Enhancing energy efficiency in buildings with model predictive control

Louis-Gabriel Maltais, Louis Gosselin
Department of Mechanical Engineering
Université Laval, Quebec City, Quebec, Canada

Context
- For economical and environmental purposes, considerable research efforts have been devoted to diminish our overall energy consumption.
- Buildings have been found to contribute to approximately 41% of the energy consumption in the United States.
- There are uncertainties on how to increase the energy efficiency in buildings without replacing mechanical systems.

Objectives:
1. Develop a control strategy for heating, ventilation, and air conditioning (HVAC) systems to increase the energy efficiency of buildings while providing thermal comfort.
2. Compare the performance of the obtained controller with conventional control strategies.

Model predictive control (MPC)
- Intelligence acting on one or several manipulated variables (e.g., hot and cold air flow rates) to reach setpoints of controlled variables (e.g., air temperature).
- Prediction model of the dynamics of the controlled system to evaluate its future behaviours depending on the considered operation points.
- Optimisation process to find best operation points based on objectives such as reducing the energy consumption.

Results
- 48-hour simulations in summer and winter.

<table>
<thead>
<tr>
<th>Energy consumption of the HVAC system as a function of the controller.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy consumption [kWh/m²-day]</td>
</tr>
<tr>
<td>Fans Heating Cooling</td>
</tr>
<tr>
<td>Control strategy</td>
</tr>
<tr>
<td>48 h in summer 48 h in winter 48 h in summer 48 h in winter 48 h in winter</td>
</tr>
<tr>
<td>Traditional controller</td>
</tr>
<tr>
<td>0.090 0.080 0.558 0.092 0.007</td>
</tr>
<tr>
<td>MPC</td>
</tr>
<tr>
<td>0.077 0.057 0.011 0.308 0.091 0.009</td>
</tr>
<tr>
<td>Savings by MPC</td>
</tr>
<tr>
<td>14.5% 28.8% - 44.8% 1.1% -</td>
</tr>
</tbody>
</table>

Profile
- Better use of flexible comfort zone with MPC.
- Overall time outside of comfort zone reduced by 95.1% with MPC.

Design tool
- Provide information to design the optimisation process depending on objectives.
- Relative importance between energy consumption and comfort impacts MPC.
- Sharp increase in time out of comfort zone at \( r_w \)-value around 0.0002.
- Designer should be careful if energy consumption is the main objective.
- MPC sensitive to small variations of the weights ratio \( r_w \).

Conclusions
- A model predictive controller has been developed and implemented in a 12-room institutional building.
- It successfully increased the energy efficiency of the HVAC system by reducing its energy consumption by ~33% during simulated time.
- A design tool has been produced to facilitate the work of control engineers in enhancing the energy efficiency of buildings with better control.
- The development of prediction models in buildings contexts is complex. Future work could include the use of methods such as artificial intelligence to facilitate this process.

Acknowledgements
- This project was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC).

Methodology
1. Produce prediction models to represent:
   a) The thermal behaviours of the test case building;
   b) The impact of the decisions on the HVAC system.

\[
\begin{align*}
W_{\text{int}} &= m_c \left( T_{\text{in}} - T_{\text{out}} \right) / \eta_i \\
W_{\text{conv}} &= m_c \left( T_{\text{in}} - T_{\text{out}} \right)
\end{align*}
\]

2. Develop an optimisation process to find the best operation points.

\[
J_{\text{cost}} = W_{\text{conv}} + \sum_{j=1}^{i=1} (\Delta T_{\text{m,j}} + \Delta T_{\text{f,j}}) + \sum_{i=1}^{j} W_{\text{HVAC,j}}
\]

3. Test the MPC on the numerical model of the test case.
4. Analyse energy efficiency performance results.
5. Produce a novel design tool for engineers to estimate performance based on the defined optimisation process.