Investigation of an Innovative Energy System and Its Advanced Control in EnergyPlus

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Abstract

As a powerful whole building simulation tool, *EnergyPlus* is considered ideal for the investigation of integrated building technologies. This paper develops a unique energy system, with hybrid ventilation and radiant heating/cooling, for a high performance building in *EnergyPlus*. Based on this system, its application for advanced control is also proposed by using an *EnergyPlus* and *Matlab* unified approach. By presenting the modeling process in details, this study enriches the reference for researchers and modellers who model creative unconventional systems. The main challenges addressed include the implicit simulation of vertical pipe water mullions, the ductless convective chilled beams, and the missing of a single component for a hybrid rooftop air-conditioner. The model in *EnergyPlus* serves as a core part for the development of an advanced controller for the high performance building.

1 Introduction

Buildings account for about 40% of the total primary energy consumption in the U.S. (DOE 2011). Improving the energy utilization efficiency with high performance techniques for building operation is thus critical to achieve energy and environmental sustainability (Yu et al 2011). An informative performance analysis of such novel techniques in building energy systems will certainly benefit the understanding and promotion of the innovations. Simulating the real-time building system in a whole-building simulation (WBS) tool is valuable before conducting a field test. It helps us gain more insights of the system and identify the opportunities to improve the overall operational efficiency. With modules in a structured architecture and an integrated environment, a WBS allows the analysts to perform a systematic analysis of a building system by changing the settings and exposing the system to different conditions.

Among the WBS tools, *EnergyPlus*, the official building simulation program of the United States Department of Energy (DOE), is widely adopted as such a tool in building and heating ventilation and air-conditioning (HVAC) industry to model building and energy systems (Zhou et al 2003). Advance simulation features, including variable time steps, dynamic set point reset, and external interface, etc, make it more open and powerful in simulating wide range of systems. With the recent integration of powerful airflow modeling mechanism as *AirflowNetwork*, it provides an ideal simulation environment for a comprehensive investigation of innovative energy systems.

However, currently most applications of *EnergyPlus* still remain in the design stage to qualitatively evaluate energy systems and support a decision making. Since it is by and large a conceptual level utilization, where the system combinations are limited to conventional options and the system constraints are hidden by using auto-sizing, the features of new components and their utilization in *EnergyPlus* can hardly be touched or learned by the users. The absence of users' deep involvement might lead to problematic simulation applications of *EnergyPlus* and prevent it from improving in return. There are two factors, as mutual cause and effect, resulting in this situation. First, as a simulation engine in essential, it is difficult to program in *EnergyPlus* directly. Second, few system model oriented references in literature are available for advanced applications.

This study develops and investigates an unconventional as-built mechanical system in *EnergyPlus*. The system consists of a group of vertical radiant water mullions, radiant ceilings, convective chilled beams, and a dedicated hybrid rooftop unit. High energy efficiency features, e.g., heat recovery, desiccant dehumification, mixed mode ventilation, are embedded in this advanced system. This newly developed model could facilate the analysis of the novel building system in multifarious applications, such as advanced control, automated fault diagnosis, etc. In this article, an exemplary application for the purposes of advanced control is thereby proposed by using an *EnergyPlus* and *Matlab* integrated approach. In addition, the study enriches the reference of *EnergyPlus* by presenting the modeling methodology of the innovative energy system.

The paper starts with the introduction of the studied building system and mainly focues on the three mechanical subsystems: 1. radiant water mullions and ceilings; 2. ductless chilled beam ventilators; and 3. a hybrid rooftop air conditioner. The corresponding modeling methodology and development issues in *EnergyPlus* for these subsystems are then provided. After that, the application of this innovative energy system model for the advanced control is elaborated. The study concludes, with demonstration, that the constructed energy model in *EnergyPlus* is promising in further applications for informative performance analysis. Additional information of the model and its calibration is collected in the Appendix for readers' reference without breaking the flow of article.

2 Building energy system in IW

Building system overview


Figure 1: Outside view of the IW

The Robert L. Preger Intelligent Workplace (IW), sitting atop Margaret Morrison Carnegie Hall, is a living and lived-in laboratory for the research on high performance building technology. Fig. 1 gives the side view of the space and the surroundings of IW. The building features a reconfigurable open space and accommodates some thirty graduate students and facul-

ty as their offices. As a living laboratory, it also supports the investigation of various types of building mechanical systems, including a set of diversified energy supply systems (e.g. combined power and thermal system, solar cooling system, etc), and integrated air and water based distribution systems.

According to a DOE report, the dedicated outdoor air system, radiant cooling/chilled beam, enthalpy/energy recovery, and displacement ventilation are listed as current technology options for commercial buildings, which could contribute around 469 billion kWh (1.6 quadrillion BTUs) potential savings in total, annually (Roth et al 2002). Two of them have near zero payback years. The technologies also possess non-energy benefits, covering from downsizing of HVAC equipment, enhanced indoor air quality, improved humidity control, to notable peak demand reduction. Understanding the characteristics of the technologies and the integration, and developing an advanced control is certainly critical to generalizing the technologies. IW has systems with all of the four energy efficient technologies installed and deployed in the space. It provides a good test environment and serves as a show case for the application of the advance technologies that can be readily adopted into buildings.

Building system characteristics

The investigated system is the north part of the workspace, IW_n. For the research on the dynamic performance of the system in the next stage, the space model is kept as thirteen zones, including six conference rooms, five offices, one kitchen and one hallway. The internal zones are divided with virtual partion walls with one or two rectangular holes. Fig. 2 shows the isometric view of the building model in *EnergyPlus*. The interface of IW_n with the south side of the workplace is treated as adiabatic walls with no heat transfer or cross airflow. The conditioned floor area is 345m^2. It is a lightweight construction space with some 70% of fenestration area for enhanced dayliting and scenic view. The envelopes are double aluminum sided with a layer of 6.7m^2 K/W (R-38) bat insulation. The zigzag shaped roof is constructed with steel deck and 6.7m^2 K/W (R-38) insulation. The space is mainly occupied from 8:00am to 8:00pm for all the calendar days.
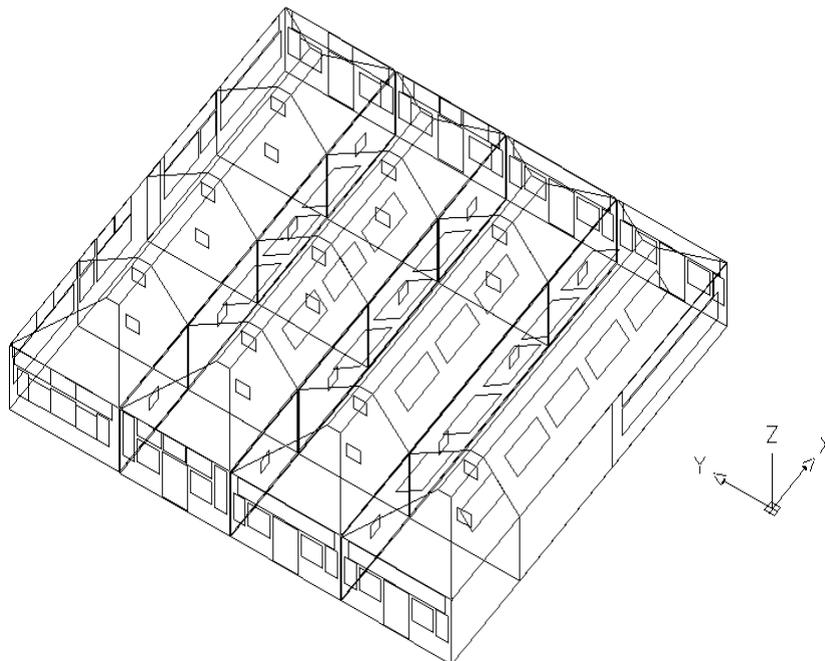
Figure 2: Isometric view of IWn

A group of vertical pipes (i.e. water mullions) are deployed along the exterior walls. Conditioning water is fed into the mullions from the campus grid to warm up and cool down the

space. To strengthen the local comfort control, ten more convective chilled beam ventilators and four radiant panels are distributed in the space. The ventilation of the space is provided by a hybrid direct-expansion and active-dehumidification rooftop unit. This unit also assumes the latent load of the space to avoid surface condensation in cooling seasons. Eight transom windows on the east, west and north wall are actuated and automated to naturally ventilate the space when the outside air is favorable for space cooling.

3   Module development

In this section, the modeling methodology and development issues of the sub-systems in the innovative energy system are detailed. The performance of calibrated model is collected in the Appendix for reference.

Radiant heating/cooling

Radiant heating and cooling system heats and cools the surroundings by radiation exchange and indirect convection. It is usually embedded in the floor, walls or ceiling to condition the space. In *EnergyPlus*, a module group, *Zone HVAC Radiative/Convective Units*, collects the modules of radiation based air-conditioning components. Except baseboard units, all the other types of radiant components need to be assigned to a building surface. The water mullions and radiant ceilings in IW_n belong to this category.

Fig. 3 illustrates the water mullions, radiant ceilings, and the configuration process of the radiant heating/cooling in *EnergyPlus*. The object *ZoneHVAC:LowTemperature Radiant(LTR):VariableFlow* is picked to represent the heat transfer mechanism of water mullions. No implicit mixing or recirculation loop in the model, as in a constant flow variable temperature radiant system model, is included. According to *EnergyPlus* documentation (DOE 2010), this component can model any "radiant system" where water is used to warm up or cool down the space through a building surface. A wide range of low temperature panel, pipes, etc, can be covered.
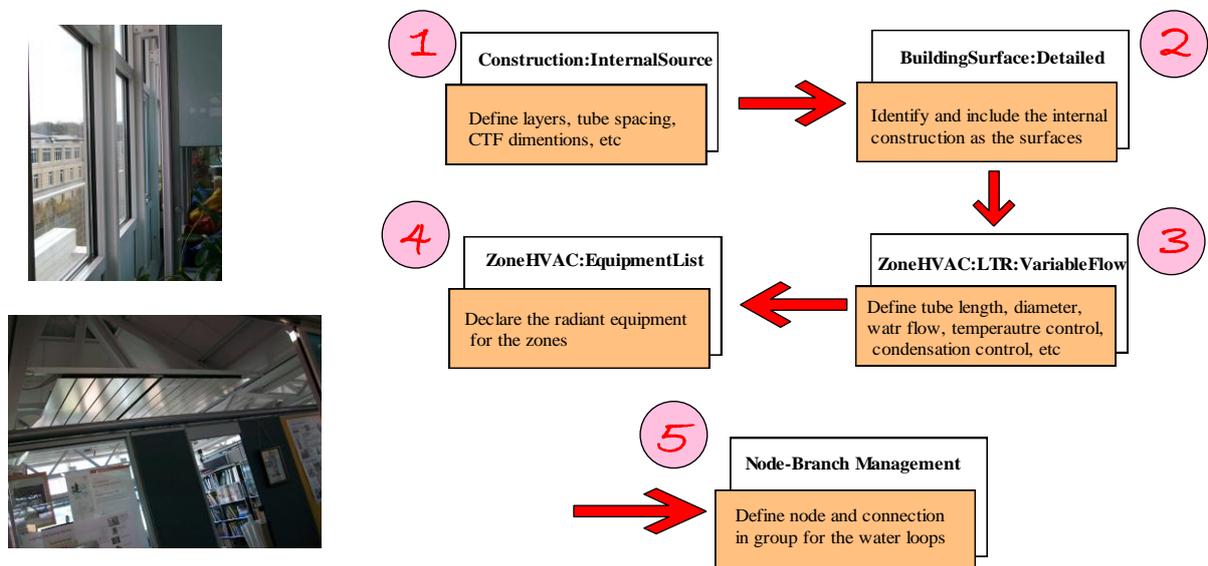

Figure 3: Configuration of radiant system in EnergyPlus

An obscure constraint on the modeling lies in construction of the embedded surface of the radiant system. While the drop-down menu of the IDF file editor in *EnergyPlus* allows all types of surfaces defined in the group *Thermal Zones and Surfaces*, not all of them work. In the documentation, only window/door surfaces and internal mass are specifically mentioned

not valid for the radiant system object. To make a legal surface work, the surface construction must first include a sink or source construction from the object *Construction:InternalSource*. With *Construction: InternalSource*, the users can define the layers of the construction, tube spacing, dimensions for conduction transfer function calculation, etc. For water mullions, the pipes are chosen behind the most inside layer. For radiant ceilings, the pipes are put behind the radiant panel. The construction serves as a thermal sink and source for the heat transferred between the fluid and the space.

The control methods of *ZoneHVAC:LTR: VariableFlow* applied in *EnergyPlus* can be mean air temperature-, operative temperature-, outdoor dry bulb temperature-, or outdoor wet bulb temperature-based. The tubing length and inside diameters are specified within this object as well. Field *heating and cooling control throttling range* sets the modulation band of the water flow rate for heating and cooling respectively. The water flow rate is modified from zero up to the maixmum when the controlling temperature is beyond the range. A low value, but no less than $0.5^{o}C$, gives more sensitive system response to the temperature difference.

A radiant system exists in the space as both a zone heat balance element and a conditioning system. A state space based formulation for multilayer material conduction transfer function, and a heat exchanger based formulation for the source energy from the fluid are adopted in *EnergyPlus* to model a radiant system. The desired nodal temperature, surface temperature, and heat flux can be obtained by organizing the corresponding output matrix. The radiant surface selected for a radiant system is automatically included and treated identical as other building surfaces in the overall heat transfer balance network and space comfort model.

Chilled beam ventilator

Chilled beams are widely used in European commercial office buildings for the attractive features, e.g. low cost and high cooling capacities (Rumsey et al 2009). A chilled beam is a mixed air-hydronic combined cooling coils with or without the primary air. Such systems offer many compelling benefits, including high cooling capacities, excellent performance, and dramatic energy savings for little or no additional costs over conventional systems. In the recent version of *EnergyPlus*, a simple module for the chilled beam is included in the group of *Zone HVAC Air Loop Terminal Units* (DOE 2010).
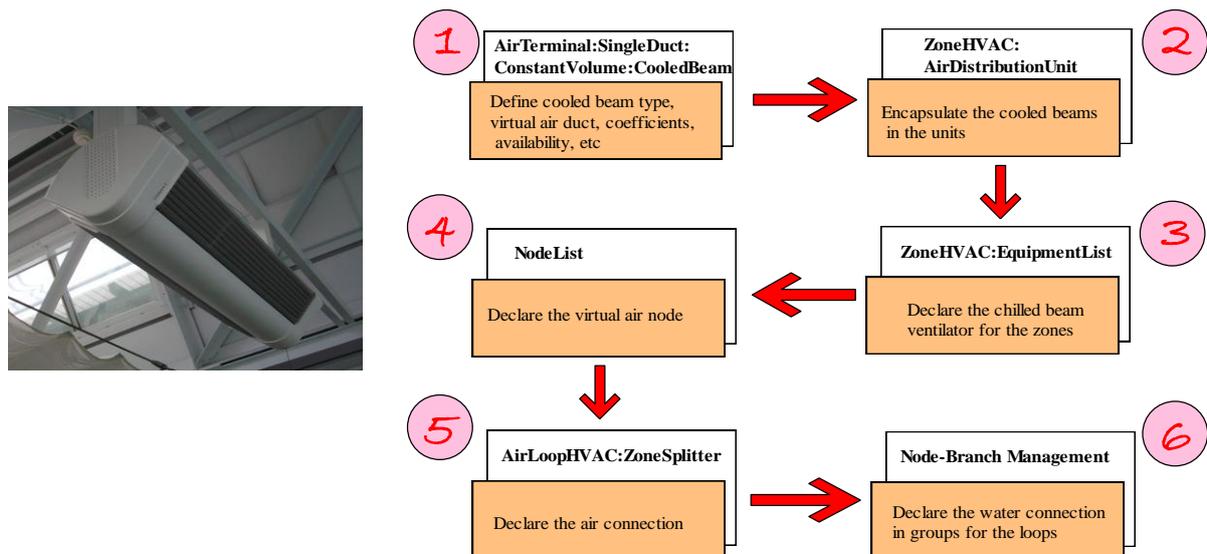

Figure 4: Configuration of chilled beam ventilator in EnergyPlus

The chilled beam ventilators installed in IW_n are equipped with an oscillating fan to improve the heat transfer capability of the inside coil. Unlike coventional ceiling mounted units, the chilled beam ventilators are designed for under-ceiling installation with no primary air supply.

The indoor air is cooled and falls into the occupied zone by convection and circulation through the inside coils. Similar to radiant cooling units, the chilled beam ventilators only supplies sensible cooling. A fan, oscillating between two heat exchangers, generates pulsating streams of cool air. The resulting eddies rapidly decay, giving rise to a gentle, uniform flow of cooling air throughout the entire room.

The configuration process for a chilled beam ventilator is illustrated in Fig. 4. The chilled beam ventilators are modeled as *AirTerminal:SingleDuct: ConstantVolume:CooledBeam*. The effect of the additional oscillating fan is adjusted by improving the coefficient of induction. As required by the existing module in *EnergyPlus*, the unit works only with the primary air from a central constant volume forced air system. The workaround in this study is to set up virtual supply air that links into the unit. The supply air volumetric flow rate is reduced to zero to approximate the duckless configuration. In addition, an implicit constraint of using *AirTerminal:SingleDuct:ConstantVolume:CooledBeam* in *EnergyPlus* is that they are not considered as air distribution terminals that can be directly claimed in the *ZoneHVAC:EquipmentList*. The chilled beam modules need to be encapsulated in a module *ZoneHVAC:AirDistributionUnit* to function in the model.

Hybrid rooftop air-conditioner (HRAC)
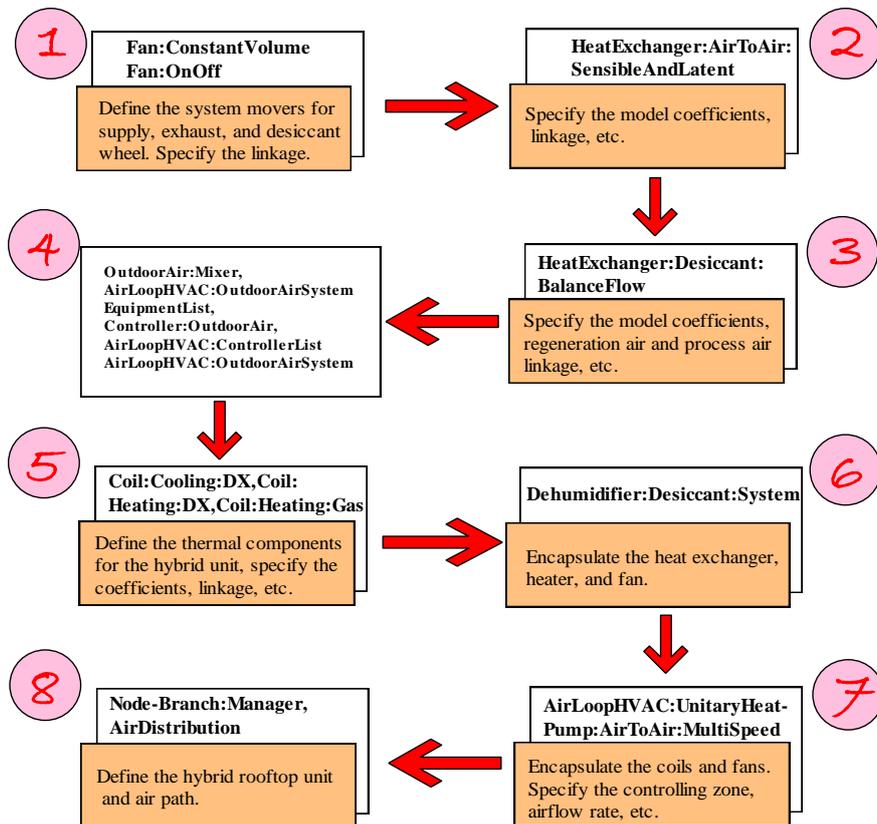
Figure 5: Configuration of HRAC in EnergyPlus

As a mixed mode air-conditioning system, the space requires a low humidity level in summer to prevent condensation on the radiant surfaces. Conventionally, dehumidification is achieved by cooling the air down to a dew point. This practice couples the sensible load and latent load in cooling mode. A huge amount of energy is wasted when this operation triggers on reheat to offset the excessive sensible cooling when the space is in partial load condition. Another drawback of this operation is that the humidity ratio of the supply air is limited by the cooling coil surface temperature. When the space is sensitive to the air humidity in humid weather, an improvement on the air processing is needed.

The hybrid rooftop air-conditioner provides additional flexibility for the circumstance of dehumidification. It consists of three essential parts that are, following the flow path of outside air, a total heat recovery wheel, a revertible direct expansion unit, and a solid desiccant wheel. The desiccant wheel is regenerated by a parallel air stream with a gas burner and a pulling fan. The physic state of the supply air is achieved by controlling the heat pump and the active desiccant wheel. Fig. 5 illustrates the objects and linkage of the compounded HRAC air loop system accomplished in *EnergyPlus*.

Heat recovery device

The total heat recovery unit transfers both heat and moisture between the exhaust air and outside air intake. *EnergyPlus* has a group *Heat Recovery* that lists three types of heat recovery devices: flat plate, heat recovery exchanger, and desiccant heat exchanger. For the heat recovery unit applied in IW_n, the object *HeatExchanger:AirToAir: SensibleAndLatent* is used. The model focuses on the basic thermal performance of the device and requires no geometric data. Users should provide the sensible and latent effectiveness at 75% and 100% airflow condition for both heating and cooling operation.

Operation of the heat exchanger is further detailed by specifying the supply air outlet temperature contol, frost control and econmoizer lockout. Depending on the operation, additional component or advance control object might be needed to make the model function in *EnergyPlus*. As in the IW_n application, the total heat recovery does not perform on it own but serves as part of the outside air system. Therefore, the supply air outlet of the heat recovery device should also appear as the outside air stream inlet of object *OutdoorAir:Mixer* and *Controller:OutdoorAir*.

An outside air and exhaust air mixing process is modelled as an outdoor air sytem in *EnergyPlus*, including four objects across two groups:

Controller:OutdoorAir and *AirLoopHVAC: ControllerList* in the group *Controllers*; and *AirLoopHVAC:OutdoorAirSystem:EquipmentList*, *AirLoopHVAC:OutdoorAirSystem*, and *OutdoorAir: Mixer* in the group *Air Distribution*. The total heat recovery device, the exhaust fan, and the nodes need to be accordingly configured in the four objects to make the device model function well.

Desiccant dehumidifier

The desiccant dehimidifier is not treated as a one-stop object in *EnergyPlus*. It is an assembled object including a regeneration air heater, a desiccant wheel, and a regeneration air fan. The combination is then packaged as a compound object *Dehumidifer: Desiccant:System* in the group *Humidifiers and Dehumidifiers*. The desiccant wheel includes the objects *HeatExchanger: Desiccant:BalancedFlow* and *PerformanceDataType1*. The former one provides the configuration for the air connection across the wheel and the latter one specifies the performance of the wheel. The humidifier is controlled by a humidity setpoint placed on a process air node.

In the HRAC, a bypass duct is in parallel to the desiccant wheel to balance the control of air temperautre and humidity. The corresponding layout can be configured by using additional *Duct*, *Connector:Mixer* and *Connector:splitter* in *EnergyPlus*. In fact, the physical system is implictily represented by the virtual desiccant system model, which calls the device on and off to maintain the humidity set point. When the device is off, the process air is directly bypassed. The internal logic in *EnergyPlus* controls the average outputs if the device cycles on/off during the simulation time step.

The performance of desiccant wheel is determined by first computing the dry bulb temperature and humidity ratio of the regeneration outlet air. Eight regression coefficients of the process and regeneration air states are needed for the two curves, respectively.

Heat pump unit

An air loop heat pump is a compound unitary object placed in the primary air loop in *EnergyPlus*. The components, including the cooling and heating coils, the supplementary coil, and the fan are separately defined in advance in the corresponding objects. For this application, the coils are selected as *Coil:Cooling:DX:MultiSpeed*, *Coil:Heating:DX: MultiSpeed*, and *Coil:Heating:Gas* from the group *Coils*. Due to the complexity of the direct expansion coils, *EnergyPlus* does not provide default parameters for the operation. The users are required to enter the coefficients of performance curves for the cooling and heating capacities and energy input in rated conditions.

The actual part-load outputs and energy consumption of the unit are modeled based on the temperature and airflow rate correction, and run time fraction. This approach is analogous to the NTU effectiveness calculations used for sensible-only heat exchanger modeling, extended to a cooling and dehumidifying coil (DOE 2010). Linear interpolation is used when the needed cooling or heating capacity is between the defined speed models, with the fraction of time at each speed established by the speed ratio. For a load condition below the minimum, the unit cycles on and off. Bi-quadratic functions are employed to rectify the cooling coil output and energy input ratio at a specific entering air temperatues different from the rated conditions. The influence of various supply airflow rate is accounted by using a cubic curve.

The coils and fan are assembled as a unit in *AirLoopHVAC:UnitaryHeatPump: AirToAir:MultiSpeed* in the group *Unitary Equipment*. While the heat pump in IW_n is operated for dehumidification instead of zone thermal conditioning, the unitary heat pump object is, by default, a zone load control oriented equipment in *EnergyPlus* and needs a specified zone to supervise the operation. It operates based on the thermal load in the zone and the availability schedule. The fan is considered as a continuously operating fan during the availability period unless otherwise mentioned. A zero value in the fan operating mode schedule makes the fan response only to the zone thermal load.

Combined HRAC and airloop

With the models of three key devices constructed, the HRAC can be defined by linking them together in the object *Branch* in the group *Node-Branch Management*. The branch object is then specified in *AirLoopHVAC* with supply and demand side connection nodes indicated. All the objects in the group *Air Distribution* needs to be accordingly configured for the HRAC air loop. The exhaust fan, heat exchanger, and outside air mixer are included in the object *AirLoopHVAC:OutdoorAirSystem: EquipmentList* and declared as one in *AirLoopHVAC:OutdoorAirSystem*.

4 Exemplary application for advanced control

General Configuration

The model developed in the previous section can perform general simulation of this innovative system in IW_n. Multifarious applications, such as advanced control, system optimization, automated fault diagnosis, etc, could be built up based on this novel model.

Implementation of a real-time control in the simulation tool *EnergyPlus* is critical to further study the performance of the integrated advanced air-conditioning system. As a whole building simulation tool, *EnergyPlus* has many local controls implicitly embedded in the existing modules. A desired user control is historically often fulfilled by using the set point and system availability schedules (Ellis 2007). This framework has limited capability and is only suitable for very simple control logic. Recently, the limitation has been gradually improved with the addition of high-level control modules. *Setpoint Managers*, *System*

Availability Managers, *Energy Management System* (*EMS*), and *External Interface*, are the four groups belonging to the high-level control constructs in *EnergyPlus*.

The high-level controls reside outside of the HVAC system loops, executed at the start of each HVAC system time step. *Setpoint Managers* and *System Availability Managers* can access data from any of the HVAC system nodes. They jointly extend the basic control in *EnergyPlus* by resetting the availability of the building systems and the set points on the system nodes. To gain more flexibility, *EMS* may be used in parallel or in stead. It mimics the functionality of digital energy management systems in real buildings. Logics can be programmed to sense the variables, make decisions, and actuate the variables by following the *EnergyPlus Runtime Language* syntax and coding in the *EnergyPlus* text- line structure.

While using the three high-level control groups can greatly improve the HVAC system control in *EnergyPlus*, it is still not adequate to support any advanced control application. The *External Interface*, allowing a distributed simulation structure, is utilized in this exemplary application for the implemenation of advanced control and data interpretation. The controller is placed outside of *EnergyPlus* to utilize the powerful functions of advance program language, e.g. *Matlab/Simulink*. *Builidng Controls Virtual Test Bed* (*BCVTB*) (Wetter and Haves 2008) and *MLE+* (Nghiem 2010) are two of the available platforms for a distributed simulation. The building envelope and HVAC system are simulated in *EnergyPlus* and the control logic in an external program. The data of specified variables are exchanged at each time step between *EnergyPlus* and the external tool as they simulate. The required configuration processes of the two platforms could be refered in the literature from Wetter (2011) and Nghiem (2010).

Demonstration

The application of advanced control for the integrated energy system is fulfilled with *MLE+* to inspect the system dynamic performance and energy saving potentials. This layout can make full use of the available optimization toolboxes and data aquisition and processing capability in *Matlab/Simulink*.
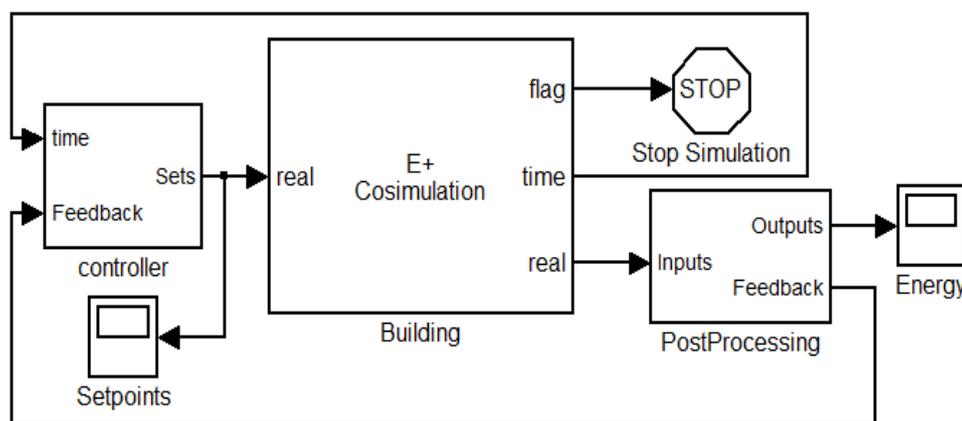
Figure 6: Co-simulation setup with EnergyPlus and Matlab/Simulink

Fig. 6 illustrates the setup of co-simulation part for the application. The advanced controller is placed in the *Controller* block, which takes the simulation results and time of day as basic inputs and makes supervisory level decision for the system. The *PostProcessing* block handles the simulation results for display. In real time implementation, the occupancy prediction, weather data and energy price information, etc, which have strong impacts on the operation cost, are fed into this control block to find the optima. The decision is then passed on to and exectuted by the inner loop local multivariable controller (Song, 2011).

The demonstration of utilizing the out-loop advanced control with the model is briefly described for: 1. Piloting control between air-conditioning modes; 2. dynamic resetting outside air intake based on occupancy and outside air condition. Piloting control provides the system or device with a set of manipulated set-point trajectories to avoid energy waste and ensure smooth transition between modes (Lee, 2007, Yu, 2010). The strategy can also be utilized to minimize the peak demand over trimming period when the price differences are known. The trajectory is typically identified by an optimal algorithm based on simulation with real time information.
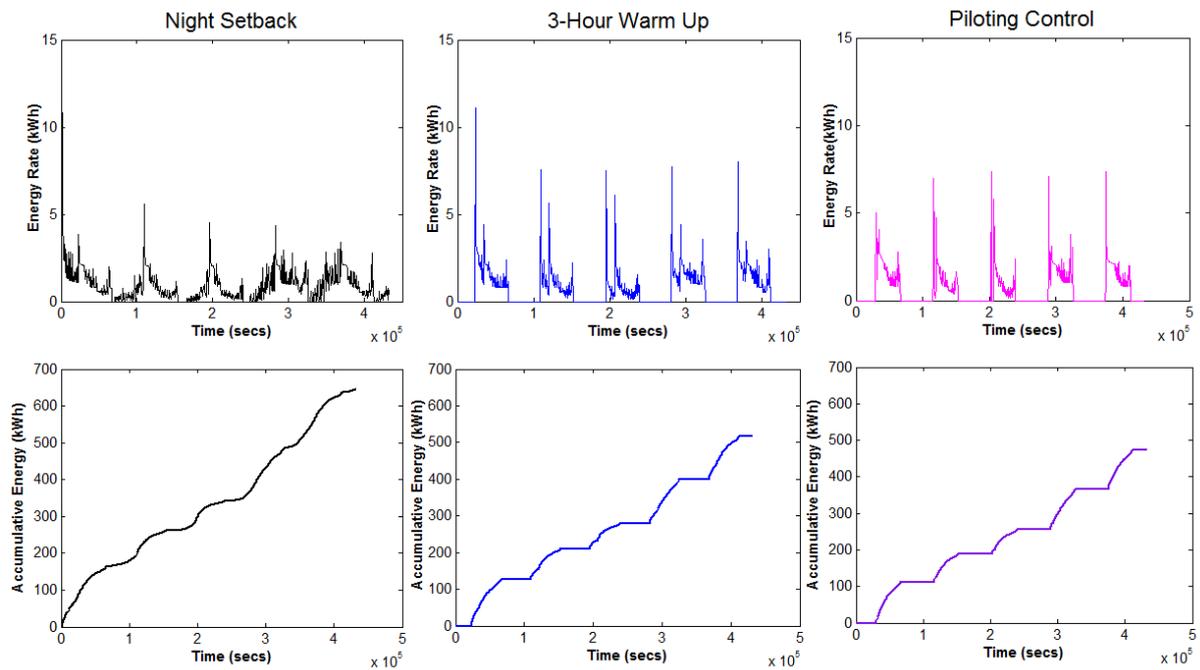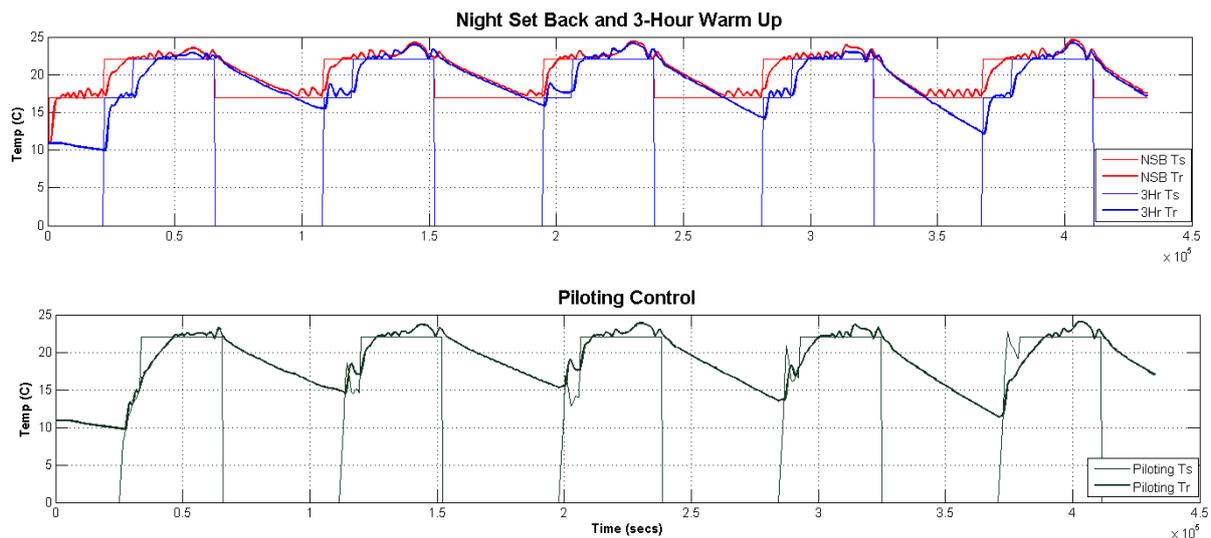

Figure 7: Energy consumption comparison

Figure 8: Room air temperature comparison

The co-simulation is conducted for one week in winter to illustrate the piloting control for morning warm up when the space transits from unoccupied mode in the night to occupied mode in the morning. The energy consumption is computed every 15 minutes (900 seconds).

As shown in Fig. 7, the conventional night setback strategy or morning fixed three-hour warming-up consume more energy than the piloting control, by about 34% (130kWh) and 10% (38kWh) respectively for the sampled week. The morning hour comfort when the space starts to be occupied is maintained for the three algorithms to be no lower than 20°C. The setpoint and the room air temperature for the three scenarios are indicated in Fig. 8.
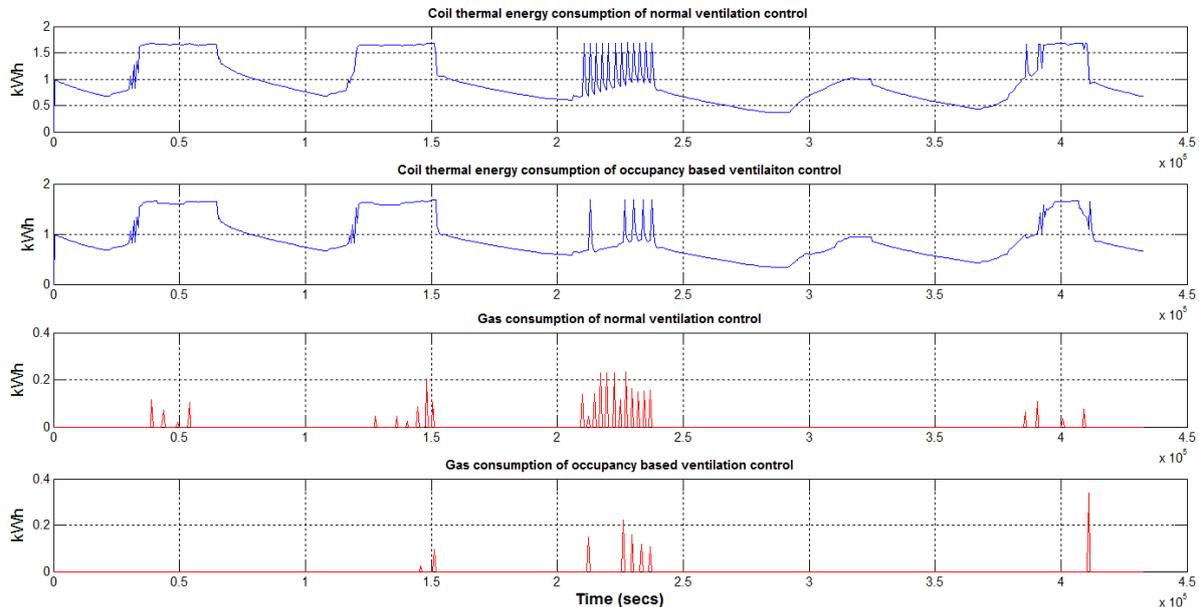
Figure 9: HRAC performance comparison with different OA intake control

Outside air intake is utilized to maintain the indoor air quality. However, improper control of the intake could lead to over-ventilation and unintended energy waste. For example, if the space is less occupied during a period of day, there is no need to maintain a fixed outside air intake. The co-simulation shows that if the ventilation rate can be adopted into the advanced control strategy, about 6% (35kWh) coil thermal energy savings and 150% (1.8kWh) gas savings compared to a fixed intake strategy can be achieved. Fig. 9 provides the simulation results of the HRAC for a summer week. To maintain the humidity ratio, when the outdoor air is humid, the equipment has to be off and on more frequently as well in fixed outdoor intake control.

5   Conclusion and discussion

EnergyPlus is a powerful whole-building simulation engine, with strictly validated models, but without friendly user interface. To use the in-depth capability of the valuable tool for research, the users need to be familiar with and program directly in the two-level text-line based modeling environment. It could be a challenge to even an experienced modeler when the studied system is unconventional and the study purpose of the model is comprehensive and dynamic.

This paper presents the solution of creating the model for an existing advanced energy system in *EnergyPlus*. The challenges resolved include the implicit model of vertical pipe water mullions, the ductless radiant cooling equipment, and the missing of a single component for a hybrid rooftop air conditioner. The method of setting up a distributed simulation application for advanced control is discribed by utilizing an *EnergyPlus* and *Matlab* integrated approach as well. Additionally, this study provides the readers a reference for constructing similar advance energy components or systems in *EnergyPlus*.

6   Acknowledgement

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8   Appendix

The model geometry, as shown in Fig. A-1, is established in DesignBuilder. Due to the influence of the heavy building below the space and the large fenestration, both the space temperature and the load show the combined features with large time constant and rapid temperature rise in a sunny day. To catch the temperature lag from the thermal mass, one plenum layer and one heavy building block are added at the bottom of the space. Temperature data loggers are placed in the plenum and the surface of the ceiling below IWn. The model has been calibrated by using Genetic Algorithm with the trended data during the weekends in October 2011. The fourteen parameters, including the window U-value, solar heat gain coefficient (SHGC), wall conductivity, et al, are adjusted automatically in GA to minimize the root mean square error. The real temperature and the trended temeprature are

plot in Fig. A-2. It can be seen that the model provides great predicting accuracy. Fig. A-3 plots the room air temperature distribution of the 13 zones in a week of summer. The hallway shows the highest fluctuation due to the large window area and skylight. An energy conservation measure for the space could be installing automaded shading device along all the fenestrations.
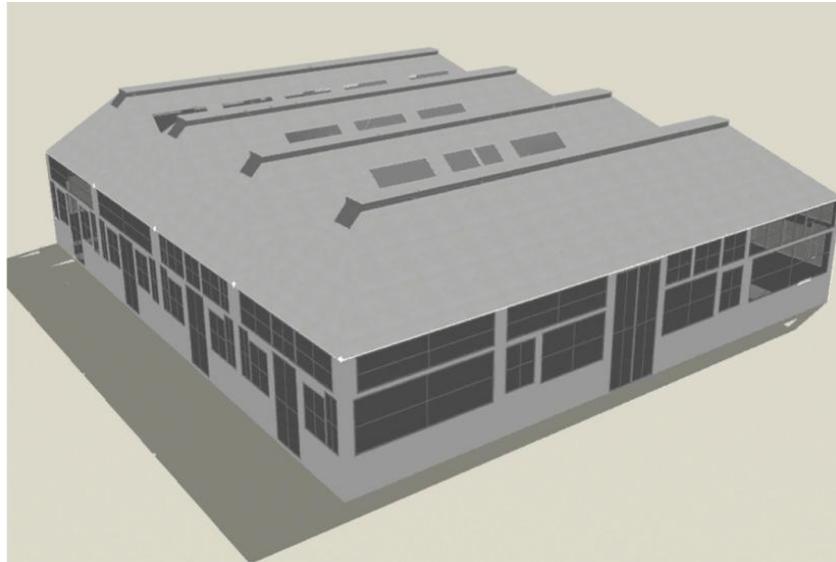
Figure A-1: 3-D model view in DesignBuilder
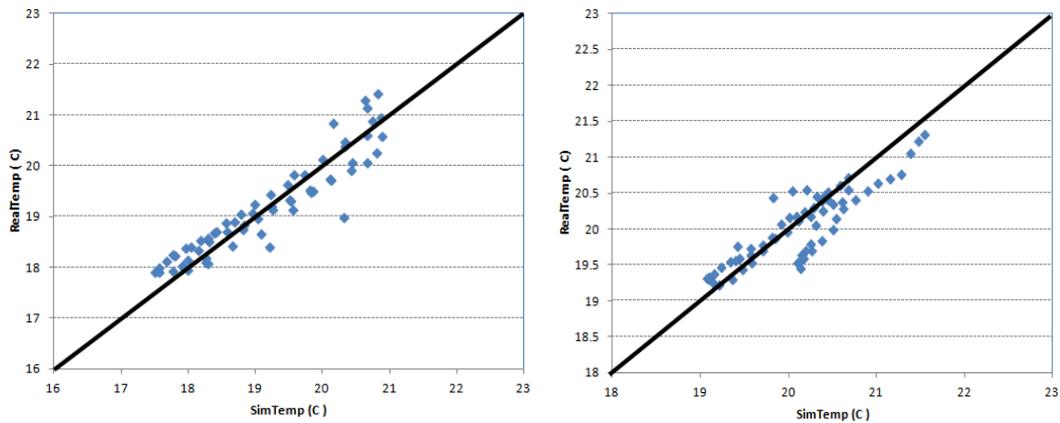
Figure A-2: Average room air temperature and plenum air temperature comparison (Left: Room air, Right: Plenum air)
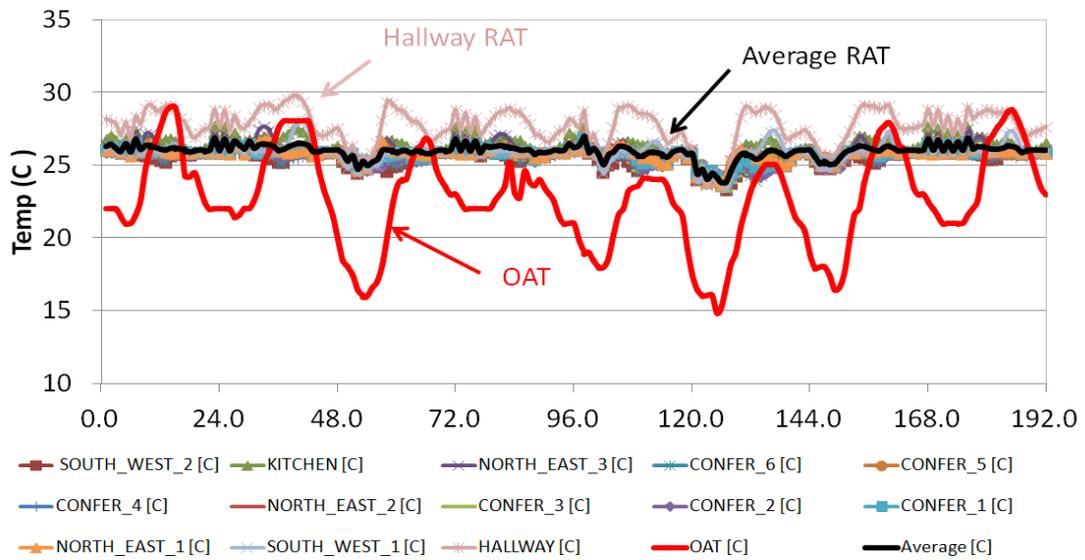
Figure A-3: Simulated room air temperature distribution for the zones