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BOPTEST: Initial FRP Test Case Development

Yeonjin Bae, PhD
Piljae Im, PhD

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Electrification and Energy Infrastructure Division

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831-6283
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1. INTRODUCTION

To support an emulator model development of Building Optimization Testing (BOPTEST) framework, a team at the US Department of Energy's Oak Ridge National Laboratory developed a medium-sized office building written in Modelica to serve as a reference test case. The reference test case was modeled based on an actual research platform that represents a typical medium-sized office building. This test case would encourage model-based design and testing of new controllers in which a developer first prototypes and debugs on a model before implementing in the real world. The developed preliminary model and control parameters will be further calibrated and tuned with actual measured data from experiments.

2. BUILDING DESCRIPTION

Built in 2013, the two-story flexible research platform (FRP) (Figure 1) is located in Oak Ridge, Tennessee (84°19' longitude, 35°55' latitude). The FRP, with a footprint of 40 ×40 ft (12 × 12 m), is an unoccupied research apparatus that can be used to physically simulate light commercial buildings common in the United States' existing building stock.

Figure 1. Oak Ridge National Laboratory FRP.

The building is exposed to natural weather conditions for research and development, leading to system- and building-level advanced energy efficiency solutions for new and retrofit applications. Additionally, a dedicated weather station (Figure 2) is installed on the roof of the FRP so that actual weather data can be used in performance analysis and modeling.

Figure 2. Weather station on the roof of the FRP.

The HVAC system in the FRP building is a rooftop unit (RTU) variable air volume (VAV) system with electric reheat, and the building has 10 thermal zones (8 perimeter zones and 2 core zones) that can be individually controlled. Energy performance in this building has been monitored since the summer of 2013 by ~1,071 sensors, most of which are recorded at 30 s intervals. The baseline envelope and HVAC characteristics of the FRP test building are shown in Table 1.

Table 1. FRP characteristics.

General characteristics	
Location	Oak Ridge, Tennessee
Building width	40 ft (12.2 m)
Building length	40 ft (12.2 m)
Story height (floor to floor)	14 ft (4.3 m)
Number of floors	2
Number of thermal zones	10 (8 perimeter and 2 core)
Construction characteristics	
Wall structure	Concrete masonry units with face brick
Wall insulation	Fiberglass R_{US}-11 (R_{SI}-1.9)
Floor	Slab-on-grade
Roof structure	Metal deck with polyisocyanurate and ethylene propylene diene monomer
Roof insulation	Polyisocyanurate R_{US}-18 (R_{SI}-3.17)
Windows	Aluminum frame, double-pane, clear glazing
Window-to-wall ratio	28%
HVAC systems and equipment characteristics	
Baseline systems	RTU VAV system with electric reheat, natural gas furnace
RTU cooling capacity	12.5 ton
RTU efficiency	9.7 energy efficiency rating
Natural gas furnace efficiency	81% annual fuel utilization efficiency

3. MODEL DESCRIPTION

The multi-zone model was developed using the room model in Modelica Buildings Library (Version 6.0.0). Although 12 zones were modeled, only 10 zones were conditioned under the mechanical system, and 2 zones were unconditioned (e.g., the stairwell). The HVAC system consisted of 1 rooftop air handling unit and 10 VAV terminal units.

1.1. BUILDING ENVELOPE MODEL

Each zone was connected through HeatPort, as shown in Figure 3, and the ground floor was assumed to be adiabatic. Construction layers and materials were defined based on construction drawings, and seven types of layers were used for the wall, roof, and floor construction. The eight windows were evenly distributed on the top floor. The window distribution for the first floor was identical to the top floor except that two windows on the north and east sides were replaced by glass doors. Detailed information is in Appendix A. No internal gain (e.g., radiant, convective, and latent heat gain) was defined, and the individual infiltration rate (0.432 air changes/h) was applied to the perimeter zones.

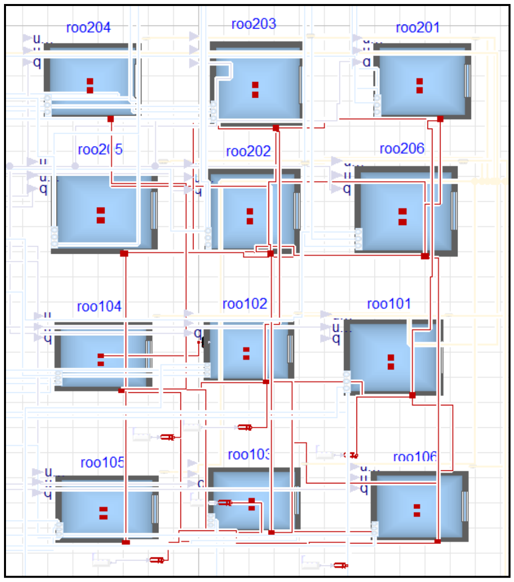

Figure 3. Thermal connectivity of zones.

1.2. BUILDING HVAC SYSTEM MODEL WITH CONTROL

The multi-zone HVAC system of the FRP is shown in Figure 4. The following assumptions were made for model simplification. The direct expansion (DX) coil was modeled as a variable speed DX coil with a 12.5 ton capacity. The RTU had a 9.6 energy efficiency rating, and each room had a VAV box with electric resistance reheat, and the heating coil was modeled as an electric heating coil. The zone electric heat in the VAV boxes was activated to provide the necessary perimeter heat. The electric reheat capacities were set from 1,000 to 5,000 W, and each nominal airflow rate was set from 0.118 to 0.297 m^3/s. The central fan in the air handling unit drew return air from each room, and the nominal airflow rate of the system was set to 1.86 m^3/s.

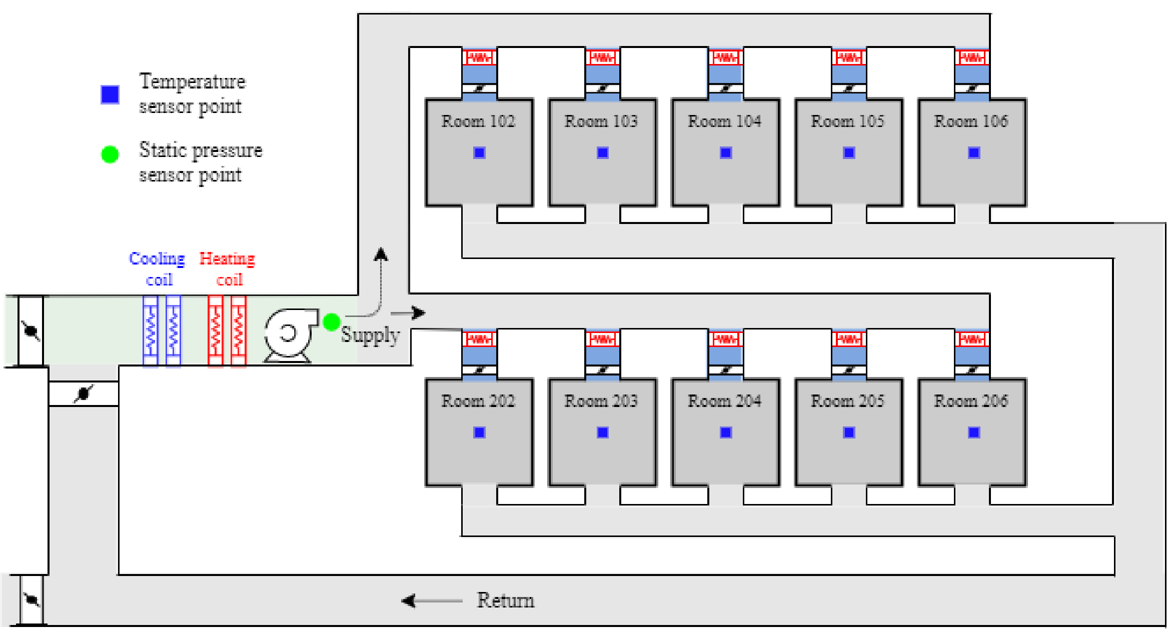

Figure 4. Schematic of the HVAC system.

The supply fan controller and VAV terminal controllers are shown in Figure 5. The supply fan was controlled by a local proportional-integral (PI) controller to maintain a static pressure of 1,000 Pa. To be consistent with the experimental condition of the FRP, the outdoor air damper in the Modelica model was fully closed, and the DX coil was controlled by a PI controller to meet the supply air temperature of 15°C. The PI controller manipulated the VAV damper position, and the control variable was the zone air temperature (cooling setpoint temperature: 22°C; heating setpoint temperature: 20°C).

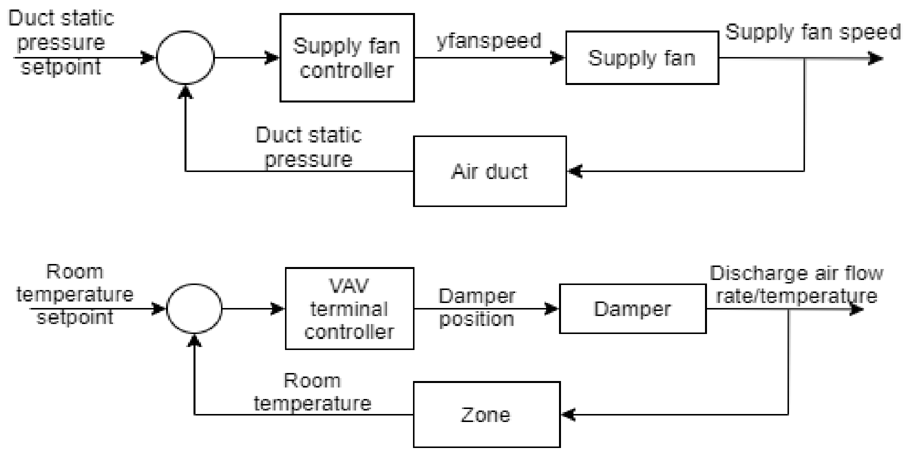

Figure 5. Supply fan controller and VAV terminal controller

Figure 6 shows the final model developed in Dymola, which shows the HVAC system model with local controllers, the air distribution and VAV system model, and the multi-zone envelope model from left to right.

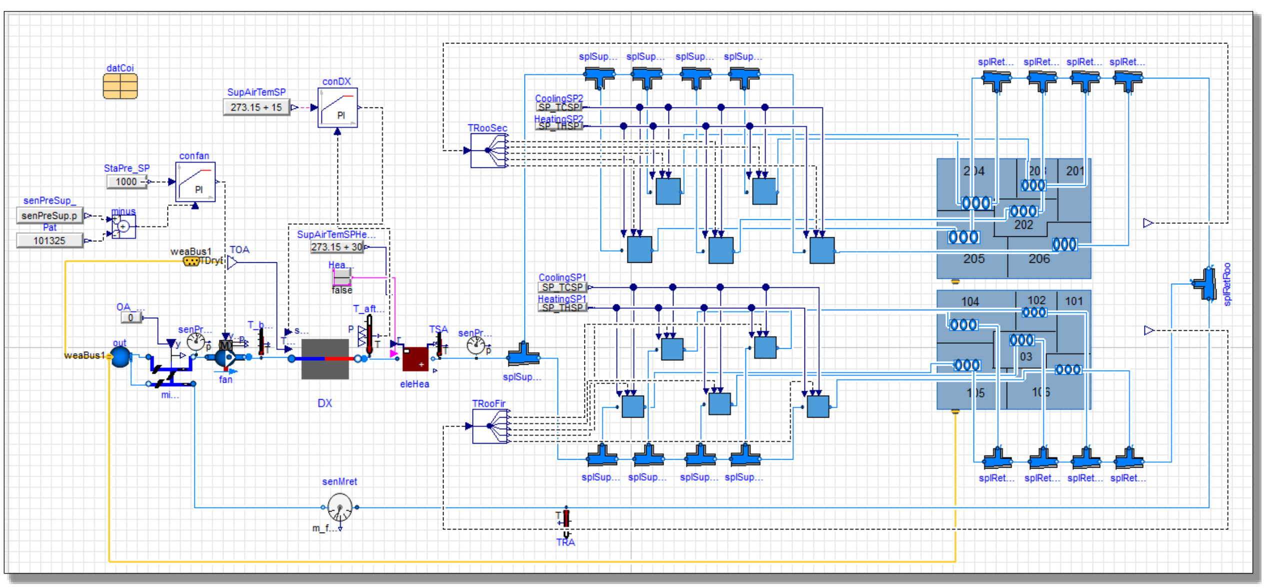

Figure 6. Graphical user interface of the model.

4. INTERFACE CONFIGURATION

The descriptions of developed Modelica models are as follows. The package consisted of Baseclasses, Envelope, RTUVAV, and Example packages. The base classes used for modeling were defined in the

Baseclasses package, and the multi-zone envelope model were defined in the Envelope package. The VAV reheat controllers, VAV reheat example, and performance curves were defined in the RTUVAV package. The final model was defined in the Example package. The model inputs and outputs are summarized in Table 2 and Table 3.

Table 2. Interface configuration-input.

Input	Description	Parameter name in the model	Input value	Unit
Supply air temperature	Supply air setpoint (SP) temperature	SupAirTemSP	293.15 + 15	K
Fan static pressure	SP for static pressure	StaPre_SP	1,000	Pa
SP temperature	Zone heating SP temperature	SP_THSP	293.15 + 20	K
	Zone cooling SP temperature	SP_TCSP	295.15 + 22	K

Table 3. Interface configuration-output.

Output	Description	Parameter name in the model	Unit
Zone temperature	Zone temperature of 101[a]	TRooFir.y1	K
DX coil	DX coil power consumption	DX.P	W
	DX coil sensible heat flow rate	DX.QSen_flow	W
	DX coil latent heat flow rate	DX.QLat_flow	W
Electric heater	Electric heater power consumption	elecHea.P	W
VAV	VAV reheat power consumption[a]	VAVREheat_withCtrl_TrooCon105ReHeat.Q_flow	W

[a] Outputs are available for all zones.

5. SIMULATION RESULTS

5.1 SIMULATION SETUP

The 2018 actual meteorological year weather file for Oak Ridge, Tennessee was used for this simulation. The authors chose five days for the cooling season (Days 181–185, June 31 to July 4) and five days for the heating season (Days 11–15, January 11 to 15) for the simulation. The Dassl algorithm with 10^{-6} tolerance was used for the numerical solver.

5.2 COOLING SEASON SAMPLE RESULTS

The developed building HVAC system model with local controllers was simulated, and Figure 7 shows the zone air temperature and Figure 8 shows the control outputs on the VAV box. As shown in Figure 7, the zone air temperature of the conditioned zones (except for the stairwell) was regulated at 20°C for heating and 22°C for cooling based on the control outputs shown in Figure 8. The results showed that the model captured the feedback responses and showed good agreement. For example, at midnight of the first day, the air temperature of Room 105 was regulated by heating. As the zone air temperature increased, the supply airflow rate was regulated by the PI controller to control the zone air temperature at 22°C. Because the heating controller used the same sensor input as the cooling controller, heating and cooling were simultaneously activated for the simulation period.

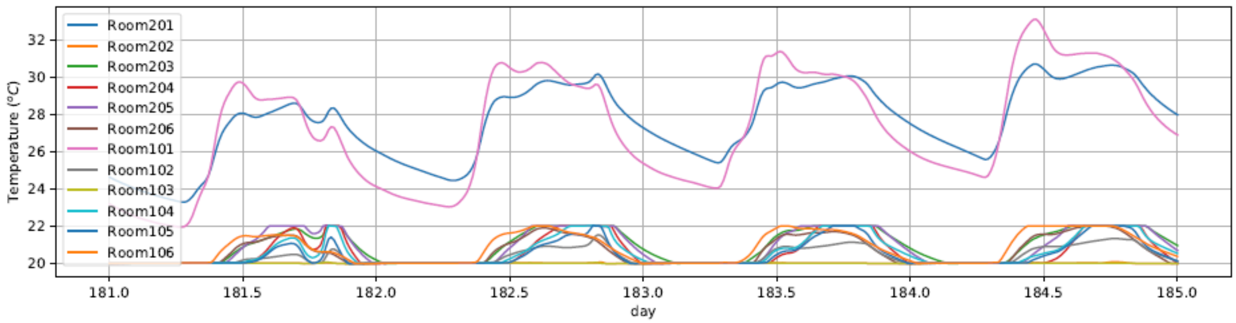

Figure 7. Zone air temperature: cooling season.

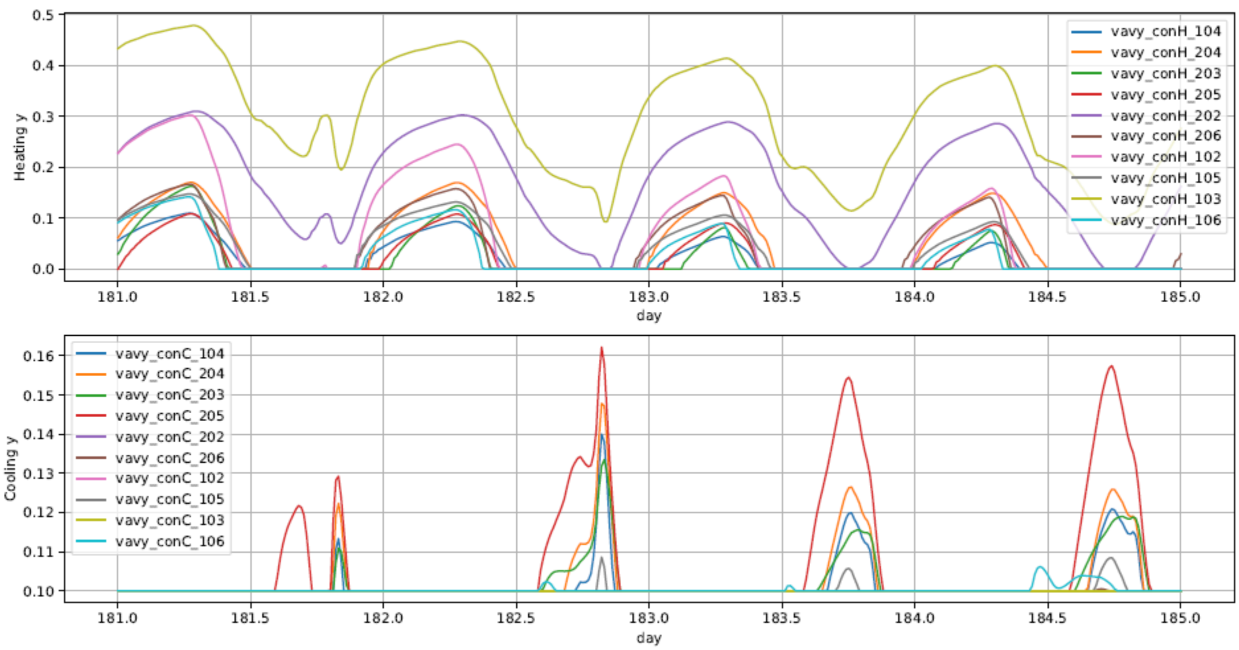

Figure 8. Control outputs on the VAV box.

Figure 9 shows the cooling capacity, DX power consumption, and VAV reheat power consumption. The maximum capacity of the cooling, maximum power of DX cooling, and sum of reheat power were 16.6, 1.2, and 1.2 kW, respectively.

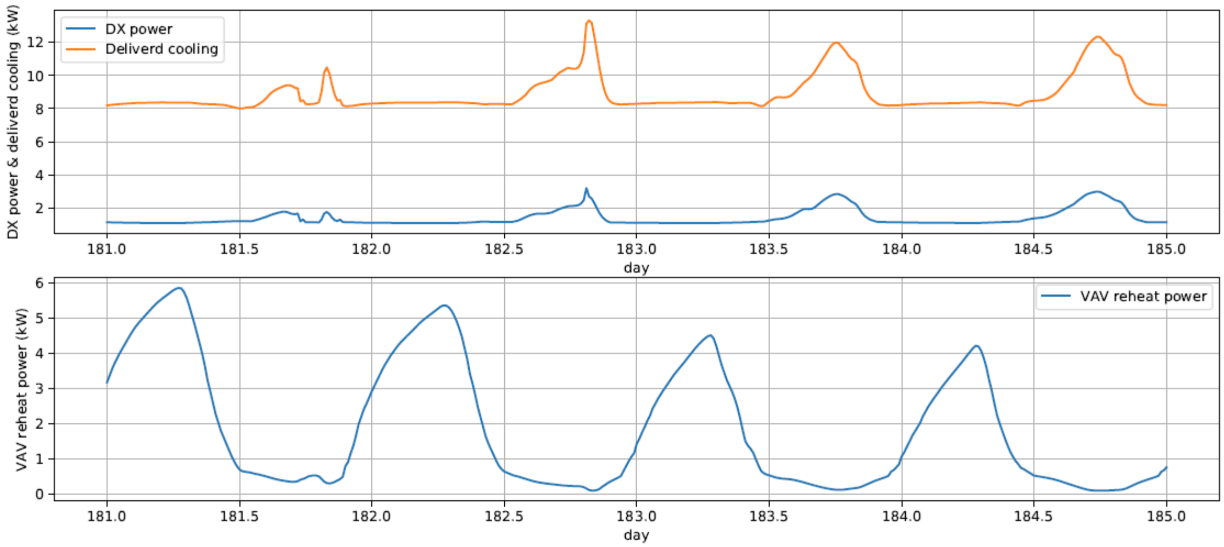

Figure 9. Cooling capacity, DX power consumption, and VAV reheat power consumption.

5.3 HEATING SEASON SAMPLE RESULTS

The developed building HVAC system model with local controllers was also simulated for the heating period. As described in Section 3, the electric heating coil was not activated during the simulation and the zones were controlled by the reheat coil only.

Figure 10 shows the zone air temperature and Figure 11 shows the control outputs on the VAV box. The results showed that the model captured the feedback responses and showed good agreement for the heating season, as well. For example, at the first day, the air temperature of Room 105 was regulated by heating throughout the day. As the zone air temperature increased, the supply airflow rate was regulated by the PI controller to keep the zone air temperature at 20°C. As shown in Figure 12, the maximum VAV reheat power consumption was 16 kW.

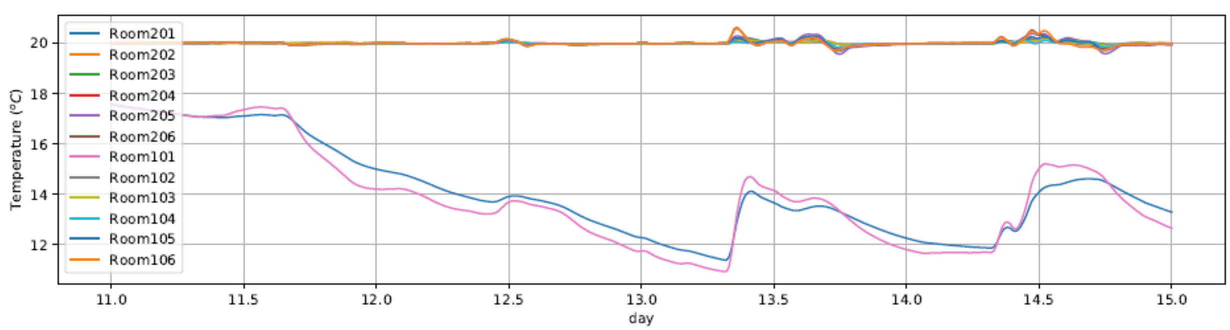

Figure 10. Zone air temperature.

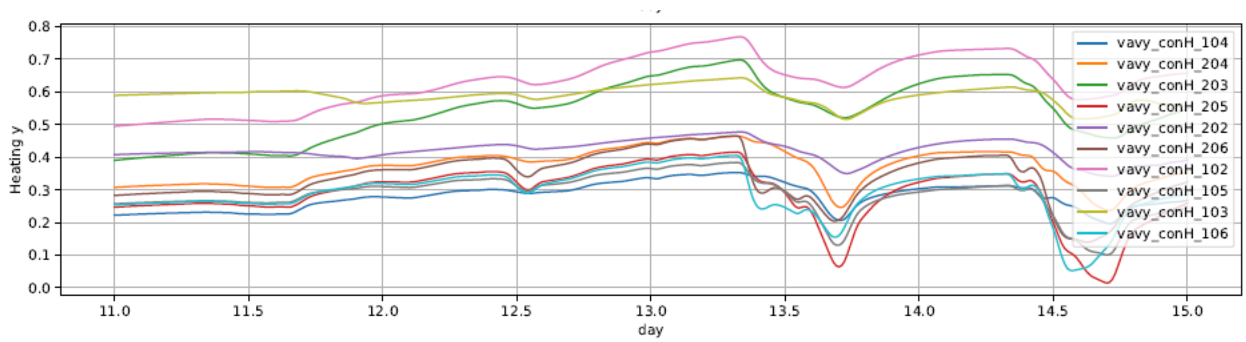

Figure 11. Control outputs for heating.

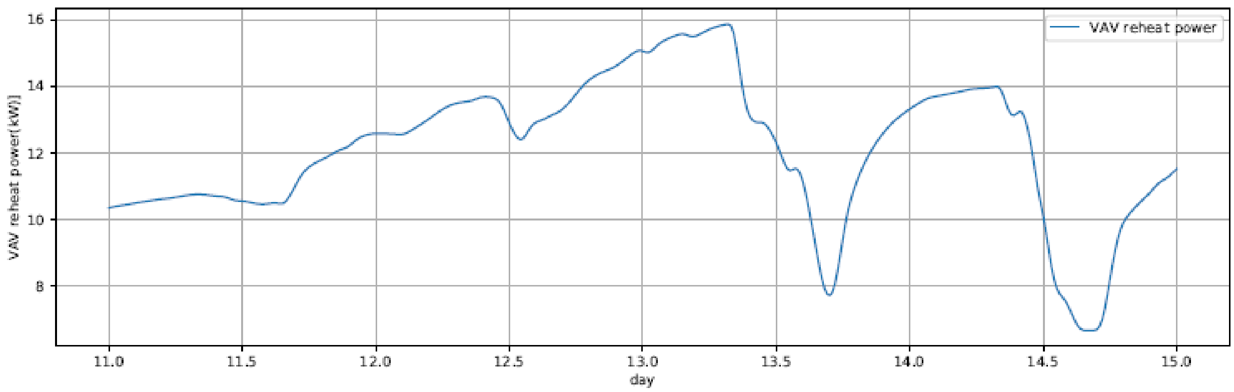

Figure 12. VAV reheat power.

APPENDIX A.

Table A.1. Construction layers and material properties.

Construction	Layer name in the Modelica model	Layers—exterior to interior	Thickness (m)	Conductivity (W/m-K)	Specific heat (J/kg-K)	Density (kg/m^3)	R (m^{2}K/W)
Roof	roof	Standard PW05	0.01909	0.115	1,213	545.0	0.166
		Roof insulation	0.0762	0.024023	836.8	265.0	3.17196
		Roof membrane	0.0095	0.16	1,460	1,121.3	0.059375
		Metal decking	0.0015	45.006	418.4	7,680.0	3.33E-05
Typical exterior wall	matExtWal	Face brick	0.092	1.31	920.48	2,082.3	0.070229
		Air	0.004106	0.0262	0.000718	1.2	0.1567
		Concrete block	0.1015	1.31	920	1,121.3	0.077481
		Concrete block	0.1015				
		Spray foam with metal stud	0.0889	0.02884	1,210	32.0	3.082524
		Gypsum	0.0158	0.16	1,090	784.9	0.09875
Exterior wall for Room 104	matExtWal1	Face brick	0.092	1.31	920.48	2,082.3	0.070229
		Air	0.004106	0.0262	0.000718	1.2	0.1567
		Concrete block	0.203	1.31	920	1,121.3	0.154962
		Spray foam with metal stud	0.0889	0.02884	1,210	32.0	3.082524
		Air	0.004706	0.0262	0.000718	1.2	0.1796
		Gypsum	0.0158	0.16	1,090	784.9	0.09875
Exterior wall for Room 204	matExtWal2	Face brick	0.092	1.31	920.48	2,082.3	0.070229
		Air	0.004106	0.0262	0.000718	1.2	0.1567
		Concrete block	0.203	1.31	920	1,121.3	0.154962
		Spray foam with metal stud	0.0889	0.02884	1,210	32.0	3.082524
		Rigid foam board	0.058	0.02605	920	32.0	2.226488
		Gypsum	0.0158	0.16	1,090	784.9	0.09875
Internal wall	matIntWal	1/2 gypsum	0.0127	0.16	1,090	800.0	0.079375
Ground floor	matFlo	Lower concrete	0.1524	1.95	900	2,322.6	0.078154
		Insulation	0.3048	0.033	836.8	51.5	9.236364
		Upper concrete	0.3048	1.95	900	2,322.6	0.156308
2F_Floor	matFlo1	Concrete block 1/2	0.08255				