HVAC CONTROL AND DEMAND MANAGEMENT DEVELOPMENT USING SMART PREDICTIVE OPERATIONAL STRATEGIES

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ABSTRACT

Residential houses (RHs) present great opportunity for managing/controlling electric demand at the user side. Demand management can be achieved by taking advantage of advanced predictive strategy planning models (SPMs) implemented on the heating, ventilating and air conditioning (HVAC) system as one of the largest energy consumer in the residential houses. However, implementing these predictive SPMs on the building energy simulators is challenging since these simulators are not inherently equipped with advanced control tools and mechanisms. This article discusses the development of a Matlab-TRNSYS co-simulator that allows TRNSYS program to implement different advanced predictive SPMs including Load Shifting (LSH), Smart Dual Fuel Switching System (SDFSS), and LSHSDFSS, as the combination of fuel switching and load shifting strategy planning models, on the case study house HVAC system. The development of each advanced predictive SPM is described in details in this paper.

INTRODUCTION

Buildings must be seen as significant elements of the larger, dynamic energy system. This means when working on improving buildings' performance, the impact of buildings behavior on the network energy system should be considered; this includes criteria such as distribution networks of electricity, district heating, and natural gas consumption [1]. In this context, timing is essential, particularly in the case of electricity, which cannot be readily stored. In other words, time of consumption, as well as consumption itself, matter when it comes to improving the buildings' performance in terms of energy system [1]. One of the issues which threatens the power network is peak load. Peak power is used only a small fraction of the time, but the utility has to deliver it, even if it is more polluting and expensive to do. Hence, to be a grid-friendly consumer, we should avoid pulling energy from the utility grid during peak times [2]. This could be achieved by having smart buildings with control of strategy planning models (SPMs). In addition to supporting the local grid, lower overall energy cost could be achieved for the homeowners using such smart building controllers [2]. Among different strategy planning models, the ones concentrate on HVAC load are the most useful ones since HVAC system is one of the largest electrical consumers of a typical house [3].

Different methods have been used previously in order to control the HVAC system demand. In developed/advanced controllers, a model of the system (building and its HVAC system) and the forecast weather condition are used to determine the best set of control operations [3]. In these control models, the prediction of the future state of the system (is based on system model) and generation of control vector signals as the output of them, drive the system towards desired state [4]. However, implementing these kinds of advance predictive controllers on the building energy simulator is too difficult due to their lack of advance controller tools. This article discusses the development of an advanced predictive control model. This control model is designed by taking advantage of two powerful simulators. The overall conception of the building and its HVAC system is modeled using TRNSYS simulation environment while implementing of control strategies is performed using Matlab. The main purpose of this article is to design a grid-friendly smart residential house controller. To this end, three different predictive strategy planning models are developed in order to manage the hourly load demand of HVAC system for the next 24 hours by taking advantage of this predictive control model.

Smart Dual Fuel Switching Strategy Planning Model (SDFSS-SPM) is the first one used to reduce the HVAC system energy cost. The second SPM developed in this article is Load Shifting Strategy Planning Model (LSH-SPM). And (LSHSDFSS) is the third SPM developed by integrating both SDFSS-SPM and LSH-SPM models together. The development of each advanced SPM is described in details in the article.

METHODOLOGY

I. Historical and Forecast Weather Information

Deterministic and Probabilistic are two different methods used for generating predicted data. Each method has its own advantages [5]. Deterministic forecast is based on one scenario as the result of one or two predictive models. The data accuracy in this method is very high and this predicted data is usually used for short-term control process. Probabilistic forecast is the result of a group (sometime 21) of models produce a range of forecast data. This method is suitable for planning long-term control process [5, 6]. GRIB2 is the most common format used for presenting the forecast dataset. However, it should be retrieved into a standard numerical format to be useable in TRNSYS and Matlab.

Based on the nature of the project (accurate short-term forecast weather), High Resolution Deterministic Prediction System (HRDPS) source (bandage 2.5km) (http://dd.weather.gc.ca/model_hrdps/east/grib2/12) from the Canadian Meteorological Centre (CMC) web site is selected as the forecast dataset. In order to collect this information off of the database, wget was installed on the computer and a system command was called from within Matlab to collect the necessary data using wget [5]. Temperature (as the most important parameter which has impressive impact on the house energy system) for the next 24 hours is obtained by filtering this data. Figure 1 illustrates the grid format of the GRIB2 data. In this study, the TRNSYS program models the house [10] that is located at Kortright Centre for Conservation in Vaughan, Ontario, for this reason the grid element of (210, 490), corresponding to the location of the house, is selected to collect data from. In order to create an interface between Matlab and the GRIB2 data that is collected, the NCToolbox is installed and the ncgeodataset function is used.

II. Estimation of 24 Hours-ahead HVAC System Electrical Demand Based on Weather Forecast Dataset (WFD)

A. House Description

The twin Archetype Sustainable Houses (ASH), were constructed by the Toronto and Region Conservation Authority (TRCA) [8, 10] at the Kortright Centre. These twin-houses demonstrate sustainable housing technologies through experimentation and research and are one of the first Canadian projects to achieve a Leadership in Energy and Environmental Design (LEED) for Homes Platinum Certification [8]. House A, which is made to have an air-tight building envelope according to the standards of ASHRAE 90.1 [13], is selected in this project as the case study for testing different SPMs.

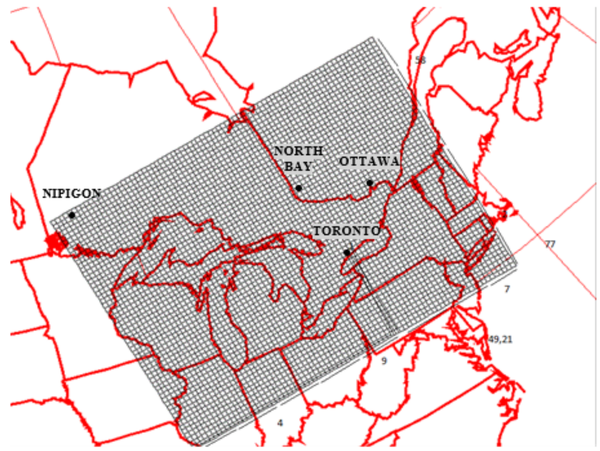


Figure 1: The grid format of the GRIB2 data – Eastern Ontario

B. TRNSYS Model

TRNSYS is a transient system energy modeling software designed to solve complex energy system problems [9]. The House A TRNSYS model, developed in [9] research work, is used in this project for testing different strategy planning models. According to a study on various energy modeling programs [11], TRNSYS is reasonably powerful in terms of HVAC system modeling.

C. Methodology

The sequence of the study starts with downloading and processing of forecast weather data, running House A TRNSYS model with forecast data, implementing strategy planning models on TRNSYS system by generating operational command matrix, and lastly post processing the generated data. Figure 2 demonstrates the framework of the house energy simulation system is made by making linkage between different but complementary software.

Matlab is used in this study to control and manage each sequence, drive each process on time, make linkage between different programs, and store or call the required data.

D. Process Step Time

Initially, all the simulation was done based on one hour time step. But the obtained results were not very accurate since the events were taking place during given hours could not be monitored/processed by the control algorithm. In order to solve the problem, 5-minute time step was determined to be suitable after a few trials.

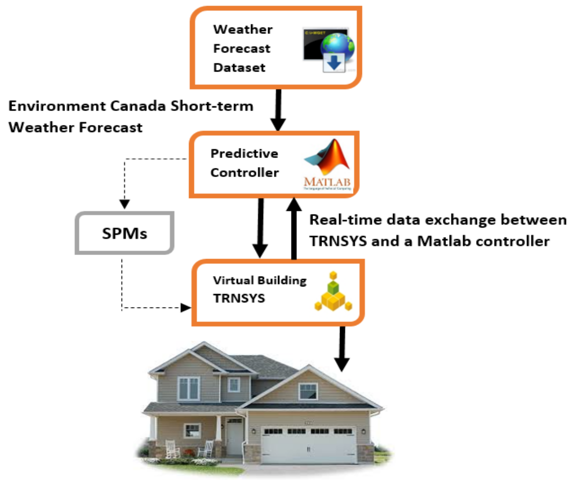


Figure 2: Framework of the house energy simulation system

E. Electricity Prices

The electricity prices used in this project are 11.70 ¢/kWh, 15.40 ¢/kWh and 18.00 ¢/kWh respectively, for off-peak, mid-peak and peak hours, estimated by considering the Ontario Energy Board (OEB) Time-of-Use (TOU) prices.

III. *HVAC System Energy Cost Reduction with Smart Dual Fuel Switching System Strategy Planning Model (SDFSS-SPM)*

House A, has a natural gas mini boiler and an electric two-stage variable capacity ASHP to generate warm air through the Air Handling Unit (AHU) to meet the space heating demand. Based on SDFSS-SPM, at each time step, least expencive fuel (electricity or natural gas) would be selected and accordingly related system (ASHP or min boiler) would be set up to meet the space heating demand.

A. Calculating the fuel price consumed by ASHP

Outdoor temperature and electricity price are two essential parameters affect the ASHP energy cost. Outdoor temperature has direct impact on ASHP Coefficient of Performance (COP). Figure 3 shows the experimentally validated House A COP curve [10, 14]. After determining COP and electricity price for the given hour, the cost of one unit energy produced by ASHP is calculated by using Equation (1):

$$(\$/\text{kwh}) = \frac{\text{Electricity price } (\$/\text{kWh})}{\text{COP} * 100} \tag{1}$$

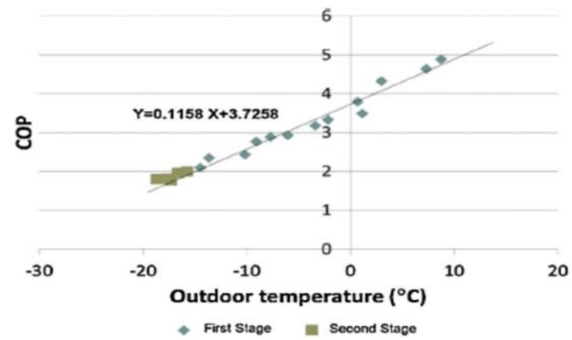


Figure 3: House A ASHP COP during different outdoor temperature [10]

B. Calculating Mini Boiler consumed fuel price

Natural gas price (41.60 ¢/m^3 estimated based on OEB prices) is constant for all hours. Thus, mini boiler efficiency is the only variable used to estimate the cost of each unit of thermal energy produced by the boiler. The efficiency of the boiler is determined based on the flow rate of water (load percentage) circulating through the boiler. Figure 4, illustrates the mini boiler efficiency curve provided by the manufacturer [12]. The fuel cost of Mini Boiler (for preparing one unit of heat energy) is calculated by using Equation (2). In this equation, the 10.3 constant is used for converting 1m^3 of natural gas energy content into kWh.

$$(\$/\text{m}^3) = \frac{\text{Natural Gas price } (\$/\text{m}^3)}{\text{Efficiency} * 10.3} \tag{2}$$

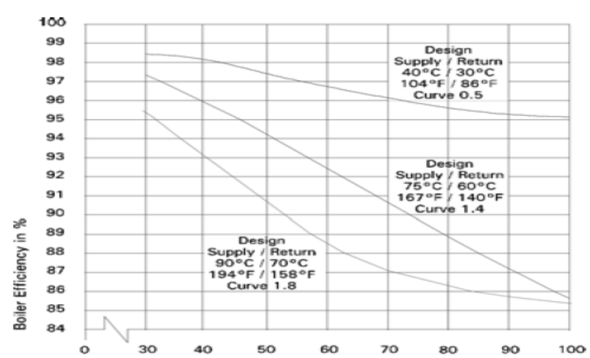


Figure 4: Mini boiler efficiency curve provided by the manufacturer (12)

C. Using SDFS system as a strategy planning model

After solving Equations (1) and (2) considering outdoor temperature and TOU pricing, -14°C, -5°C and 0°C are found as the switching points of ASHP and mini boiler during off-peak, mid-peak and peak hours respectively. Figure 5 demonstrates the flowchart of SDFSS strategy planning model.

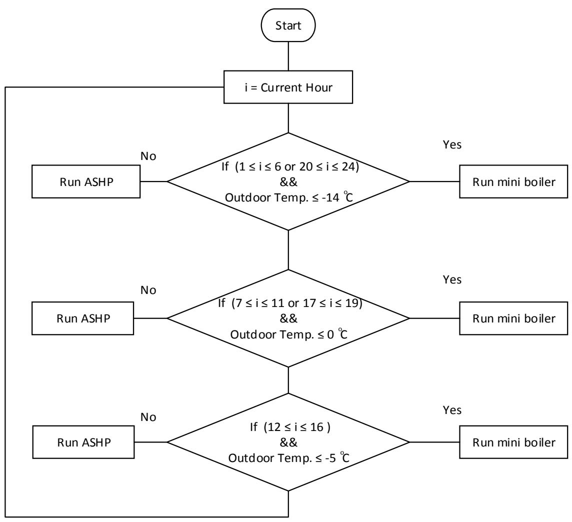


Figure 5: SDFSS strategy planning model

Figure 5 flowchart is implemented on the develop model using the following code. Since 5-minute is selected as the step time, a matrix with 288 (24 * 60/5 = 288) cells is used as the operational command matrix in order to cover whole day.

IV. *HVAC System Demand Management Using Load Shifting Strategy Planning (LSH-SPM)*

The most important issue that should be taken into consideration in the design process of LSH-SPM model is occupant thermal comfort. Based on the ASHRAE Standard [13], the indoor temperature in the winter season should be kept between 20℃ and 24℃ for thermal comfort during occupied hours. To run the simulation, 21℃ is selected as the set point temperature.

A. Methodology

Figure 6 demonstrates the framework used in this study for implementing LSH-SPM.

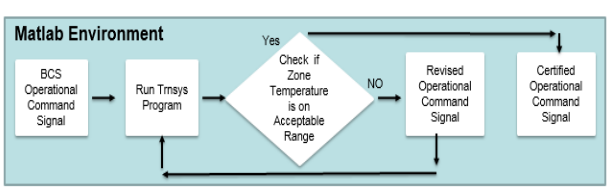


Figure 6: The operational mechanism of LSH-SPM model

B. Pre-heating starting time

There will be no opportunity for shifting the HVAC load to off/mid hours without storing thermal energy with pre-heating process. If pre-heating process was started sooner than its optimum time, more electricity would be consumed and room temperature would exceed the ASHRAE Standard range.

If pre-heating was started later than its optimum time, the stored heat energy would not be sufficient to fully support LSH-SPM during peak load hours. In this study, House A TRNSYS model is run at each outdoor temperature to seek the optimum starting time.

Figure 7 shows the arrangement of different cells of operational command matrix for the afternoon peak hours. These cells are dynamically set during running LSH-SPM. The "x" parameter in Figure 7, indicates the HVAC condition (ON=1 or OFF=0) which is set after comparing "Tzone" and the set-point at each time step. The cells which are already set to "1", indicate the step times in which HVAC system is kept ON.

These cells are determined set based on the pre-heating starting time. In the Best Case Scenario (BCS), LSH-SPM keeps the HVAC system OFF during the peak hours. To implement that, the related cells of operational command matrix (during peak hours), are set to "0". These cells are again re-set during next iteration based on the methodology described in Figure 6.

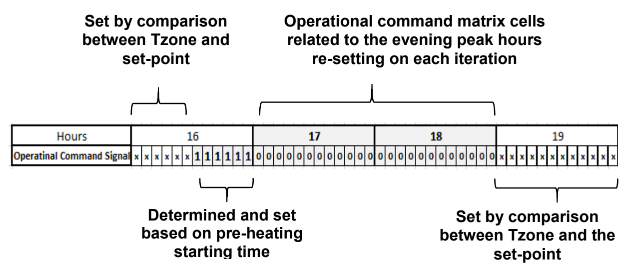


Figure 7: The arrengment of different cells of operational command matrix in the afternoon peak hours

V. *LSH-SPM Development by Integrating Smart Dual Fuel Switching System Strategy Planning Model (LSHSDFSS-SPM)*

Under this scenario, SDFSS-SPM and LSH-SPM models are combined together to construct a developed intelligent strategy planning model, named LSHSDFSS-SPM. This model takes the advantages of load shifting and fuel switching system together.

SIMULASION

A. Calculating the impact of SDFSS-SPM on DFC at different outdoor tempretures

Matlab model is run when the average outdoor temperature changes between 0°C and -20°C . The energy cost saving occurs after using SDFSS-SPM is illustrated in Figure 8.

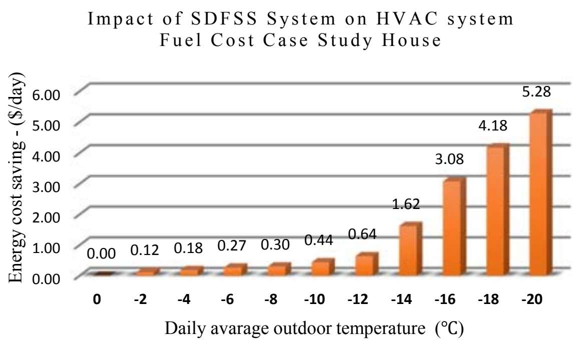


Figure 8 : Energy cost saving using SDFSS-SPM at House A in different outdoor temperatures

B. Calculating the impact of LSH-SPM on DEC at different outdoor tempretures

Figure 9 illustrates the energy cost savings as the result of LSH-SPM on House A HVAC system. Based on Figure 9, the advantage of LSH-SPM can be taken when the daily average outdoor temperature changes between -2°C and 14°C..

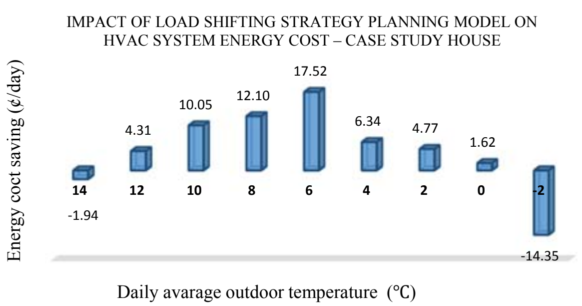


Figure 9: Energy cost saving using LSH-SPM at House A in different outdoor temperatures

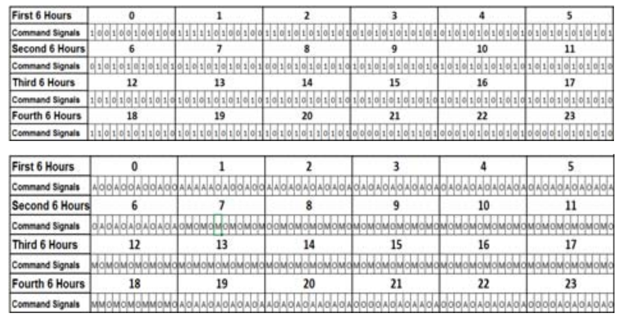
RESULTS

A. Baseline scenario

The model is run by January 4th, 2015 weather forecast data. The outdoor temperature changed between -4.6°C and -9.8°C during this specific day. The Daily Electricity Cost (DEC) of the HVAC system for this sample day is $3.61. It should be taken into consideration that no strategy planning model is run yet.

B. SDFSS-SPM

In Figure 10, first table shows operational command matrix (OCM) generated with Matlab program after implementing weather forecast dataset while the second one shows modified OCM after using SDFSS-SPM. "A" and "M" characters in this figure, respectively stand for ASHP and mini boiler.



First 6 Hours	0	1	2	3	4	5
Command Signals	100100100100	111110100100	110101010101	010101010101	010101010101	010101010101
Second 6 Hours	6	7	8	9	10	11
Command Signals	010101010101	010101010101	001010101010	101010101010	101010101010	101010101010
Third 6 Hours	12	13	14	15	16	17
Command Signals	101010101010	101010101010	101010101010	101010101010	101010101010	101010101010
Fourth 6 Hours	18	19	20	21	22	23
Command Signals	110101011010	101101010101	101010110101	000010101101	000101010101	000010101010

First 6 Hours	0	1	2	3	4	5
Command Signals	A00A00A00A00	AAAAA0A00A00	AA0A0A0A0A0A	0A0A0A0A0A0A	0A0A0A0A0A0A	0A0A0A0A0A0A
Second 6 Hours	6	7	8	9	10	11
Command Signals	0A0A0A0A0A0A	0M0M0M0M0M0M	00M0M0M0M0M0	M0M0M0M0M0M0	M0M0M0M0M0M0	M0M0M0M0M0M0
Third 6 Hours	12	13	14	15	16	17
Command Signals	M0M0M0M0M0M0	M0M0M0M0M0M0	M0M0M0M0M0M0	M0M0M0M0M0M0	M0M0M0M0M0M0	M0M0M0M0M0M0
Fourth 6 Hours	18	19	20	21	22	23
Command Signals	MM0M0M0MM0M0	A0AA0A0A0A0A	A0A0A0AA0A0A	0000A0A0AA0A	000A0A0A0A0A	0000A0A0A0A0

Figure 10: Operational command matrix (OCM) before and after implementing SDFSS-SPM

The Daily Fuel Cost (DFC) of the HVAC system is found to be $3.39 after implementing SDFSS-SPM. In other words, $0.22 is saved on the HVAC system energy cost by implementing SDFSS-SPM.

C. LSH-SPM

Figure 11 demonstrates zone tempreture when no SPM is implemented on the model.

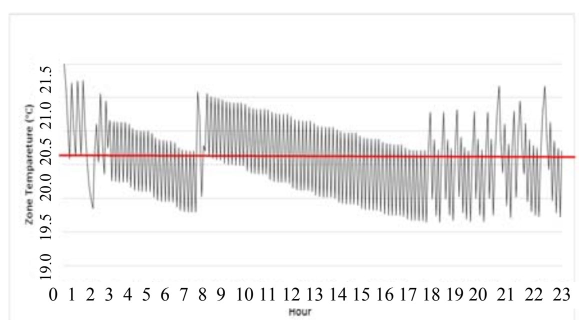


Figure 11 : Zone temperature on baseline condition

Figure 12 shows zone temperature variation occurred based on the first operation command matrix (which generated based on the BCS strategic plan). As Figure 12 depicted, the ASHP ran from 6:18 am (which selected based on pre-heating starting time) till 7:00 am and 16:21

pm till 17:00 pm to pre-heat the house and was kept off during peak hours.

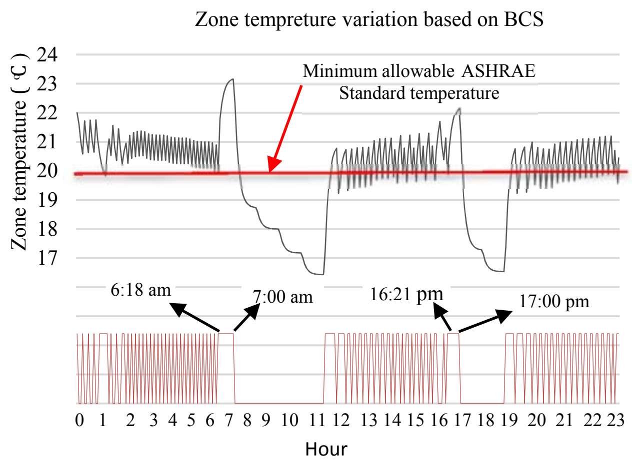


Figure 12: Zone temperature and OCM based on BCS scenario

Since there is temperature violation during occupied period, OCM should be modified based on the method described in Figure 6 in the next iteration. Figure 13 shows the modified OCM and corresponding zone temperature. As it seen from Figure 13, zone temperature increased up to the ASHRAE Standard range in the next step time.

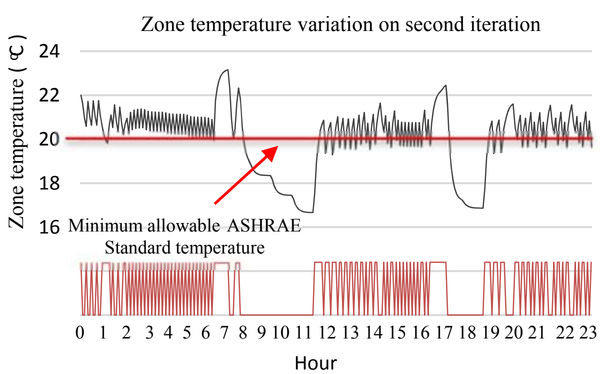


Figure 13: Zone tempreture and OCM on second iteration

After 12 iterations, the final OCM is generated in which zone temperature ensures the ASHRAE Standard range in all time steps. Figure 14 shows the zone temperature and OCM on last iteration.

$4.01 is estimated for the DEC of the HVAC system in the sample day after running LSH-SPM. In other words, due to specific weather condition of sapmle day, no saving occurred by implementing LSH-SPM.

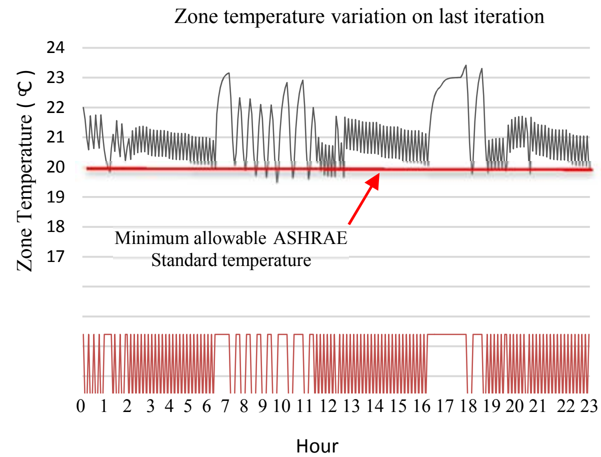


Figure 14: Zone temperature and OCM on last iteration

D. LSHSDFSS -SPM

The DFC of the HVAC system after using this model is found to be $3.73 which is higher than the baseline scenario because of the effect of LSH-SPM.

The result of different SPMs for House A in the sample day is presented and compared in Figure 15.

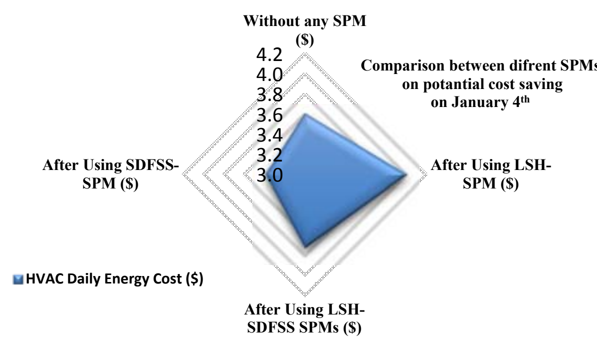


Figure 15: Comparing the potential cost savings of different SPMs

CONCLUSION

Since residential houses (RHs) have the potential of storing thermal energy, they present great opportunity for managing/controlling their demand using controller based on advanced predictive strategy planning models. However, implementing these predictive SPMs on the building energy simulators is challenging since these simulators are not inherently equipped with advance predictive control tools and mechanisms. Hence, a Matlab-TRNSYS co-simulator along with three different predictive SPMs are developed in this article to control/manage the demand of case study house HVAC system. SDFSS as the first SPM, could notably reduce the HVAC energy cost. As the outdoor temperature gets colder, higher energy cost saving is achieved using this SPM. Implementing this SPM on January 4th, 2015 could bring $0.22 saving on the HVAC energy cost. LSH-SPM was the second strategy planning model implemented in this study. A smart method was used to determine the best HVAC pre-heating starting time. Due to the cold outdoor temperature on test running day, this SPM could not bring any saving on the HVAC energy cost. LSHSDFSS-SPM was the third strategy planning model examined. This model took the advantage of the combined load shifting and fuel switching strategies together into a single system. The daily energy cost of the HVAC system after using this SPM was $3.73 which is higher than the baseline scenario because of the effect of LSH-SPM.

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