2018 Building Performance Analysis Conference and
SimBuild co-organized by ASHRAE and IBPSA-USA
Chicago, IL
September 26-28, 2018

MODEL-BASED COUPLING OF AIR AND HYDRONIC SYSTEMS OPERATION ON A TYPICAL CLASSROOM OF A HIGH-PERFORMANCE ACADEMIC BUILDING

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ABSTRACT

A High-Performance Academic Building (HPAB) was studied following the evidence fsrom design documents, an energy model, and operational data suggesting that the building's performance is not entirely reflecting the design intent. Several operational anomalies were detected, including the operation of the mechanical system on the demand side, where an air system and a radiant system work in parallel.

EnergyPlus was used to simulate the building's mechanical system response for one typical classroom. The model was calibrated until it reproduced similar responses to those seen in the room thermostat, slab, and VAV data. Various features of the Energy Management System (EMS) module of EnergyPlus were utilized to create a responsive mechanical system control for the baseline classroom operation, as well as for five improvement strategies.

The control strategies were compared using predefined comfort and energy metrics. The most suitable strategy was resetting the air and radiant system setpoints based on the room temperature. Harmonizing the air and radiant systems, in addition to increasing the consistency of the radiant system operation, were the most effective approaches to reduce the operation and improve the comfort.

The study demonstrates the effectiveness of simulation in understanding and handling the complex three-way interaction of the systems with the classroom. It will be proposed to test the strategies in the actual building.

INTRODUCTION

Classroom conditions have direct effect on the academic performance of students [1], [2]. Regardless of the socioeconomic background, student math scores has been shown to be impacted by the ventilation rate [3]. At the same time, due to the increased fuel costs and higher expectations in thermal comfort, demand-side parameters such as room temperature setpoint and the ventilation rate are set in accordance with the energy targets of the high-performance buildings. Thus, the HVAC system of a high-performance academic building must find the middle ground between creating the proper learning environment, and maintaining reasonable energy consumption.

Meanwhile, within the building industry, there is increasing concern about a mismatch between the predicted energy performance of buildings and actual measured performance, typically addressed as "the performance gap" which is seen to be larger in state-of-the-art, energy efficient and green buildings; in an extreme case, measurements have shown five-fold difference between the actual and the predicted performance [4], [5]. This is in part because designers do not always have the means to accurately simulate or verify the responsiveness of these systems. Furthermore, building control systems – that are responsible for substantiating the system responses and interactions – are seldom engineered to meet these requirements even though the systems are characterized as "green," "low energy," or "high performance" [6].

The HPAB case-study building incorporates, at the source side, ground-coupled water-to-water heat pumps (WWHP) and solar-thermal as primary means of heating, with boiler used as a backup source. Cooling is provided by the cold side of the WWHP system. On the demand side, heating and cooling are delivered via thermally active radiant floors; while air system ventilates, de/humidifies, and provides supplementary heating and cooling. Thus, the classroom zones of the building are being conditioned by the air and radiant systems in parallel. The building features operable windows and a central atrium.

The thermally active building is not adequately meeting the demands from some critical zones. Furthermore, the operation is not consistent with the reduced hours of summer operation of an academic building. These and other observations on the building indicate that the air and radiant systems are not operating in synergy. Naturally, due to the operational deficiencies, some parts of the HVAC system are occasionally being operated manually, which does not always holistically improve the situation due to dynamic, interdependent, and synergistic nature of the air and radiant systems.

Furthermore, some systems appear to respond too fast to the room conditions; meaning that their setpoints change rapidly. This could occur in both air and radiant systems. As Figure 1 shows, at the start of a typical day of operation, the slab temperature setpoint decreases to the minimum. This setpoint temperature is a supervisory-level value that establishes the desired slab temperature, which the local controls (i.e. water valves) must attain. Before the slab is able to completely adapt the new temperature (at the day's end) the slab temperature setpoint rises again, so the radiant system is now working to nullify its operation of the previous hours. This pattern can potentially cause unnecessary HVAC operation and increase energy consumption.

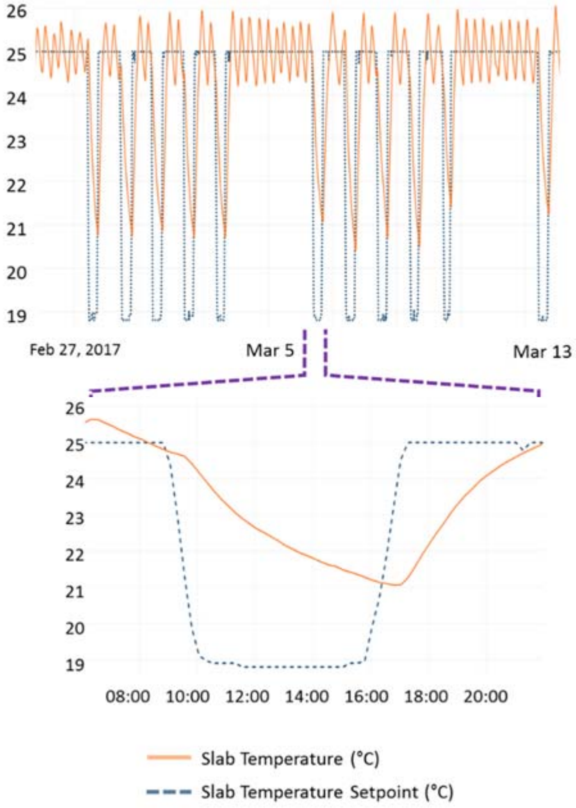


Figure 1 - Rapid changes of system setpoints

LITERATURE REVIEW

Existing industry practices in building controls systems, and the available research, show limited evidence of efforts to attempt to harmonize these two complementary systems. Separate comparison of the systems have been made by researches such as Haddad et al. [7] which showed that, the comparison is affected by the air change rate, and envelope. Sastry and Rumsey [8], claiming *"the world's largest side-by-side comparison of HVAC"* discovered that the radiant system is superior in costs, energy usage, and occupant satisfaction throughout their server spaces in a cooling-dominant climate. Baskin [9] experimented with both air and radiant systems in one building. It was concluded that the system coupling provides better control over the peaks. In some studies, HVAC systems similar to that of the case-study building, could be spotted (e.g. [10]), but not with a focus on the coupling.

The focus of Cigler et al. [10] was developing a control that exceeds the performance of the building's rule-based control. In one case-study, "performance of MPC was compared in simulations to the performance of a well-tuned rule-based controller similar to the one currently deployed in the real building. MPC yielded similar energy usage (to within 5%) as the reference controller at a comparable amount of thermal comfort violations", the authors suggest.

"Keep-it-simple-and-do-it-well" approach is also suggested by Boardass and Leaman [11] who halved the gas consumption of an academic building by a rule-based control logic that was explained briefly and clearly: "during occupancy hours, the AHUs endeavored to maintain a supply air temperature of approx. 21C by varying the amount of heat recovery. If slab temperatures in locations towards the room ceiling outlets fell below 20C, the heating was boosted to maximum, with recirculation at night. If the slab temperatures rose above 22C, the heat exchangers were bypassed and outside air cooling was extended overnight".

This study was also influenced by the work of Baumann [12] in the methodology and the control of the radiant system. The study points out specific characteristics of the radiant system — related to the thermal mass — such as a self-tuning effect that anchors the room temperature to the temperature of the slab. Moreover, the study uses a specific control based on the outdoor air temperature averaging that seem to establish an stabilized pattern of operation for the radiant system.

Commonly, it was seen in the mentioned studies, and other reviewed papers, that the researchers would utilize energy modeling software to test and verify control strategies. If enough effort has been put into properly calibrating the model, energy modeling is convenient since it enables testing strategies quickly with different "what if" scenarios [13]. As such, simulation was used to re-create the HPAB building's mechanical system response, thus the "model-based" title. The implementation was in EnergyPlus modeling software.

For the purpose of this research, accurate implementation of the controls in the model is crucial. The typical approach to control implementation in EnergyPlus has been co-simulation (e.g. [10] and [14]) since studies claim that frequently used computer programs for building modeling lack the flexibility in designing advanced control systems [15]–[17]. Namely, Building Control Virtual Test Bed (BCVTB) has been frequently used as an external interface to take advantage of a numerical computing environment (e.g. MATLAB) for the controls. Co-simulation may enable the development of more sophisticated controls but it also inserts two more software dependencies (at minimum) to the simulation. Considering the additional maintenance and configuration involved, for this research, native control capabilities of EnergyPlus provide acceptable results. These native controls can be found in the Energy Management System (EMS) module of the software and are partially used by the co-simulation as well. In the review of literature, mentions of the system and its utilization for overcoming specific limitations can be seen [18] but there is a lack of comprehensive and detailed use-cases of the system despite its availability.

CLASSROOM MODEL

To focus on the mechanical system response in the scale of the classrooms in the case-study building, a simplified construction was created to represent one classroom (**Error! Reference source not found.**). The simplified model reduces the unnecessary effort caused by uncertainties and redundant entities, while it allows rapid testing of control strategies. The modeled classroom is surrounded by a buffer zone representing the adjacencies [19].

The size and the construction material of the classroom is similar to the classrooms on the first and second floor of the case-study building. One wall of the classroom is exposed to the elements and has a window while the other three are internal. The boundary (buffer) zone has high thermal mass, no internal cooling/heating load and a separate mechanical system. The mechanical system of the classroom is identical to the real classrooms on the demand-side, with the exception that the VAV box was removed as the room is the only connection of its Air Handling Unit. Design documents, and historic operational data from the building automation system (BAS) were used for calibration. Employing various features of Energy Management System (EMS) module of EnergyPlus, a responsive mechanical system control was created within the simulation which replicates the typical responses of the building spaces.

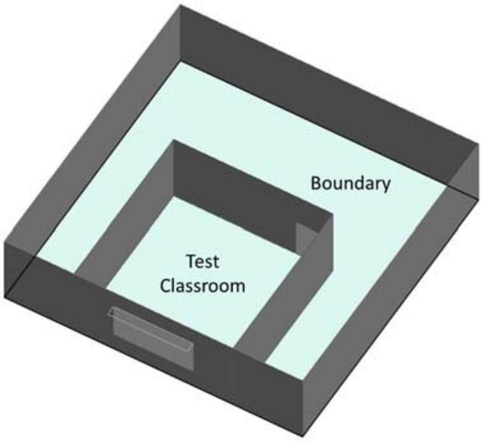


Figure 2 - Modeled classroom and the boundary zone

STRATEGIES

This construction is used to explore different control *Strategies*. These strategies will define how the air and radiant systems are controlled. The first strategy (i.e. Strategy A) is the baseline case designed to recreate the behavior patterns of the actual rooms being modeled. Other strategies each attempt to explore the response from a specific standpoint. The strategies are introduced in Table 1. The strategies are designed to be applicable to the case-study building, with the goal of harmonizing the operation of the systems and taking full advantage of system/building characteristics. For fair comparison of the strategies, the following four metrics were defined:

- Number of uncomfortable hours as per AHSRAE 55-2004
- Energy transferred by the air and radiant systems
- Room temperature difference with the baseline condition
- Time of HVAC setpoint below condensation threshold

The comparison of the strategies was done once with the classroom (and therefore its window) facing north, and once facing south.

Implementing of these strategies required extensive use of the EMS module. Although EnergyPlus provides objects such as *FollowSystemNodeTemperature* and *OutdoorAirReset* in its setpoint managers, that come close to what is needed for some strategies, significant gaps would have remained if the controls were not customized. For example, the latter can work with the radiant system in the baseline condition for one mode

Table 1 - Strategies

Strategy	Radiant Controller	Air Controller	Notes
A **(Baseline)**	Building Mode (cooling or heating) and room temperature	Room temperature	Above 18°C outdoor air temperature the slab temperature is statically set to 18.8°C
B	Room temperature	Room temperature	Temperatures are set with subtraction of the room temperature from setpoint
C	Constant slab temperature	Room temperature	Exploring the slab's self-tuning effect
D	Constant slab temperature	Comfort thermostat	Air system control by EnergyPlus object: ZoneControl:Thermostat:ThermalComfort
E	3-day average outdoor air temperature	Room temperature	Slab temperature as per Baumann (2003)

where the temperature is fixed but not for the other where the temperature changes. The object does not have an availability schedule to be mixed with any other type of control as well [20].

Moreover, proper implementation of operation with many of native controllers in EnergyPlus would require fixed schedules made from the weather data as additional inputs. This means, if the weather data was changed, the controls and schedule may need modification. In case of customized controls, the controls react to the weather and other conditions during the simulation. This provided an advantage as for this model there were multiple weather file candidates.

The goal of EnergyManagementSystem is controlling the "Actuators". These are nodes within the EnergyPlus model, made available to be controlled. "Programs" are where the system logic to modify Actuators is written in form of instructions. The language used in the Programs is EnergyPlus Runtime Language (ERL). The Program may need to import the state of the building to perform its calculations, so the condition of different nodes in the building are inserted in the EnergyManagementSystem using the "Sensors".

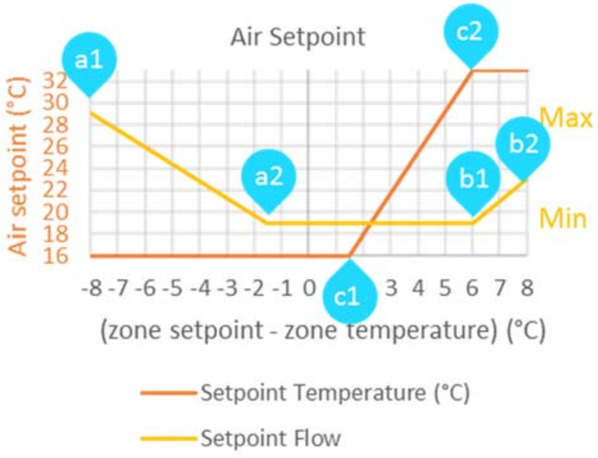
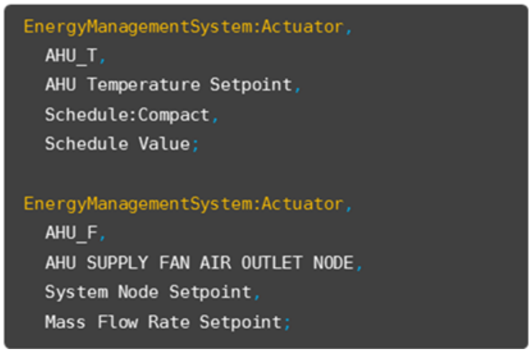


Figure 3 - Air system room temperature control

Room temperature controller of the air system is provided as an example of EMS use. The aim of this control is to use the difference between the room temperature and the room setpoint to calculate the supervisory level setpoints of the VAV coil and damper (Figure 3). This control has been used in Strategies B, C, and E as presented, and was simplified for Strategy A.

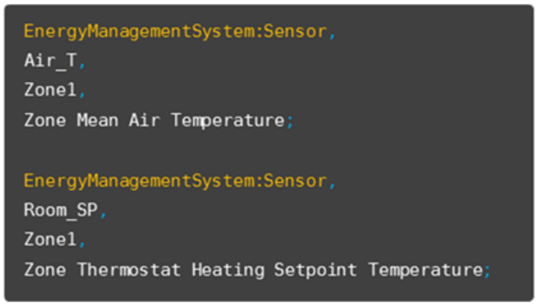


```
EnergyManagementSystem:Actuator,
  AHU_T,
  AHU Temperature Setpoint,
  Schedule:Compact,
  Schedule Value;

EnergyManagementSystem:Actuator,
  AHU_F,
  AHU SUPPLY FAN AIR OUTLET NODE,
  System Node Setpoint,
  Mass Flow Rate Setpoint;
```

Figure 4 – EMS Actuators

The next step would be gathering the building data for the EMS, which is done via the Sensors as shown in Figure 5. The mean air temperature of the zone will be used for assessing the room condition at a given time in the simulation (*Air_T*) and the thermostat temperature will be the setpoint (*Room_SP*). In this model, the heating and cooling thermostat setpoints are separate but both have the same value, so heating is used.

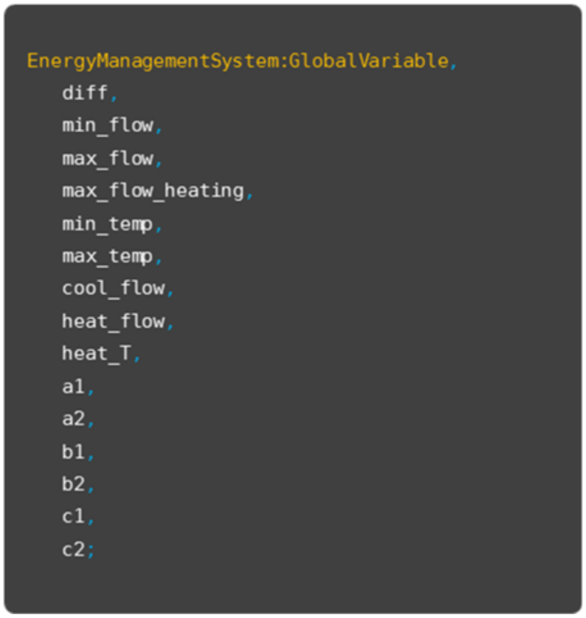


```
EnergyManagementSystem:Sensor,
Air_T,
Zone1,
Zone Mean Air Temperature;

EnergyManagementSystem:Sensor,
Room_SP,
Zone1,
Zone Thermostat Heating Setpoint Temperature;
```

Figure 5 – EMS Sensors

The above steps create the foundation for writing the program. The names given to the Sensors and Actuators will be used in the program. In addition, some *variables* will be incorporated in the Program to store values; those will make the future changes easier and clarify the program. The declaration of the variables is shown in Figure 6. The variables are declared as *GlobalVariables* meaning that they are accessible from everywhere.

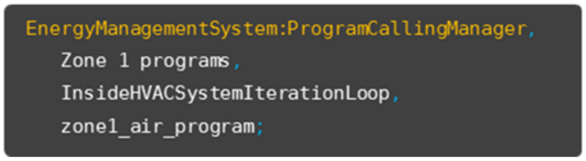


```
EnergyManagementSystem:GlobalVariable,
   diff,
   min_flow,
   max_flow,
   max_flow_heating,
   min_temp,
   max_temp,
   cool_flow,
   heat_flow,
   heat_T,
   a1,
   a2,
   b1,
   b2,
   c1,
   c2;
```

Figure 6 – EMS GlobalVariables

The program receives or calculates the variables, and finds the proper values for the air flow and temperature depending whether the zone temperature to setpoint difference falls on a ramp or on a horizontal section of the Figure 3 graph. The program is shown in Figure 8.

Finally, the program calling points must be specified so that the software run the program at the desired times. This is done with the *ProgramCallingManager* as shown in Figure 7.



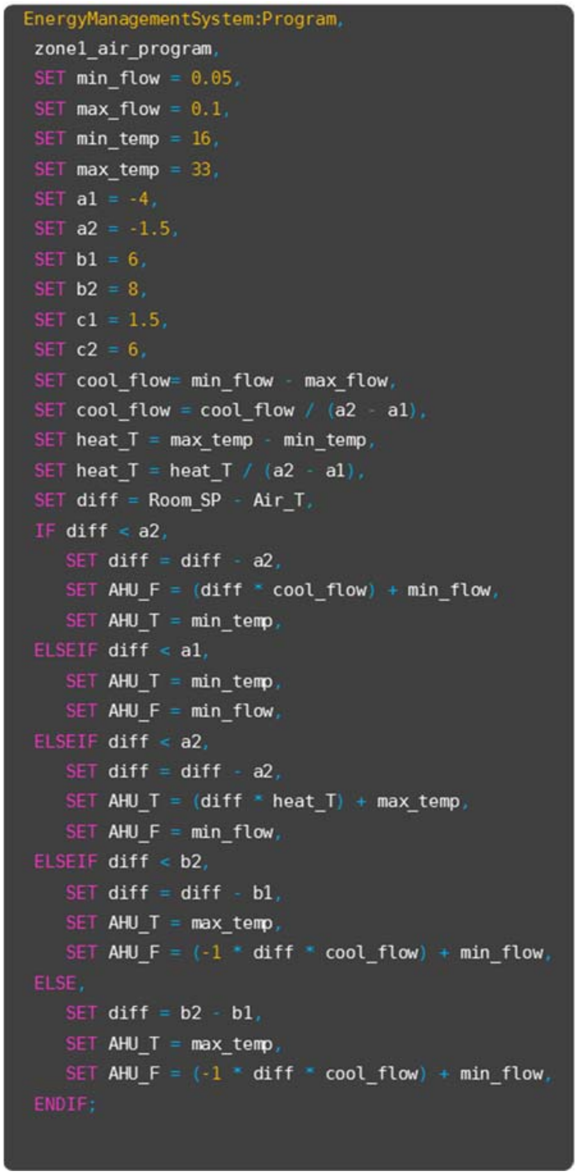
```
EnergyManagementSystem:ProgramCallingManager,
   Zone 1 programs,
   InsideHVACSystemIterationLoop,
   zone1_air_program;
```

Figure 7 - EMS ProgramCalling Manager

Three other objects in the EMS module are of note: The first object is TrendVariable which stores a predefined number of variables. These stored variables can then be recalled individually or as a sum, average, etc. The TrendVariable was used in the slab controller of the Strategy E, in which the outdoor air temperature at each timestep was collected by a TrendVariable. The sum of values was then recalled once for the previous 24 hours and once for the previous 72 hours. The weighted average of the two was used in the controller.

The second object is *OutputVariable* which creates a custom EnergyPlus output in the ESO file and writes its value there with the selected resolution.

Finally, *Subroutines* are ERL snippets that are meant to be run by other Programs. Subroutines can be used for storing repetitive pieces of programs. This not only makes the programs smaller, but also creates a single point to which changes can be made quickly. If values need to be given to the subroutines or the opposite, dedicated GlobalVariables may be defined for transferring the values.



```
EnergyManagementSystem:Program,
 zone1_air_program,
 SET min_flow = 0.05,
 SET max_flow = 0.1,
 SET min_temp = 16,
 SET max_temp = 33,
 SET a1 = -4,
 SET a2 = -1.5,
 SET b1 = 6,
 SET b2 = 8,
 SET c1 = 1.5,
 SET c2 = 6,
 SET cool_flow= min_flow - max_flow,
 SET cool_flow = cool_flow / (a2 - a1),
 SET heat_T = max_temp - min_temp,
 SET heat_T = heat_T / (a2 - a1),
 SET diff = Room_SP - Air_T,
 IF diff < a2,
    SET diff = diff - a2,
    SET AHU_F = (diff * cool_flow) + min_flow,
    SET AHU_T = min_temp,
 ELSEIF diff < a1,
    SET AHU_T = min_temp,
    SET AHU_F = min_flow,
 ELSEIF diff < a2,
    SET diff = diff - a2,
    SET AHU_T = (diff * heat_T) + max_temp,
    SET AHU_F = min_flow,
 ELSEIF diff < b2,
    SET diff = diff - b1,
    SET AHU_T = max_temp,
    SET AHU_F = (-1 * diff * cool_flow) + min_flow,
 ELSE,
    SET diff = b2 - b1,
    SET AHU_T = max_temp,
    SET AHU_F = (-1 * diff * cool_flow) + min_flow,
 ENDIF;
```

Figure 8 - EMS Program

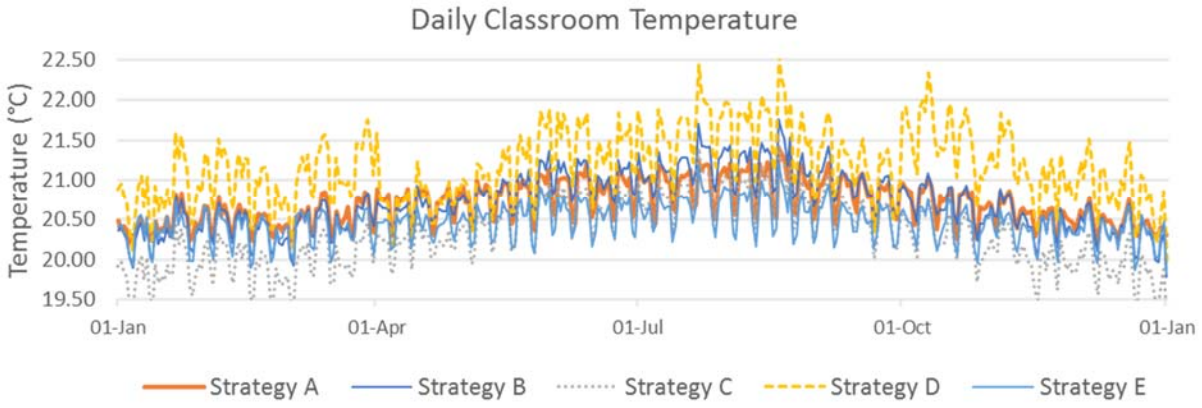


Figure 9 - Room temperature in different Strategies over the period of one year

RESULTS AND ANALYSIS

The energy transfer rates found in the simulation results are shown in Table 2. The results show that all strategies have been successful in reducing the energy transfer rates. This shows that the general approach of the Strategies to make the systems more responsive to the room or environmental trends have been successful. Moreover, change of the facing to south, which increases the cooling loads due to the solar heat gain, causes further reduction as the Strategies are more flexible to load changes.

Table 2 - Strategy Energy Transfer

Facing	Strategy	Energy transferred for heating [KWh]	Energy transferred for cooling [KWh]	Total transferred energy [KWh]	Change [%]
N	**A**	33973	4284	**38257**	Baseline
	B	18400	1267	**19667**	**49%**
	C	24029	842	**24871**	**35%**
	D	22053	289	**22342**	**41%**
	E	25498	794	**26292**	**31%**
S	**A**	32306	4819	**37125**	Baseline
	B	16862	1623	**18485**	**50%**
	C	21934	906	**22840**	**38%**
	D	22052	288	**22340**	**40%**
	E	23438	867	**24305**	**34%**

Reviewing the comfort metrics show that the number of hours within the comfort zone ranges from nearly 6000 hours to about every hour of the year; however, the difference may be exaggerated given that the Strategies are developed to reproduce the baseline room temperature which is very close to the lower threshold of the comfort zone. As Figure 9 shows, all strategies create comparable room temperatures that may not be distinguishable by the occupants in a real-life scenario; however, since being (or not being) in the comfort zone is a binary condition, the slight differences and the drops of temperature at night may increase the number of uncomfortable hours greatly.

Considering the above, Strategy B better used the air system and stabilized the operation of the radiant system, also reduced the energy transfer significantly without negatively impacting the indoor conditions (Figure 3). In addition to stabilizing the radiant system setpoint, which was achieved by Strategy E as well, Strategy B uses the air system for most of the energy transfer – proportionally more than any other strategy (Figure 10). In general, the strategies that used the air system more, perfrormed better in energy transfer, but a correlation could not be found.

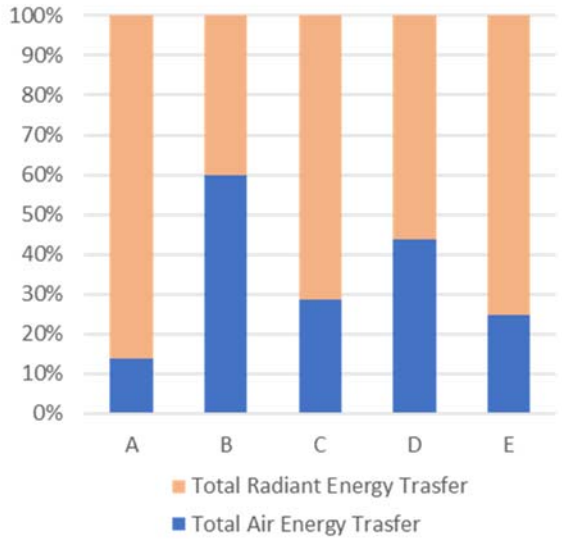


Figure 10 - Strategy Energy Transfer Percentage

CONCLUSION

The challenges a High-Performance Academic Building is currently facing in its operation was discussed. The building's mechanical system on the demand-side includes an air system and a radiant system working in parallel without direct connection. This causes lack of responsiveness and operation harmony. Moreover, each system individually has operation inconsistencies. The radiant system setpoints was provided as an example. The setpoints fluctuate faster than the radiant system can respond. Thus, in some cases, the system starts working against itself.

This operation was simulated in a classroom level model developed and calibrated based on the data obtained from the building. The simulation contained a detailed implementation of the control system in EnergyPlus Energy Management System module. Due to the lack of literature for this procedure, the implementation was illustrated and an example was provided for the air system control.

Four strategies were developed based on the existing literature to explore the responses of the systems. The same EnergyPlus module was used for the implementation of the strategies. These strategies, and the baseline, were compared using defined comfort and energy metrics. It was seen that the operation can be improved with control of both air and radiant system with the room temperature. The major advantages of the best performing strategy were stabilization of the radiant system setpoints and better use of the air system.

ACKNOWLEDGEMENTS

This research was supported by BCIT Green Value Strategies Fund. We also thank Ron Kato and the building owners, managers, and operators for making the project possible.

REFERENCES

[1] S. Urlaub, G. Grün, P. Foldbjerg, and K. P. Sedlbauer, "The impact of ventilation and daylight on learning in schools – a summary of the actual state of knowledge," 2016.

[2] M. Turunen, U. Haverinen-shaughnessy, O. Toyinbo, R. Shaughnessy, M. Turunen, T. Putus, J. Metsämuuronen, J. Kurnitski, and U. Haverinen-shaughnessy, "Building characteristics, indoor environmental quality, and mathematics achievement in Finnish elementary schools," *Build. Environ.*, vol. 104, no. May, pp. 114–121, 2016.

[3] U. Haverinen-Shaughnessy and R. J. Shaughnessy, "Effects of classroom ventilation rate and temperature on students' test scores," *PLoS One*, vol. 10, no. 8, 2015.

[4] P. De Wilde, "The gap between predicted and measured energy performance of buildings: A framework for investigation," *Autom. Constr.*, vol. 41, pp. 40–49, 2014.

[5] C. Miller, Z. Z. Nagy, and A. Schlueter, "Automated daily pattern filtering of measured building performance data," *Autom. Constr.*, vol. 49, no. PA, pp. 1–17, 2015.

[6] B. D. Hunn, J. Bochat, and I. Process, "Measurement Of Commercial Building Performance," *ASHRAE J.*, no. July, pp. 66–72, 2012.

[7] K. Haddad, J. Purdy, and A. Laouadi, "Comparison of the Performance of a Forced-Air and a Radiant Floor Residential Heating System Connected to Solar Collectors," *J. Sol. Energy Eng.*, vol. 129, no. November, pp. 465–72, 2007.

[8] G. SASTRY and P. RUMSEY, "VAV vs . Radiant Side-by-Side Comparison," *ASHRAE J.*, no. May, 2014.

[9] E. Baskin, "Evaluation of Hydronic Forced-Air and Radiant Siab Heating and Cooling Systems," *ASHRAE Trans*, pp. 525–534, 2005.

[10] J. Cigler, D. Gyalistras, J. Siroky, V.-N. Tiet, and L. Ferkl, "Beyond Theory: the Challenge of Implementing Model Predictive Control in Buildings," in *Clima 2013 - 11th REHVA World Congress & 8th International Conference on IAQVEC - "Energy Efficient, Smart and Healthy Buildings,"* 2013, pp. 1008–1018.

[11] B. Boardass and A. Leaman, "CIBSE Case Study : Investigation of 90s Building for Energy Performance," *CIBSE J.*, 2012.

[12] O. Baumann, "Design and Optimization of Control Strategies and Parameters by Building and System Simulation," 2003.

[13] M. Donnelly, "Building Energy Management : Using Data as a Tool, Issue Brief," *Inst. Build. Effic.*, p. 9, 2012.

[14] S. Privara, Z. Vana, D. Gyalistras, J. Cigler, C. Sagerschnig, M. Morari, and L. Ferkl, "Modeling and identification of a large multi-zone office building," *Int. Conf. Control Appl.*, no. September, pp. 55–60, 2011.

[15] D. B. Crawley, J. W. Hand, M. Kummert, and B. T. Griffith, "Contrasting the capabilities of building

energy performance simulation programs," *Build. Environ.*, vol. 43, no. 4, pp. 661–673, 2008.

[16] C. Sagerschnig, D. Gyalistras, A. Seerig, S. Privara, and Z. Vana, "Co-simulation for building controller development: the case study of a modern office building," *Proc. CISBAT*, no. 2005, pp. 955–960, 2011.

[17] S. Prívara, "Building Modeling and Identification for Predictive Control," Czech Technical University in Prague, 2013.

[18] A. Tzoulis, "Performance assessment of building energy modelling programs and control optimization of thermally activated building systems," *Delft Univ. Technol.*, 2014.

[19] J. . A. Clarke, J. Cockroft, S. Conner, J. W. Hand, N. J. Kelly, R. Moore, T. O. Brien, P. Strachan, T. O'Brien, and P. Strachan, "Simulation-assisted control in building energy management systems," *Energy Build.*, vol. 34, no. 9, pp. 933–940, 2002.

[20] U.S. Depratment of Energy, *Input Output Reference, EnergyPlus Version 8.7 Documentation*. 2016.