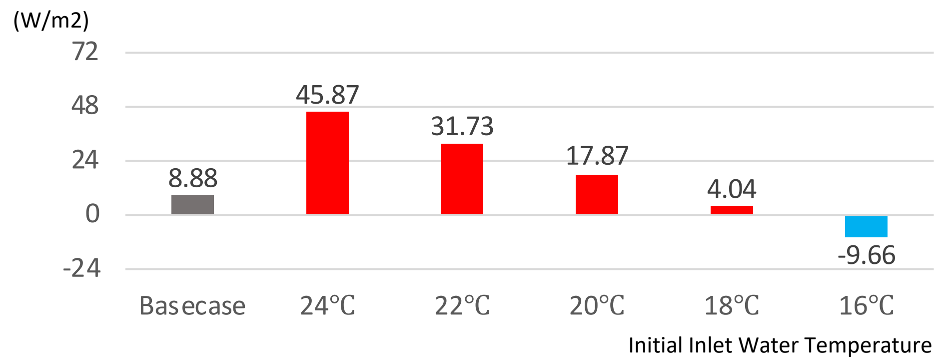


3.

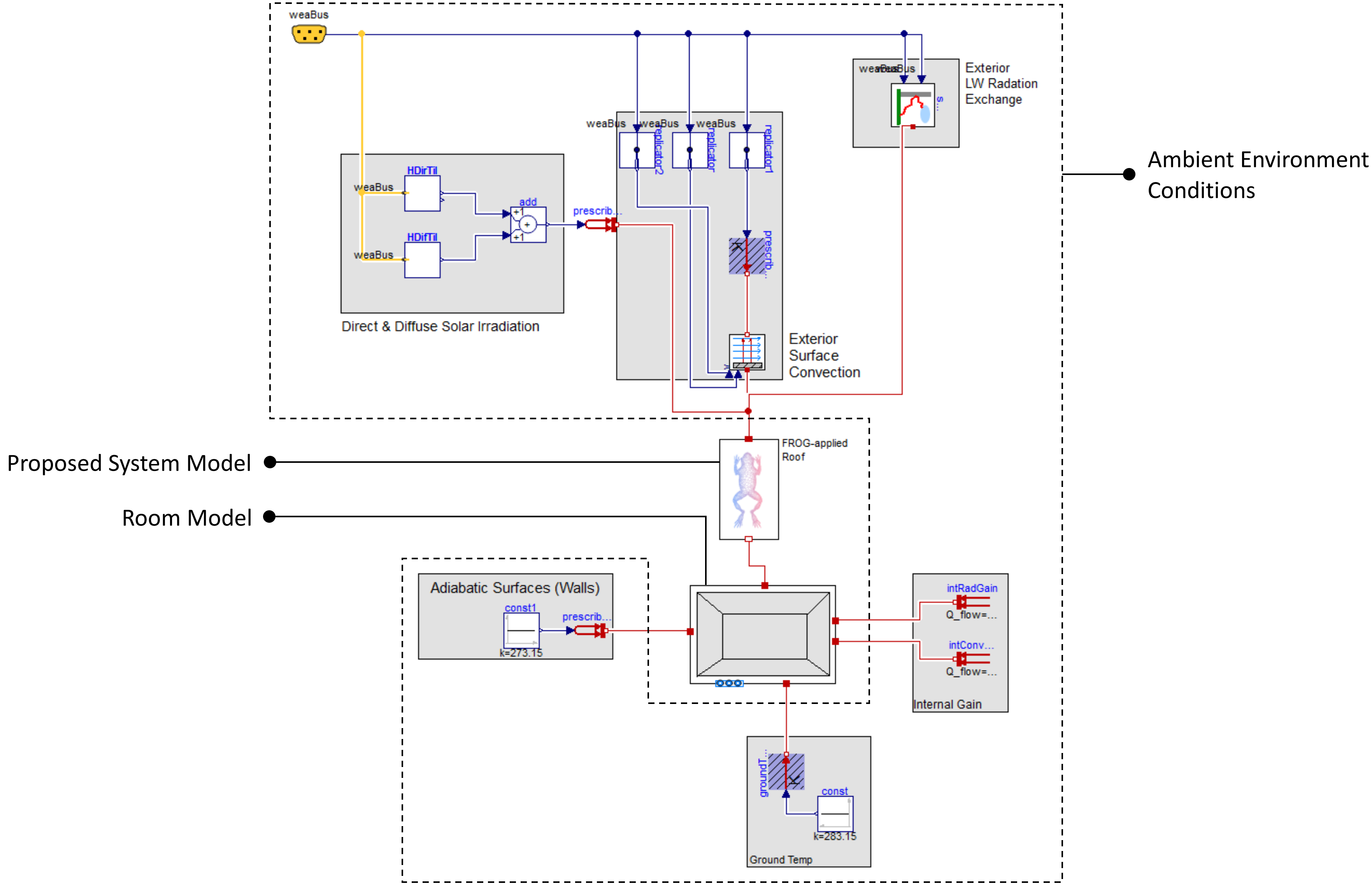
$T_{out} > T_{in}$

$Q_{sol} > 0$

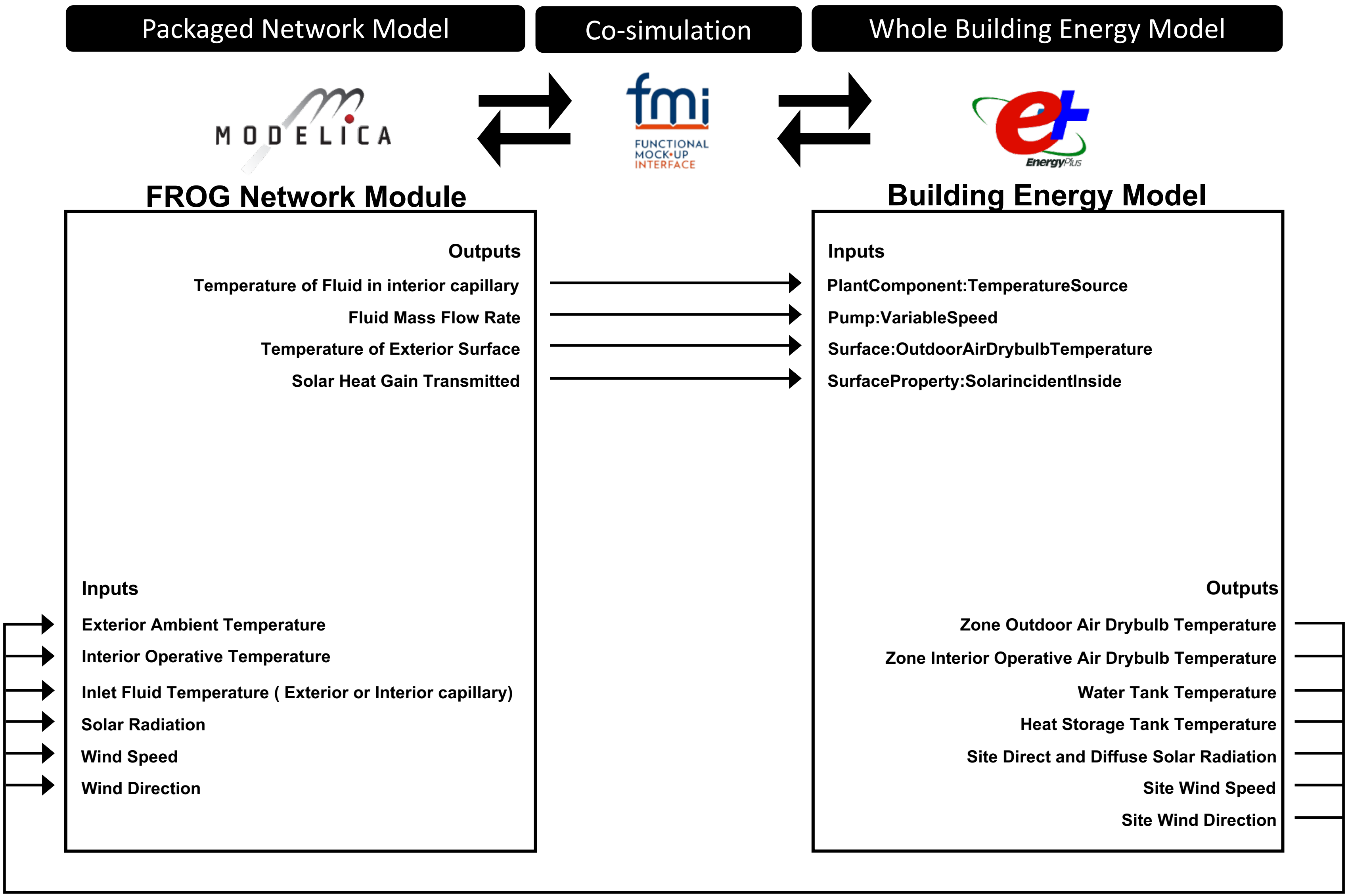




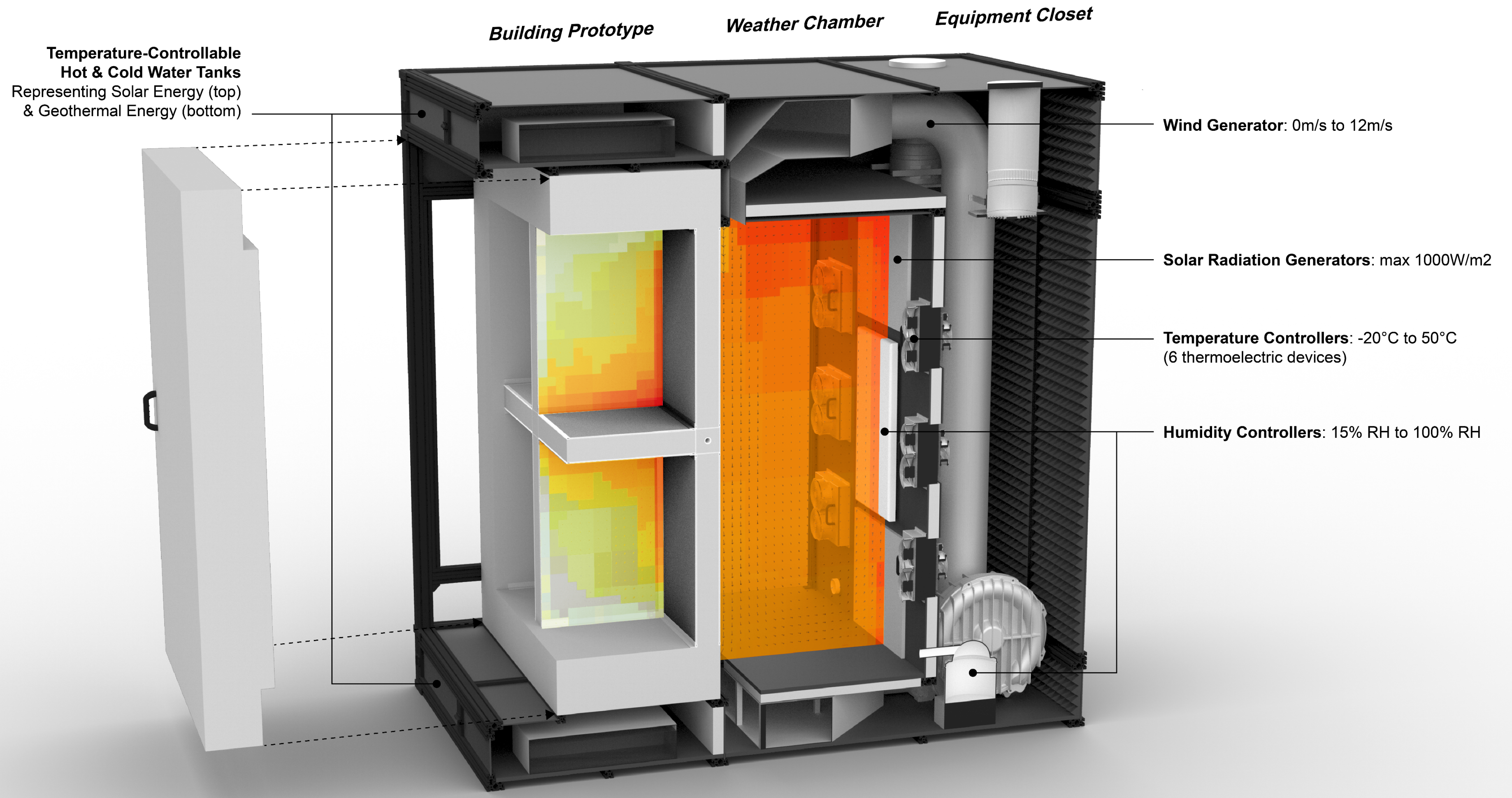
2-2. A Digital Twin Model of the FROG System by using the Modelica Language



Future research 1. Co-Simulation Model

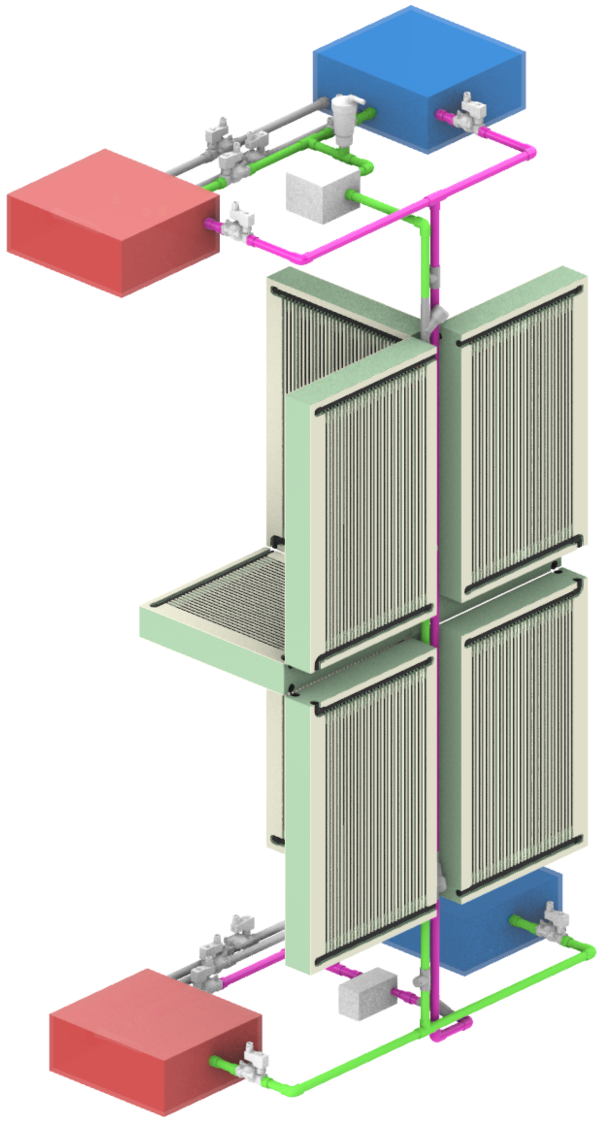


Future research 2. Validation: Physical Experiments



Future research 2. Validation: Physical Experiments

Top Tanks with Temperature Controllers
Solar Thermal Energy Collector:



Bottom Tanks with Temperature Controllers
Geothermal Energy Systems:
(Ground Source Cooling + Heating)

Conclusions

- Novel climate adaptive opaque building technologies can dramatically reduce building heating and cooling demands with additional benefits such as comfort and well-being.
- The development of a climate adaptive building envelope is challenging due to the lack of modeling and simulation features for climate adaptive system in modern stand-alone BEMS tools.
- A Modelica-based simulation approach can offer complementary means to address the critical needs of modern BEMS tools for advanced modeling.
- A co-simulation technique can provide advanced modeling features with high accuracy while using well-established modern BEMS tools.

Bibliography

- A. Berge, C.E. Hagentoft, P. Wahlgren, and B. Adl-Zarrabi, "Effect from a variable u-value in adaptive building components with controlled internal air pressure," *Energy Procedia*, 2015; 78; 376-381.
- F. Favoino, M. Doya, R.C.G.M. Loonen, F. Goia, C. Bendon, and F. Babich, Eds., *Building performance simulation and characterization of adaptive facades-adaptive façade network*, Delft, Netherlands: TU Delft Open, 2018.
- International Energy Agency, *ANNEX 60 Final Report: New Generation Computational Tools for Building & Community Energy Systems*, September 2017.
- J. Langevin, C.B. Harris, and J.L Renya, "Assessing the Potential to Reduce U.S. Building CO2 Emission 80% by 2050," *Joule*, 2019; vol.3 (10); 2403-2424.
- K. Biswas, Y. Shukla, A. Desjarlais, R. Rawal, "Thermal characterization of full-scale PCM products and numerical simulation, including hysteresis, to evaluate energy impacts in an envelope application," *Applied Thermal Engineering*, 2018; 138; 501-512.
- M. Formentini and S. Lenci, "An innovative building envelope (kinetic facade) with Shape Memory Alloys used as actuators and sensor," *Automation in Construction*, 2018; 85; 220-231.
- M. Ibrahim, E. Wurtz, J. Anger, and O. Ibrahim, "Experimental and numerical study on a novel low temperature solar thermal collector to decrease the heating demands: A south-north pipe-embedded closed-water-loop system," Solar Energy, 2017; 147; 22-36
- M. Kimber, W.W. Clark, and L.Schaefer, "Conceptual analysis and design of a partitioned multifunctional smart insulation," *Applied Energy*, 2014; 114; 310-319.
- P.C. Tabares-Velasco, C. Christensen, and M. Bianchi, "Verification and validation of EnergyPlus phase change material model for opaque wall assemblies," *Building and Environment*, 2012; 54; 186-196.
- T.S. Nouidui, M. Wetter, and W. Zuo, "Functional Mock-up Unit Import in EnergyPlus for Co-simulation," in *Proceedings of BS2013 13th Conference of International Building Performance Simulation Association*, Chamber, France.
- T. Yamanashi, T. Hatori, Y. Ishihara, N. Kawashima, and K. Niwa, "Bio Skin Urban Cooling Façade," Architectural Design 2011; 08.
- U.S. Energy Information Administration, "Annual Energy Outlook, 2018," Washington, D.C, 2018.
- Y. Yu, F. Niu, H.A. Guo, and D. Woradechjumroen, "A thermo-activated wall for load reduction and supplementary cooling with free to low-cost thermal water," *Energy*, 2016; 99; 250-265.
- Z. Zhang, Z. Sun, and C. Duan, "A new type of passive solar energy utilization technology – The wall implanted with heat pipes," *Energy and Buildings*, 2014 84; 111-116.

QUESTIONS?

Youngjin Hwang, PhD candidate, CASE, RPI

hwangy3@rpi.edu

Amogh Wasti, PhD student, RPI, wastia@rpi.edu

Theodorian Borca-Tasciuc, Professor, RPI,

Luigi Vanfretti, Associate Professor, RPI,

Alexandros Tsamis, Assistant Professor, CASE, RPI, tsamia@rpi.edu