Simulation of HVAC Local Control Based on Occupants Locations and Preferences

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Abstract –

The Heating, Ventilation and Air Conditioning (HVAC) system consumes the major part of energy in buildings. By analyzing the gap between the actual energy consumed and the required energy to satisfy heating/cooling loads, it is estimated that an average of 38% of the energy can be saved with the adoption of more efficient control strategies. Occupancy-driven management has attracted great attention due to the potential energy savings. Therefore, the development and implementation of these strategies are of primary importance. On the other hand, future smart buildings will have the ability to detect and locate the occupants, and adjust the HVAC system to better satisfy their preferences, which is expected to result in considerable energy savings. This paper aims to simulate the energy performance that can be achieved by applying local control of the HVAC system. It proposes an HVAC localized control strategy based on the locations and preferences of occupants in an office open space with multiple zones. In order to evaluate the energy saving after applying the control strategy, DesignBuilder software is used to model one office at Concordia University and simulate its energy consumption.

Keywords –

Energy consumption; energy simulation; occupancy; locations; preferences; HVAC setpoint.

1 Introduction

It is estimated that the world energy consumption will increase by 56% from 2010 through 2040 [1]. Due to the catastrophic climate change, growing population and shortage in fossil fuels, the imbalance of increasing energy demand and limited energy resources has become a global environmental and economic problem and a driving force for researches on energy conservation techniques [2].

Buildings account for one-third of the total global energy consumption [3]. In Canada, approximately 85% of the total energy in institutional and commercial buildings is consumed by heating, cooling, lighting, and IT equipment [4]. In order to save energy in institutional and commercial buildings, a more efficient approach is to manage facilities based on actual occupancy locations and preferences.

Previous literature mainly contributed to developing occupancy models to predict the presence of the occupants. These models have been applied to controlling the HVAC and lighting systems. However, it did not consider local control combining the spatiotemporal variations of the space usage and the occupants' preferences.

This paper aims to simulate the energy performance that can be achieved by applying a localized control of the HVAC system. It proposes an HVAC localized control strategy based on the locations and preferences of occupants in an office open space with multiple zones. In order to evaluate the energy saving after applying the control strategy, EnergyPlus software and its graphical interface DesignBuilder are used to model one office at Concordia University and simulate its energy consumption.

2 Literature Review

Building energy management systems (BEMSs) are computer-based systems that can assist in the management, control and monitoring of HVAC, lighting, energy monitoring and targeting, etc. [5]. With programmed routines and repetitive functions, relatively simple operation, quick response to complaints, improved management information and graphical representation of operating conditions, BEMSs enable up to 10% reduction in energy consumption and costs [6]. On the other hand, occupants' behavior affects HVAC energy consumption with respect of the thermal loads, ventilation loads, and conditioning requirements of HVAC control settings to meet their thermal comfort and standard air quality [3].

There are four levels of occupancy models: building level, occupancy status of space, number of occupants in a space, and the location of occupants [7]. The higher level of occupancy information that can be extracted, the more accurate the simulation will be and the more energy the control strategy can save. To achieve occupancy-based control, common occupancy sensors are utilized to identify presence and advanced occupancy sensors (e.g. motion detectors) are utilized to identify the number of occupants in a zone and track their locations. Several occupancy detection and tracking technologies are utilized to sense the occupancy information. For example, optical cameras and thermal cameras are used to collect and analyze the images of the monitored areas including occupants; passive infrared (PIR) based motion detectors are used to sense movement of occupants; carbon dioxide based detection technology detects the concentration of CO_2 to measure occupancy; radio frequency technology such as Radio Frequency Identification Device (RFID) and Device Free Localization (DFL) detects location and activities of occupancy; Ultra Wideband (UWB) Real-Time Location Systems (RTLSs) use radio signals to detect the movement of occupants [8].

A report prepared for U.S. Department of Energy [9] proposes three cases to identify the energy savings using occupancy-based control in variable-air-volume (VAV) systems of large offices. The result shows that 17-23% of energy in HVAC and lighting can be saved by using advanced occupancy sensors. For individual offices, a group of researchers used synergy occupancy sensor nodes to detect occupancy and implemented the presence system in simulation [10]. They found that the daily HVAC savings can reach 10-15% after applying the occupancy system. Gunay et al. [11] developed an occupancy learning algorithm for terminal heating and cooling units to predict the arrival and departure time of occupants in private offices, leading to 10 -15% reduction in the annual heating and cooling loads. A versatile smart phone application is developed for the employees at the office building called Edge in Amsterdam to dial in their individual climate and lighting preferences. Packed with 28,000 sensors, The Edge is considered to be the greenest and most intelligent building in the world [12].

Due to the flexible work hours and large spaces that HVAC systems need to deal with, especially in office large open spaces, it is more energy-saving to apply localized heating and cooling control to specify the energy needed for occupied and unoccupied areas. Lo and Novoselac [13] developed a localized air flow with occupancy control strategy for cooling and simulated the Computational Fluid Dynamics (CFD) to examine the air quality and to calculate savings in energy consumption. It is concluded that 12% of energy can be saved. Budaiwai and Abdou [14] presented the energy saved by HVAC system operational strategies in the case of mosques, a unique type of buildings with intermittent occupancy in Saudi Arabia. To operate the HVAC system only when the space is occupied, they proposed the strategies of oversizing the HVAC system to balance the accumulated thermal load and zoning the conditioned area according to the schedule and location of occupants (e.g. one zone is occupied on all weekdays and another zone is only occupied on Friday). It is concluded that savings of 13% and 30% of energy consumption for a mosque with two zones (504 m^2) and another mosque with three zones (1050 m^2) can be achieved, respectively.

Selecting the suitable software for energy simulation is an important decision; Yang and Becerik-Gerber [3] compared available energy simulation programs in the market based on the accuracy and reliability to react to the effects of occupancy on HVAC energy consumption and response of HVAC system to occupancy-based control strategies. They concluded that the most qualified program is EnergyPlus, developed by U.S. Department of Energy, because of its capabilities for HVAC system simulation. DesignBuilder makes the simulation more user-friendly and flexible because of its graphical user interface [15]. In this paper, EnergyPlus and its graphical interface DesignBuilder are selected to simulate the proposed HVAC control strategy and to evaluate the energy savings.

3 Proposed Method

Figure 1 shows an example to demonstrate the proposed method. The figure shows a relatively large open office in a smart building equipped with Sensor Tags (STs), capturing the location of occupants at a certain frequency. To control the HVAC and lighting systems at a more detailed level, the office can be divided into two zones according to the number of HVAC terminal units, and six zones according to the number of lights. Knowing the location of a specific occupant, the corresponding HVAC terminal unit and corresponding light are activated.

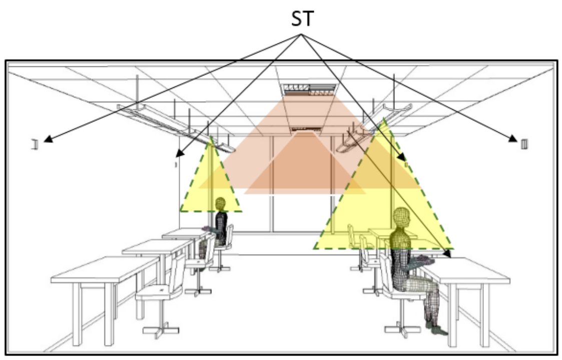

Figure 1. Proposed HVAC control strategy

In this paper, firstly, the identity and location of occupants over time are captured by UWB RTLSs [16]. The overall occupancy profiles can be created based on the collected data of the occupants on an hourly basis in one week. The probabilistic individual occupancy profiles can be used to identify the specific needs of each occupant and their preferred comfort settings. Assuming that the occupancy pattern is fixed, the resulting profiles can be used for long-term control of light and HVAC settings to avoid the problems of delays of system response that may be caused by depending only on real-time control. These profiles can be also used in the simulation of the energy consumption of the building, which can help forecast long term energy needs. It should be mentioned that providing control of the lighting and HVAC systems based on individual profiles depends on the availability of individual light units and HVAC outlets near each occupant location. As this condition may not be available in many cases, occupants' profiles should be integrated to match the actual physical layout of the lighting and HVAC systems in the specific space based on combined zones. To satisfy the occupants in one zone, when the occupants' profiles overlap, the preferences of the occupants are averaged.

3.1 Modeling of the Office Space

The open office with multiple zones is modeled in an energy simulation program. Before applying localized control, the building block model has to be divided into different zones. The criteria of zoning are: (1) different facade orientation for perimeter zones, because the wind and solar gain changes throughout the day will affect both thermal and daylight control performance; (2) different activity types in different areas, because the change in occupancy and equipment can affect the internal gains; (3) applying bespoke activity data including occupancy schedules, temperature setpoints etc.; (4) different HVAC system in different parts of the building; and (5) different lighting systems in different parts of the building [17].

The zones in the open office space are separated by virtual partitions. There are two types of partitions, standard and virtual partitions. Standard partitions are used to create enclosed spaces within the block using walls as a physical boundaries. Virtual partitions create a new zone without creating a physical boundary. They have no thermal mass and present no barrier to heat and air flow caused by the natural ventilation. Virtual partitions are used to separate open areas which have different HVAC or lighting systems [17].

3.2 Energy Simulation

Based on the occupants' schedules and preferences, the schedule of terminal heating and cooling units and lights can be adjusted. Then, the energy consumption of the proposed control strategy can be obtained by running the simulation. Three scenarios are generated to quantify the energy saving. Scenario 1 assumes the setpoint of HVAC system is always fixed to the condition that the area is occupied all the time. Scenario 2 assumes that when there is no occupant in the area, the setpoint of the HVAC system will be adjusted to save energy. When there is any occupancy in the office open space, the setpoint of the HVAC system will be changed to fit the occupants' preferences. Scenario 3 represents the case of localized control. It is assumed that the localized control can be implemented in the large open office with fixed number of users assigned to each zone. The HVAC system can be adjusted according to the occupancy in each zone. By comparing with the baseline (Scenario 1) and Scenario 2, the energy saving of Scenario 3 can be quantified.

4 Implementation and Case Study

A model is created in DesignBuilder, the graphical interface of EnergyPlus. After modeling the building, different schedules are used as input to run the simulation. Setpoint Managers are used to control the air loop of the HVAC system. By using Setpoint Managers, the setpoint of air handling units' (AHU) supply air temperature can be scheduled. The schedules of occupancy are imported to the model in DesignBuilder to quantify the energy saving after applying the local control.

To apply the proposed control strategy, a 3D model of an office space is created in DesignBuilder. The model represents an office at Concordia University in Montreal, Canada. The model is shown in Figure 2. To define the three scenarios, three schedules are generated as input for the model.

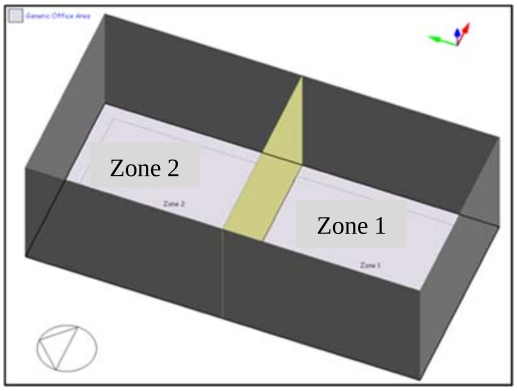

Figure 2. DesignBuilder model

4.1 Occupancy Schedules

Occupancy information can be obtained using occupancy tracking technique. The identity and location of four occupants in the room (M, N, S, L) over one week in June, 2014 are captured by an UWB RTLSs [16]. The readings of the tags are updated twice per minute. As Figure 3 shows, M and N are under the same terminal unit of HVAC system; therefore, M and N are assigned to Zone 1 of the space. Likewise, S and L are assigned to Zone 2. As an example of the occupancy data, the percentage of occupancy over time for one week is shown in Figure 4. The occupancy schedule is used for the calculation of internal loads for the HVAC system in the three scenarios.

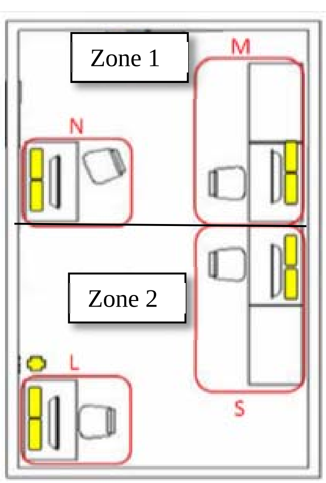

Figure 3. Distribution of occupants [16]

4.2 Defining HVAC Schedules

To achieve the proposed control, first, instead of using ideal loads in the modelling by applying the Simple HVAC model in DesignBuilder, it is necessary to apply the Detailed HVAC made by defining EnergyPlus HVAC systems graphically using components and customizing the setpoints in heating and cooling. There are two types of data in Detailed HVAC: (1) Simple HVAC data and (2) Detailed HVAC data. In Simple HVAC and Detailed HVAC/Simple HVAC data, the setpoint can be adjusted in each zone, but the value is constant. In this research, the setpoint should be specified by adding thermostat cooling and heating setpoint schedules according to the occupants' schedules and preferences for the corresponding zones. Therefore, Detailed HVAC/Detailed HVAC data is selected.

There are three schedule types for the schedule data in DesignBuilder, 7/12 Schedule, Compact Schedule and Day Schedule. Based on the collected data, the occupancy schedule for each day in the week can be customized. The text-based Compact Schedule is chosen to input the schedule. Compact Schedules are defined following a standard format which contains the elements Through (date), For (days), Interpolate (optional), Until (time of day) and Value (percentage of occupancy). Figure 5 shows an example of a compact schedule.

4.3 Defining Cooling Setpoint Schedule

As shown in Table 1, in Scenario 1, the setpoint for cooling is fixed (24^{0}C) on both weekdays and weekends. In Scenario 2, on weekdays, from 8:00 to 18:00, the setpoint is 24^{0}C when there is occupancy in the space and 25^{0}C when it is not occupied; before 8:00 and after 18:00 in the day, the setpoint is 26^{0}C when the space is not occupied and 24^{0}C when there is occupancy. On weekends, the setpoint is 26^{0}C when the space is not occupied and 24^{0}C when there is occupancy in the space. In Scenario 3, on weekdays, when there is no occupancy in the zone, the setpoint is 25^{0}C from 8:00 to 18:00 and 26^{0}C for other period of the day; when there is occupancy in the zone, the setpoint is adjusted to 24^{0}C. On weekends, for the unoccupied zone, the setpoint is set to 26^{0}C; when the zone is occupied, the setpoint is 24^{0}C.

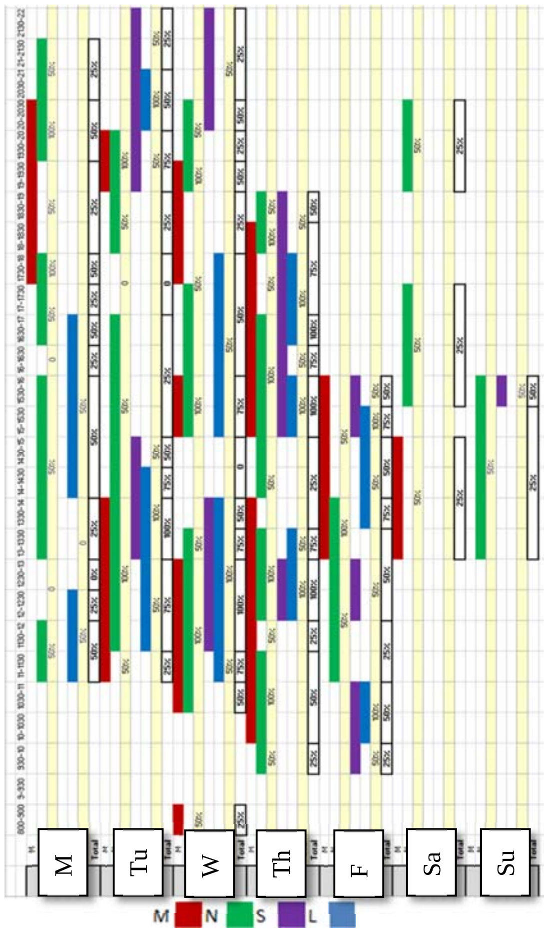

Figure 4. Occupants' schedule

```
Schedule:Compact,
Office_Occ_Z1,
Fraction,
Through: 13 Jul,
For: AllDays,
Until: 13:00, 0,
Until: 16:00, 0.5,
Until: 24:00, 0,
Through: 14 Jul,
For: AllDays,
Until: 11:00, 0,
Until: 12:00, 0.5,
Until: 13:00, 0,
Until: 16:00, 0.5,
Until: 16:30, 0,
Until: 17:30, 0.5,
Until: 18:00, 1,
Until: 19:30, 0.5,
Until: 20:30, 1,
Until: 21:30, 0.5,
Until: 24:00, 0,
```

Figure 5. Example of a compact schedule

Table 1 HVAC cooling setpoint schedule for three scenarios

		Not occupied			Occupied
		0:00-8:00	8:00-18:00	18:00-24:00	
Scenario 1	Weekdays	24 ^{0}C			
	Weekends	24 ^{0}C			
Scenario 2 (Space-level)	Weekdays	26 ^{0}C	25 ^{0}C	26 ^{0}C	24 ^{0}C
	Weekends	26 ^{0}C			24^{0}C
Scenario 3 (Zone-level)	Weekdays	26 ^{0}C	25 ^{0}C	26 ^{0}C	24 ^{0}C
	Weekends	26^{0}C			24 ^{0}C

4.4 Results and Discussion

After inputting the mentioned schedules in the model, the simulation is run for the three scenarios. The results are shown in Figure 6. By comparing Scenario 1 and Scenario 2, 1.5% of the energy can be saved at the space level without sacrificing the comfort of occupants. By comparing Scenario 1 and Scenario 3, 1.59% of the energy can be saved.

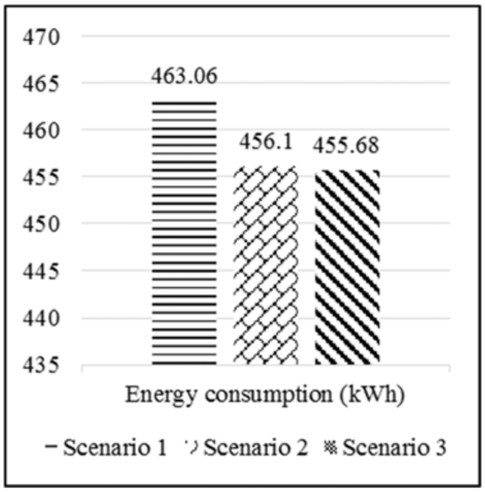

Figure 6. Energy consumption of the three scenarios

The results show only slight differences among the three scenarios. The probable reasons can be:

- The size of the model: It is expected that more significant energy saving can be achieved if the office space is large. As mentioned in [14], with strategies of oversizing the HVAC system and zoning the conditioned area, more energy can be saved in larger spaces.
- The lack of elements in the model: There is no windows in the proposed model, which play an important role in solar gain and energy consumption. Besides, the operation of equipment in the office is not considered, which can affect the heat gain in the space and the consumption of electricity.
- Number of occupants: In some office buildings, the distribution of occupants is generally based on the nature of their jobs. However, in some cases, it is possible to obtain more energy savings by the dynamic usage of the space. Reassigning the occupants with similar presence patterns or with similar preferences of heating and cooling setpoints to the same office can be one of the solutions to save energy without sacrificing the occupants' thermal comfort [18]. The zoning scheme can be applied to office buildings, which is called "hot desking" in the Edge building [12]. Without assigned seats for the occupants, a specific area in the space can be given precedence for dynamic assignment over others. With more occupants in that area, the preferred temperature for the heating and cooling setpoints can be averaged to satisfy the several occupants under same terminal unit.
- Setpoint: The setpoint can be adjusted within the range of the recommended values in ASHRAE standards. With greater difference in setpoints between the base case (Scenario 1) and other scenarios, the energy consumption difference can be more significant.
- Variety of occupants' schedules: In Scenario 2, the HVAC cooling schedule is based on the occupancy in the space; but the profiles of the four occupants are of little difference. Therefore, the schedules in Scenario 2 and Scenario 3 are very similar.

5 Conclusions and Future Work

In this paper, a localized control strategy of HVAC system is developed to adjust the setpoints and HVAC operation in an office open space with multi users according to the occupancy to save energy. According to the results of simulation, by setting different setpoints based on the occupancy presence, 1.59% of the energy can be saved.

Our future work will aim to validate the proposed control strategy by comparing the results of the simulation and the actual energy consumption. Furthermore, in this study, the occupancy profile is developed based on occupant detection using UWB RTLSs. Going forward, we will conduct tests using Bluetooth Low Energy (BLE) SensorTags with iBeacon [19]. Bluetooth is a set of wireless technologies for communication between mobile devices in short range. BLE is the enabler of the Internet of Things [20]. Compared with UWB RTLSs and other detection technologies, BLE is less expensive and more practical. Besides, it is much less energy consuming than the classic Bluetooth. The BLE hubs can be any device that implements the BLE standard, such as smart phones. The occupants do not have to wear tags as their smart phones can be tracked.

References

[1] SUSRIS. (2013, July 25). International Energy Outlook 2013. On-line: http://susris.com/2013/07/25/international-energy-outlook-2013/, Accessed: 06/06/2015.

[2] Bratt, N., Johansen, C. and Singh, M. P. Driving forces for energy demand. On-line: http://etreeprojects.com, Accessed: 02/05/2015.

[3] Yang, Z., and Becerik-Gerber, B. Coupling occupancy information with HVAC energy simulation: a systematic review of simulation programs. *Proceedings of the 2014 Winter Simulation Conference*, (pp. 3212-3223). Los Angeles, US, 2014.

[4] NRCan. 15th edition of energy efficiency trends in Canada. On-line: http;//www.nrcan.gc.ca, Accessed:

12/06/2015, 2011.

[5] Levermore, G. J. *Building energy management systems: applications to low-energy HVAC and natural ventilation control*. London: E & FN Spon, 2000.

[6] Defence Estates. *Building Energy Management Systems*. Stationery Office Books, 2001.

[7] Feng, X., Yan, D. and Hong, T. Simulation of occupancy in buildings. *Energy and Buildings*, 87:348-359, 2015.

[8] Priyadarshini, R. and Mehra, R. M. Quantitative Review of Occupancy Detection Technologies. International Journal of Radio Frequency Design, Vol.1 Issue 1, 2015.

[9] Zhang, J., Lutes, R., Liu, G., and Brambley, M. Energy savings for occupancy-based control (OBC) of Variable-Air-Volume (VAV) systems. Washington: Pacific Northwest National Laboratory, 2013.

[10] Agarwal, Y., Balaji, B., Gupta, R., Lyles, J., Wei, M. and Weng, T. Occupancy-driven Energy Management for Smart Building Automation. *Proceedings of the BuildSys, in conjunction with ACM SenSys Conference*, Zurich, Switzerland, 2010.

[11] Gunay, H. B., O'Brien, W. and Beausoleil-Morrison, I. Development of an occupancy learning algorithm for terminal heating and cooling units. *Building and Environment*, 93(2015) 71-85, 2015.

[12] BREEAM. The Edge, Amsterdam. On-line: http://www.breeam.com/index.jsp?id=804, Accessed: 14/09/2015.

[13] Lo, L. J. and Novoselac, A. Localized air-conditioning with occupancy control in an open office. *Energy and Buildings*, 1120-1128, 2010.

[14] Budaiwi, I., and Abdou. A., HVAC system operational strategies for reduced energy consumption in buildings with intermittent occupancy: the case of mosques. *Energy conversion and Management*, 73(2013) 37-50, 2013.

[15] DesignBuilder. DesignBuilder. On-line: http://www.designbuilder.co.uk/, Accessed: 20/06/2015.

[16] Masoudifar, N., Hammad, A., and Rezaee, M. Monitoring occupancy and office equipment energy consumption using real-time location system and wireless energy meters. *Proceedings of the 2014 Winter Simulation Conference*, pp. 1108-1119, 2014.

[17] DesignBuilder. DesignBuilder video tutorials. On-line: http://www.designbuilder.co.uk/content/view/105/184/, Accessed: 14/07/2015.

[18] Yang, Z., and Becerik-Gerber, B. The coupled effects of personalized occupancy profile based HVAC schedules and room reassignment on building energy use. *Energy and Buildings*, 78(2014) 113-122, 2014.

[19] Texas instruments. Texas instruments. On-line: http://www.ti.com/, Accessed: 05/09/2015.

[20] Bluetooth. Bluetooth. On-line; https://www.bluetooth.com/what-is-bluetooth-technology/bluetooth, Accessed: 12/09/2015.