BUILDING ENERGY SYSTEM CONTROL USING MPC AND ON/OFF CONTROLLER – AN ASHRAE CASE 600 TEST

**Abstract**

A buildings energy usage due to heating, ventilation, and air conditioning (HVAC) has a significant impact on a company’s scope 2 emissions which has negative effects on both the environment as well as the corporation’s bottom line. This paper lays out two models which seek to optimize a building’s energy system. The focus will be on the investigation of two control methods: an on/off controller and model predictive control (MPC). To do this, two key performance indicators (KPIs) will be assessed when investigating the effectiveness of the methods. The first KPI is how well the HVAC system remains within a given set of upper and lower temperature bounds. The second KPI is the overall energy usage of the system.

**Introduction**

HVAC systems are an integral part of a building’s composition. In cold climates it is necessary to provide proper heating to ensure that the inhabitants of the building are warm and comfortable. Similarly, in warm climates it is necessary to provide proper cooling. Unfortunately, however, HVAC systems, can be rather inefficient. In fact, studies have shown that on average 25% energy savings can be achieved by improving the efficiency of an HVAC system. This naturally leads to the question of how can this energy saving be achieved? Well one possible answer to that question, as described above, lies in the controller and the methodologies that the controller uses (MPC vs. On/Off).

First, MPC is the standard for advanced control in the industry. MPC essentially involves three steps. First it needs a predictive model, second it needs optimization within a given range, and finally it needs a feedback correction. Now, model predictive control, is, as the name suggests, a predictive model. It essentially uses past information of the given process, coupled with predicted future input, to predict the future output[[1]](#footnote-1). For the purpose for this paper. MPC will use past information of the buildings data recordings as well anticipated future input to predict the future output and therefore adjust the HVAC system accordingly. The on/off controller on the other hand will simply heat with a set amount of power when the zone temperature, or temperature within the building, falls below a given range and will cool with a set amount of power when the zone temperature rises above a given temperature bound.

**Case 600**

The model that will be developed for this lab is based on ASHRAE case 600 as described in “*Standard Method of Test for the Evaluation of Building Energy Analysis Computer Program*”, ASHRAE standard 140-2017. The building that is being investigated is located in Denver, CO at latitude of 39 degrees, a longitude of 1609 and an altitude of 1609 meters. The dimensions of the building can be seen in Figure 1 in the appendix. Similarly, the wall materials include aluminum siding, gypsum board, plywood, and mineral fiber while the roof materials include asphalt shingles, vapor-permeable felt, mineral fiber, plywood, and gypsum board. The amount and further details of the wall and roof composition and materials can be found as figure 2 and figure 3 in the appendix.

As can be seen in the image there are two south facing windows. Further important characteristics of this case are that there is 100W of internal heat gain during workhours and 0 W during off hours as well as a 0.5 infiltration rate. The walls have a solar absorptance of 0.6 and the windows solar transmittance varies from 0.747 to 0 based upon the angle. The roof and wall materials as well as their thermal properties are defined in the standard.

**Assumptions**

The building will have an HVAC system that utilizes model predictive control and will be compared with the on/off control. Furthermore, the coefficient of performance is 1.0. Further assumptions that were made include: there being no loss through the cracks in the walls, that there is no energy emanating from the ground, and that there is no windspeed accounted for and therefore no convection, regular and forced, so convection (regular and forced) was neglected.

On top of this it will assumed that work hours are between 8AM – 6PM local time. During work hours it was assumed that the internal heat gain was 100 W. For the non-work hours, it was assumed that the internal heat gain was zero. Further assumptions with regards to the upper and lower temperature bounds can be found in the simulation setup portion of this paper. It is important to note that in the simulation set up there is a different set of temperature bounds for the winter then there is in the summer. This is done for two reasons. First it puts less stress on the HVAC system and second, in different periods of the year individuals are acclimated to different weather temperatures and therefore the optimal range for comfort is different. Finally, the peak demand period was chosen to be between 2-6 P.M. as defined by national grid.[[2]](#footnote-2)

**Building State Space Model**

Firstly, the state space model (3R2C) was constructed. A graphical representation of the thermal resistance-capacitance model can be found as Figure 4 in the appendix. In this model can be defined by the equation below

Similarly, can be defined as shown below

Now in the thermal resistance-capacitance model the below equations are used

The following variables in the above equation are defined as follows

The next step involves discretizing the state space model. This is done using the below equations

Where

**Model Predictive Control (MPC)**

To reiterate MPC is a predictive model which utilizes past information of a given process alongside predicted future input in order to predict future output. MPC essentially involves three steps. The first is that MPC needs a predictive model, next it needs optimization within a given range, and finally it needs a feedback correction. In this paper CVX solver sedumi developed by Jos F. Sturm[[3]](#footnote-3) was used to handle the optimization problem.

To begin with MPC, the goal is to find the best control sequence over a future horizon of N steps. The equations can be seen below.

The prediction model is shown below

The constraints for the problem are

With the state feedback defined as

Now at each iteration, defined as t, the followings steps occur. First, a new measurement is obtained which updates the estimate of the current state, . Then the optimization problem is solved with respect to . Finally, the first optimal move is applied. The remaining samples are discarded.

To further understand how MPC is implemented in this lab you can look at the linear prediction model which is shown below

With the below constraints to enforce

And the constrained optimal controlled problem is

(31)

With the below relationships applying

Finally, the constrained linear program can be seen below

Now there are multiple ways to solve for the minimum. For some background, the global minimum as well as global maximum is a mathematical concept that dates back to the 1600’s when Pierre de Fermat proposed a generalized technique for solving for these extrema. For this analysis, the CVX Solver sedumi was used. The sedumi solver was created by Jos F. Sturm and is used for optimization over symmetric cones. Each iteration through the sedumi solver performs its optimization and aides the MPC technique.

**Simulation Setup**

For the simulation open and closed loop simulations were ran for the entire year, as well as an open and closed loop simulation for one week in the winter (the third week in January) and one week in the summer (the third week in July). For the one-week tests both a simple on/off controller and MPC were used.

For the simulation work hours were assumed to be between 8AM and 6PM. During work hours in the winter the zone temperature lower bound was set to 18℃ (64.4°F) and the zone temperature upper bound was set to 26℃ (78.8°F). Furthermore, the internal heat gain during this period was set to 100W (341.2 BTU/hr). For the non-working hours in the winter, the zone temperature lower bound was set to 20℃ (68°F) and the zone temperature upper bound was set to 24℃ (75.2°F). The internal heat gain for this period was set to zero.

Similarly, the lower bound during work hours for the summer months was set to 19℃ (66.2°F) and the upper bound was set to 27℃ (80.6°F). During off-hours the lower bound was set to 21℃ (69.8°F) and the upper bound was set to 25℃ (77°F). Essentially all bound values were increased by 1℃ (1.8°F) because in the summer it is okay if the temperature range is slightly higher than in the winter due to how people dress during that portion of the year as well as other factors. The internal heat gain during work hours is 100W (341.2 BTU/hr) and 0 during off hours which is the same as the winter months.

For the on/off controller the power of the heating ventilation and air conditioning system for the winter months was set to 4,000W (13648.5BTU/hr). In the summer months the power was set to 3000W (10236.4BTU/hr). The same bounds on the power of the HVAC system were implemented on the MPC model for both the winter and summer months. Furthermore, the peak demand was set to be from 2PM to 6PM.

It is important to note that the upper and lower bounds for the set temperatures, the internal heat gain, the work hours, the peak demand period and the maximum power of the heating ventilation and air conditioning system is the same for both the on/off controller test and the MPC test. This is to ensure that all variables are controlled so that the only change between the two tests is the type of control that is being used.

Now individually for the MPC model, the prediction horizon was set to 2 hours and the control horizon was set to 15 minutes. Further, the sampling interval was set to 5 minutes. The on/off control similarly had a control step of 15 minutes and a sampling interval 5 minutes.

**Results**

From here results were gathered from the analysis. Peak parameters that were of interest were space heating load, space cooling load, peak heating load and cooling load during peak demand and indoor temperature. Furthermore, two different plots for each analysis week in summer, week in winter, and entire year were created.

First, the plot for the entire year will be analyzed to give a baseline understanding for the data being looked at. The open loop simulation can be seen in the appendix as figure 5 and the closed looped simulation with fixed HVAC power for the entire year can be found in the appendix as figure 6.

By analyzing the open loop simulation plot, Figure 5, you can see that our model behaves in a way such that and mimic the curve. You can see that has the highest average temperature and this is too be expected because of which impacts the wall most. This also has a slight impact on which is in contact with . has no impact on .

Next the closed loop graphs can be analyzed as shown in Figure 6, in the appendix. In the closed loop temperature plot, you cans see that there are fluctuations in the temperature readings which is a product of the HVAC system turning on to keep within the desired range. From the graph you can also see that and fluctuate more than which is to be expected because both of these temperatures depend on the outside weather whereas is a zone that is insulated and being fine-tuned via the HVAC system to ensure that it is at an optimal temperature.

Now one week in the heating season (the third week in January) will be analyzed for both the on/off controller and MPC. First, you can see the open loop simulation in Figure 7 in the appendix. Form this figure you can see that the maximum ambient temperature recorded was 17.23℃ (63°F) and the lowest was -8.9℃ (15.98°F). Figure 8 in the appendix shows the closed loop simulation with fixed HVAC power for this week. The fixed HVAC does an okay job staying within the desired temperature bounds, however, there are a lot of fluctuations that occur due to the nature of the heating system and these lead to inefficiency. The total energy usage for the on/off controller for the week in the winter was 331kWh (1.1916e9J) and the maximum power during peak demand for this HVAC system was 4,000W (13648.5BTU/hr). Figure 9 in the appendix shows the MPC simulation for this week period in January. Through this image you can see that the MPC simulation does a good job staying within the desired temperature bounds. Also, unlike the on/off controller MPC has less erratic heating fluctuation and this translates to energy saving. The total energy usage for the MPC simulation was 271.2kWh (9.7631e8J) and the maximum power usage during peak demand was 2608.3W (8898.8BTU/hr). The percentage of energy saving that was recorded by using MPC was 18.07% while the percentage of peak demand reduction that was recorded by using MPC was 34.79%.

One week in the cooling season (the third week in July) will be analyzed for both on/off control and MPC now. First, you can see the open loop simulation for this week in Figure 10 in the appendix. From this figure you can see that the maximum ambient temperature recorded was 35℃ (95°F) and the minimum was 15.7℃ (60.26°F). Figure 11 in the appendix shows the closed loop simulation with fixed HVAC power for this week. This simulation shows that the fixed HVAC method does a decent job staying within the upper and lower temperature bounds, but there are a lot of fluctuations, as in the heating season, which can lead to energy loss. The total energy usage for the on/off controller for the week in the cooling season was 45kWH (1.62e8J) and the maximum power during peak demand was 3,000W (10236.4BTU/hr). Figure 12 in the appendix shows the MPC simulation for this week in July. This simulation shows that the MPC simulation does an excellent job staying within the desired temperature bounds. There also are minimum cooling fluctuations unlike with the on/off controller. The total energy usage for the MPC simulation was 23.3kWh (8.3993e7J) and the maximum power usage during peak demand was 577W (1968.8BTU/hr). The percentage of energy saving that was recorded by using MPC was 48.15% while the percentage of peak demand reduction that was recorded by using MPC was 80.76%.

**Conclusion**

This paper analyzed the difference between an on/off controller and MPC for HVAC. Both methods did a decent job staying within the given temperature bounds, however, the on/off control had more fluctuations as well as consumed more energy. In the heating season the MPC approach created a 18.07% (331kWh, 1.1916e9J, for on/off controller and 271.2kWh, 9.7631e8J, for MPC) reduction in energy usage when compared to the on/off controller for the same period with the same temperature bounds. During this week in the winter the MPC approach also recorded a 34.79% (4000W, 13648BTU/hr, for on/off controller and 2608.3W, 8899BTU/hr, for MPC) reduction in max power used when compared to the on/off controller.

Similarly, in the cooling season the MPC approach had 48.15% (45kWh, 1.62e108J, for on/off controller and 23.3kWh, 8.3993e7J, for MPC) less energy used when compared to the on/off controller for the same period with the same temperature bounds. During this same week in the summer the MPC approach also recorded an 80.76% reduction in max power used (3,000W, 10236BTU/hr, for on/off controller and 577W, 1968BTU/hr, for MPC) when compared to the on/off controller. Therefore, it appears based upon the simulations ran that the MPC approach to a HVAC proved to do a better job staying within the defined temperature bounds as well as reduced both the total energy used by the system as well as reduced the max power during peak demand.

**References**

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**Appendix**

Diagram

Description automatically generated

Figure - Building Dimensions

Graphical user interface, application

Description automatically generated

Figure - Wall Materials

Graphical user interface

Description automatically generated with medium confidence

Figure - Roof Materials

Diagram

Description automatically generated

Figure - 3R2C Model



Figure - Entire Year Open Loop Simulation



Figure - Entire Year Closed Loop Simulation



Figure - Open Loop Simulation – Heating Season



Figure - Closed Loop Simulation with On/Off Controller – Heating Season



Figure - MPC simulation - Heating Season



Figure - Open Lop Simulation - Cooling Season



Figure - Closed Loop Simulation with On/Off Controller - Cooling Season



Figure - MPC Simulation - Cooling Season

1. Zhang, Peng. *Advanced Industrial Control Technology*. William Andrew Publishing, 2010. [↑](#footnote-ref-1)
2. “Service Rates: Rates: Bills, Meters & Rates: National Grid.” *Rates | Bills, Meters & Rates | National Grid*, www.nationalgridus.com/Upstate-NY-Home/Rates/Service-Rates. [↑](#footnote-ref-2)
3. https://sedumi.ie.lehigh.edu/ [↑](#footnote-ref-3)