Model Predictive Residential Building Climate Control at Cornell Campus

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Figure 1: Cornell Townhouse Community

1 Introduction

Approximately 40 % of the global energy consumption occurs in buildings, and half is used for HVAC (Heating, Ventilation, and Air Conditioning) systems. Energy reductions can be realized by improving a building's HVAC systems and construction. However, most of the building is already in place, and reconstructing buildings is expensive. Therefore upgrading the building control system at comparatively low costs is a good option for reducing energy consumption.[1]

Model predictive control (MPC) is an advanced process control method that is used to control a process while satisfying a set of constraints. [2] Model predictive control has been recognized as one of the essential solutions to achieve considerable energy savings in buildings. It uses a mathematical model of the building and predictions of disturbances over a given prediction horizon to formulate an optimization problem. [1] MPC controller can Find the control input trajectory that maintains the room comfort (e.g.,Thermal comfort, Blinds movements, Visual comfort, Air quality) over the whole time horizon while minimizing some objectives. (e.g., Total energy use/price) This project aims to find an optimal control solution via MPC to ensure the comfort of the occupants while minimizing total electricity costs. Figure 2 shows the general workflow of this project.

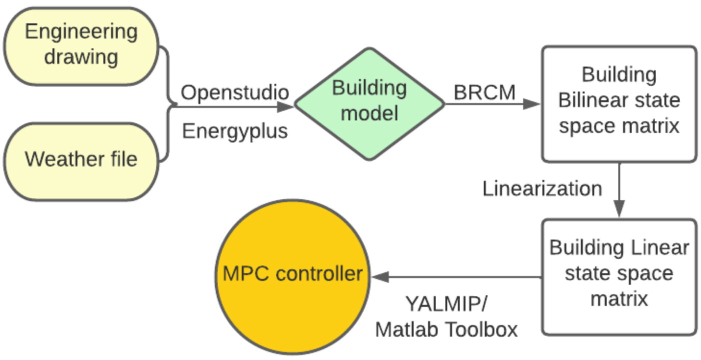
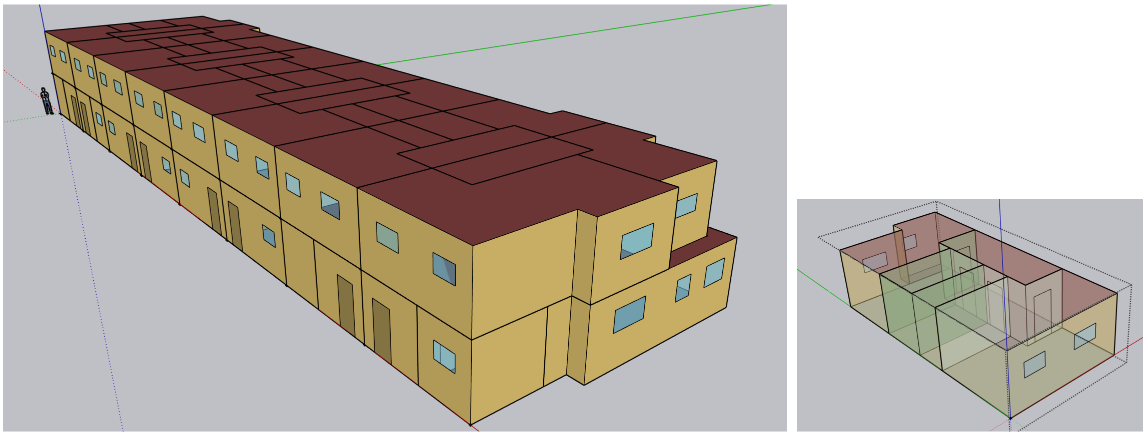


Figure 2: Work Flow chart

2 Building Model

2.1 Building Physics Model

Building an accurate model of the control plant is a key step. Figure 3 shows the physics-based townhouse building model made by SketchUp, OpenStudio, and EnergyPlus. It has 16 rooms and 16 thermal zones. The building EnergyPlus model included the building's construction, HAVC system, occupant and appliances schedule,



(a) (b)

Figure 3: (a) Whole Building EnergyPlus Model(b) Single Room

heat exchanges among the elements, and outside weather disturbances(e.g., outside temperature, solar radiation, wind direction, etc.)

2.2 Disturbances

Some factors can affect room temperature other than the HVAC system, such as lighting, occupant, equipment heat gain, outside air temperature, solar radiation, etc. Those are predictable disturbances in Model Predictive Control. This control problem will consider eight disturbances: total internal gain, outside temperature, ground temperature, solar radiation from North, South, East, West, and Horizontal. Figure 4 shows the disturbances for January 1st-2nd. The following presentation of our control results uses the disturbance data of these two days.

2.3 Building RC Model

Building resistance-capacitance (RC) model was generated from BRCM toolbox along with the Bilinear building dynamics. Figure 5 shows room temperature and every walls' temperature in this room when heating power set to 80 watts per m^2.The total energy cost for the whole building in one month will be 1841.7 USD.

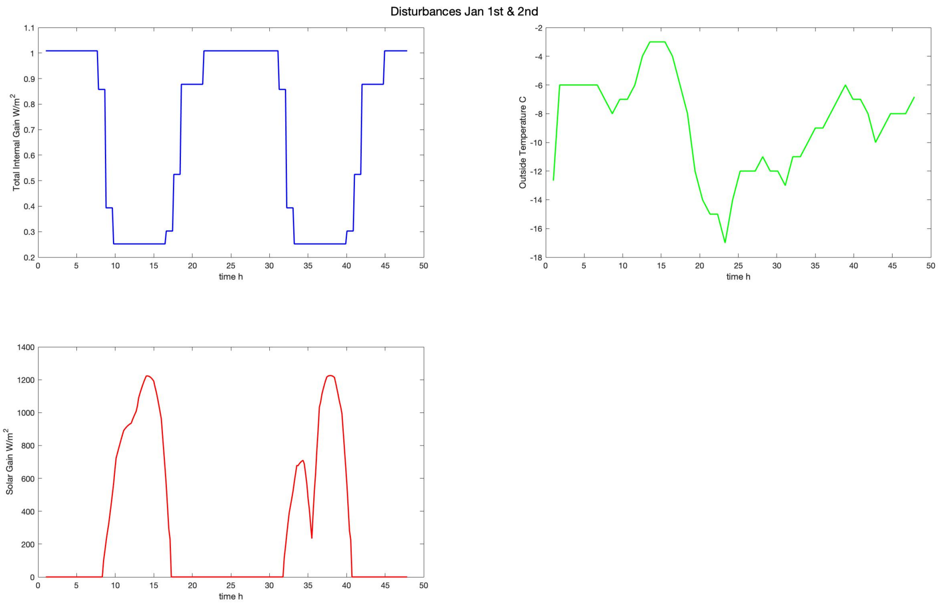


Figure 4: Building Model Disturbances

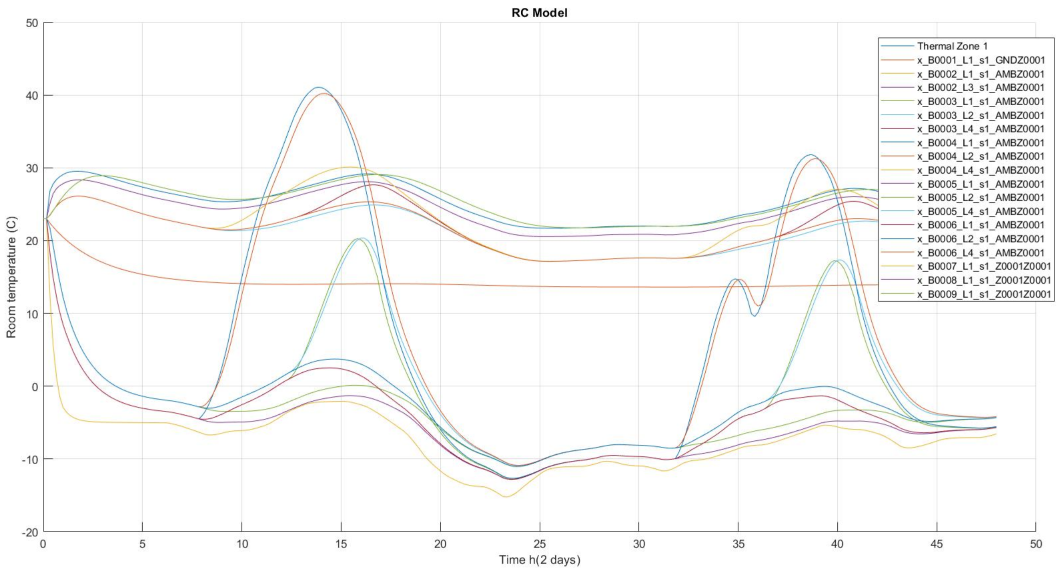


Figure 5: Building Wall Temperature

3 MPC Controller

3.1 MPC Structure

Use prediction horizon of 12, control horizon of 4, T_s=10mins, horizon length of N=289.

y:averaged room temperature

x: rooms and walls temperature

u: HVAC control inputs

v: predictable disturbances

minimize energy costs:

$$\min_u \sum_{k=0}^{N-1} c_k^T u_k$$

Room temperature constrains: 22-26°C.

s.t. $y_{min,k} \leq y_k \leq y_{max,k}$

x_{k+1}=Ax_k + $B_u u_k + B_v v_k + ... \sum_{i=1}^{n_u}(B_{vu,i}\mathrm{v}_k + B_{xu,i}\mathrm{x}_k)u_{k,i}$

y_k=Cx_k + $D_u u_k + D_v v_k + ...$

$Fx_k + Gu_k \leq g_k$

$\forall k = 0, 1, ..., N-1$

ETFE : empirical transfer function estimate

x_k denotes the states (temperatures of rooms), u_k are the inputs and v_k the predicted disturbances (solar radiation and ambient temperature)at prediction time step k.

3.2 Linear State Space Model

The building Bilinear model can be generated from BRCM toolbox once we have the EnergyPlus model. For a single room Bilinear MPC plant, there are 19 states, 4 inputs and 8 disturbances. The 4 inputs are window blind north, window blind south, AHU, and HVAC heating and cooling power. We can further linearize the state space matrix by changing the first three inputs to a constant value. The calculation process in LinearSSM.m.

Figrue 6 shows the MPC structure for a single room. In the Linearized model, we have 1 input and 8 measured disturbances. Figure 7 is the result of the Bilinear model and the Linear model checking. They are completely overlapped, demonstrating the two models are matched.

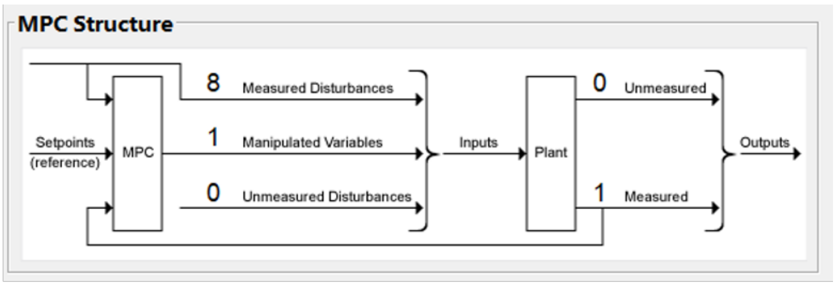


Figure 6: MPC Controller Structure

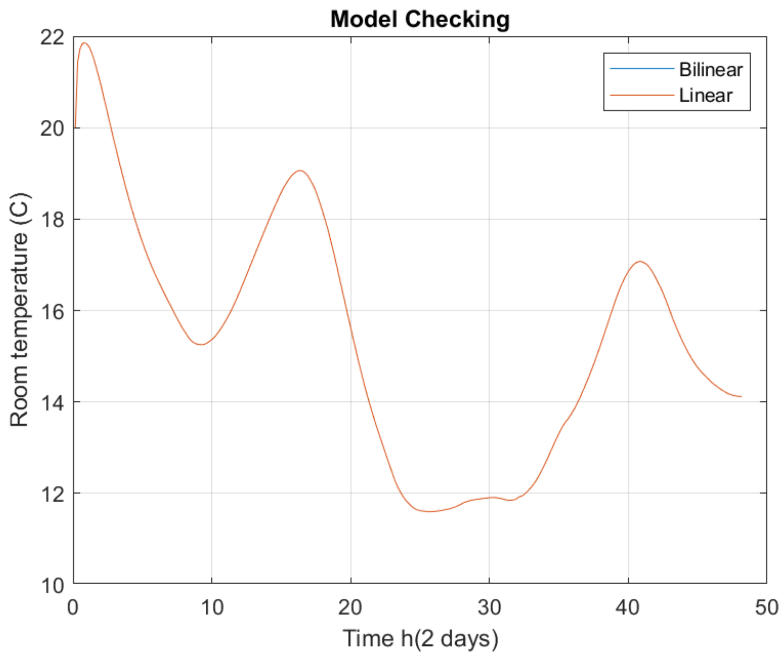


Figure 7: Bilinear Linear Model Checking

4 Results and Discussion

The building MPC controller part of this project was designed using the Matlab MPC toolbox. Here I have designed two controllers for different cost function requirements, one for a fixed cost of electricity and one for dynamic electricity cost. The specific electricity rates are taken from the national grid database [3].

4.1 Constant Electric Price MPC

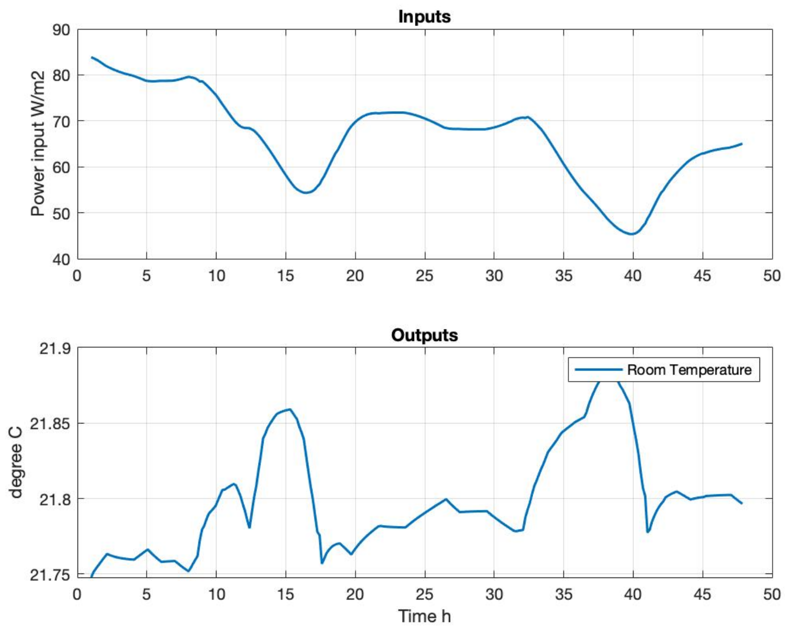


Figure 8: Constant Electric Price MPC

With a constant electricity price, the total energy cost for the whole building in one month is about 1527.1 USD.

4.2 Dynamic Electric Price MPC (Economic MPC)

In reality, the electricity price will slightly change over time. These electricity prices from the nation grid database[3] are available in one hour intervals. I discretized it

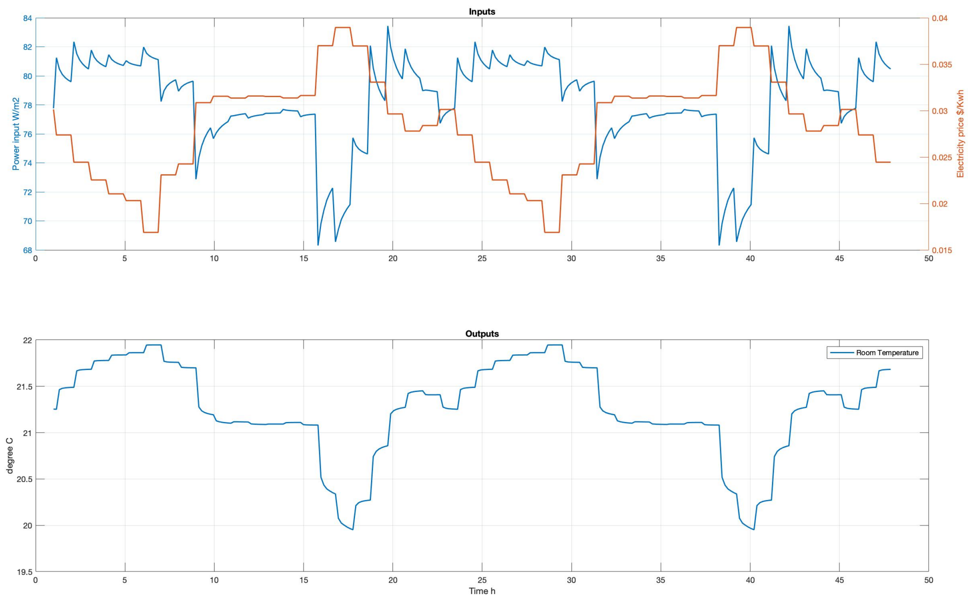


Figure 9: Dynamic Electric Price MPC

using a sample time of 10 minutes. With the Economic MPC controller, the building will buy more energy when the price is low and uses this acquired thermal energy rather than buy power at a higher price. With a dynamic electricity price, the total energy cost for the whole building in one month is about 1465.5 USD. It can be observed that the Economic MPC can save energy cost by around 25.7%

5 Conclusion

In this project, I have presented a model for the temperature in Cornell townhouse residential building with an HVAC heating system. The constant cost MPC and Economic MPC are used to manipulate the compressor in the heat pump such that the total electricity cost is minimized, while keeping the indoor temperature in a comfort level. Using actual electricity prices and weather conditions, I demonstrated that MPC performance depends largely on the optimization function and controller setting, and Economical MPCs are able to transfer the power consumption to the period of low electricity rates.

In the future, I will use the Machine learning method to build dynamic human comfort temperature constrain and use the real forecasts to investigate cases with uncertainty. EV charging sites and renewable energy will also be considered.

6 References

[1]Sturzenegger, D., Gyalistras, D., Semeraro, V., Morari, M., amp; Smith, R. S. (2014). BRCM MATLAB TOOLBOX: Model generation for model predictive building control. 2014 American Control Conference. https://doi.org/10.1109/acc.2014.6858967

[2]Wikimedia Foundation. (2022, March 8). Model predictive control. Wikipedia. Retrieved May 5, 2022, from https://en.wikipedia.org/wiki/Model predictive control

[3]National Grid hourly electric supply charges. (n.d.). Retrieved May 5, 2022, from https://www9.nationalgridus.com/niagaramohawk/business/rates/5_hour_charge.asp