Preliminary Results of Model Predictive Control of Shading Systems.

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Abstract

Shades in buildings are widely installed and are an effective technique for managing solar gains and occupant comfort. A model of a typical office space located in Ottawa, Ontario has been created and the model was developed for analysis under variable conditions. Analysis has resulted in the generation of an advanced reactive system facilitated by the use of the energy management system (EMS) built within EnergyPlus along with a predictive control system optimized for the minimizing of the energy demand by the office space. The approach to optimization is done through the use of a basic model predictive control facilitated by the use of MATLAB (Mathworks 2011) and EnergyPlus (DOE 2012). The predictive system at this stage is delivering reductions of 5% during shoulder season over its reactive counterpart but this work is still on-going.

1. INTRODUCTION

Window shading systems are installed in most commercial and residential buildings in some variety. Very rarely are these systems automatically or optimally controlled. The shade's position and movement is often determined by a user (or users) and is a function of the level of light, presence of glare, occupant position relative to the window or previously determined position preferences (Reinhart and Voss 2003). The optimal control of blinds is known to be able to reduce utility loads by 10-30% while increasing the time occupants are able to spend with a maximized view of the outside (Lee et al. 1998). The fundamental problem with manual shades is that people use them to alleviate discomfort (glare) but then they rarely re-open them and meanwhile rely on electric lighting (O'Brien et al. 2012). Due to the added cost and complication of motorized shading controls, the adoption of advanced shading technology has been slow outside of niche markets and advanced applications.

The increased availability and capability of dynamic computer simulation techniques of a building's performance provide a possible strategy for finding the ideal balance between the often-conflicting benefits from modern design and the comfort of the occupants.

1.1. Background

Numerous studies have examined the effects of shading on the utility load of buildings and the role that occupant interaction with the shades has on loads. Groups have attempted to ascertain patterns and control strategies that better mimic and model the usage of the shades by the occupants in order to better understand and predict a building's energy performance (May-Ostendrop et al. 2010, Rijal et al. 2008). Much of the recent work investigating at different methods of building control and their subsequent effects has been based on the utilization of model predictive control (MPC). Model predictive control is an advanced technique for optimizing control by predicting model behavior for a short period of time in advance and applying a cost function, which is to be minimized. Its adoption in building sciences has been a result of MPC's ability to extract benefits from system with slow reaction to changing variables (Ma et al. 2010, Ma et al. 2011, Corbin et al. 2012, May-Ostendrop et al. 2010). These authors all attempted to use MPC for building optimization but their approach and factors are highly varied. The major differences include the approach to the developing of the building model. Some utilized simplified models (Oldewurtel et al. 2012, Ma et al. 2010), while others rely on complex simulation tools (May-Ostendrop et al. 2010). The other major difference lies in what functions were used for optimization, i.e., whether cost, the amount of energy or other quantifiable costs were used.

The use of shades has long been known as an effective means of controlling glare, which effects occupant comfort, while allowing for occupants to maintain views and natural light. Recently there has been a change in thinking regarding the level of daylight that occupants require along with the increased motivation for using daylight and solar gains as a method of reducing the overall utility demand of the space (Tzempelikos and Athienitis 2007). In order to effectively manage solar gains, control must not be limited to only a reactive system (i.e., a system that acts once a condition has changed). Due to the thermal storage and, consequently, the delay in thermal effects a predictive system that can act proactively on a space is required.

1.2. Motivation

Past studies have focused on the ability of a system to be optimized in terms of overall cost either by minimizing the loads or by making informed decisions in advance. This allowed alternative and less energy demanding solutions to be utilized (Oldewurtel et al. 2012). Investigation into the potential of MPC as an actual means of control often overlooks the complex aspects of whether or not occupants will be satisfied with these sorts of systems because ultimately their interactions will be what determines whether or not this method will actually will be able to achieve the intended benefit.

2. APPROACH

The research approach used to date when studying MPC has relied on two major components: (1) an accurate model and (2) an efficient control technique. Work was started on the modelling of an existing office space that would be readily available later for measurement and experimentation of control strategies derived from its model. Using SketchUp (Trimble 2012), a geometrical model (see Figure 1) was designed for a west-facing office with a shading extrusion similar to the Delta Controls Lab found on Carleton University's campus in central Ottawa, Ontario.

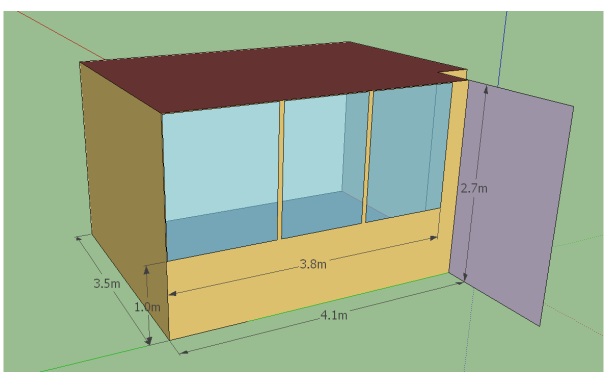

Figure 1. SketchUp model of the typical office space used in simulations.

The model has constructions for a common building in zone 6 given by OpenStudio (NREL 2012). The window system was altered to better reflect the actual windows of the office based on preliminary measurements of their performance.

This geometry was used as the basis for configuring an input for an EnergyPlus IDF file. The effectiveness of shades was initially investigated using an ideal loads HVAC system with interior walls treated adiabatically (for simplicity), a zone sensible heat capacity multiplier to account for room contents and a scheduled temperature and light profiles standard to EnergyPlus which are derived from ASHRAE standard 90.1 (ASHRAE 2010). For the reactive system, the parameters included in the investigation were incident solar energy on the surface and exterior temperature. The shades were a binary system and could only be considered as fully open or fully closed. Using MATLAB as a call manager to EnergyPlus, data analysis system and file writer, a brute force approach using all combinations for thresholds values, with shades only deployed when both setpoints were exceeded. Values from 0^oC to 30^oC (in 1^oC increments) for the exterior temperature and 0 W/m^2 to 1000 W/m^2 (in 50 W/m^2 increments) for incident energy were run in an annual simulation to determine which combinations resulted in a minimum total utility loads (heating, cooling and lighting). The results from the analysis were considered the best set points for a reactive-based system. Based off these results the set points were concluded to be at 15^oC and 150 W/m^2.

The reactive system was added to through EMS that is imbedded within EnergyPlus. Through EMS the user has the ability to write and include custom pieces of code. Of particular use is its ability to create custom sensors and actuate systems used in the model. The system of interest to be actuated here was the shades. Using EMS allowed the number of adjustments to be limited to only once per hour in order to match the limitations of the input schedule used by the predictive system. The EMS controls were used to actuate the shades to close at night, determined as periods when no solar energy was incident on the window's surface. The inclusion of this condition was based on the idea that in a commercial application the building would most likely have been scheduled to have the blinds closed during the night in order to conserve heat at night in winter.

2.1.1. 24-hour prediction horizon with single hour based analysis

The predictive system was facilitated using MATLAB to run the simulation through DOS commands as well as to write to a file that was used as a schedule for the EnergyPlus input. MATLAB ran an EnergyPlus simulation for a given number of days (not including warm-up periods) with the shades both open and closed in the first hour. MATLAB imported these results from the exported comma separated vale (CSV) file and determines which circumstance gave the minimum load for the first hour and assigned this value to a shade position schedule file that EnergyPlus imports every time it is called. This process was repeated for every hour during the time period in question. This initial scheme came with two major flaws. First, the utility minimums came with no discretion of what the comfort or the internal conditions were like. For example, the system would suggest closing the blinds for the majority of the time and rely on artificial lighting. Secondly, the limitation of only using single hour analysis was that though minimal hourly loads were taken into consideration, the true benefits of predictive simulation were left being unutilized, namely that preconditioning and use of the thermal lag of the space was not being investigated. As a result of this, there were times at which the reactive control-based system was out-preforming the predictive system through sets of circumstances in the daily weather profiles.

2.1.2. 24-hour prediction horizon with multiple hour based analysis

In order to correct and develop a more effective control strategy, both aforementioned limitations were corrected. It was concluded that a second condition needed to be introduced and the basic metric for this was the amount of energy used by the space with the inclusion of the lighting energy.

In order to make the system utilize more benefit from MPC, a variable length 'floating window' was included. In this configuration every possible shade combination was investigated over a floating window of N hours in order to determine the minimum utility load over the duration of the window. Instead of two simulations per hour, the system looked at 2^N simulations. The results of a sensitivity analysis showed that with only the two possible shade positions the effectiveness of a floating window length diminished after five hours for simulations run during different months of the year. Results for a day of simulations in both September and June can be found in Figure 2. The data illustrates that the total utility loads (heating, cooling and lighting) decreases as the length of the floating window increases. A six hour window was selected as a longer window provided minimal decrease to the loads.

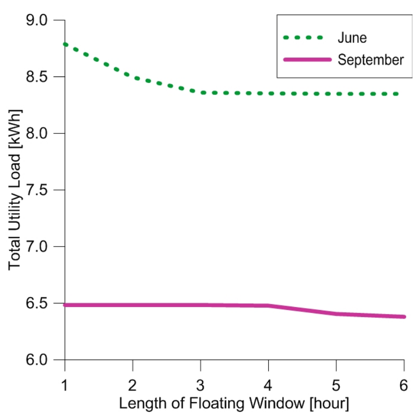

Figure 2. Results from simulations for the month of June and September using different floating window lengths.

The results from simulations for the month of September, which is typically considered a shoulder season (i.e., not predominantly a cooling or heating season), are shown in Figure 3.

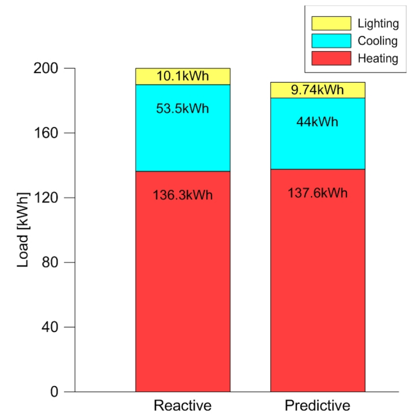

Figure 3. Results from simulations for the month of September using Ottawa weather.

A shoulder season was selected because of its particularly large temperature swings during the day and overheating is particularly problematic. The results show a savings of approximately 5% from the reactive controls described previously. The reactive control alone would represent a significant increase when compared to the manual intervention typically relied upon as a control. The energy savings come from a 20% decrease in the cooling loads, however these reductions came at an increased use of heating and lighting. These results agree with the trend found when investigating the optimal set points for the reactive control. That analysis had indicated that this particular model was cooling dominated in terms of loads and would be where most savings could be extracted.

When the shading decisions are compared, the increased lighting and heating can be explained by the predictive system making decisions proactively that saved the cooling energy later in the day. The remedy to prevent this overheating was the closing of shades earlier in the day that would put more energy usage in both electric lighting and heating for a short duration. A future extension to these results would be the inclusion of a weighting factor to the three forms of energy usage since often some are electric grid based while others are natural gas or steam generated. This means either additional monetary costs or environmental ones could be considered.

3. DISCUSSION

The work to date is a starting point for future investigation. The latest iterations of predictive analysis have shown, like other studies had previously, that MPC is a possible method for decreasing the utility load required by a zone even over an optimal reactively controlled system.

It should be noted that the results of this study are unique to the office geometry and model. For example, as the thermal properties of the office change and more or less thermal mass is introduced the lag in conditions will increase and decrease respectively which will change the appropriate length to the floating window. Similarly if the office had a different window to wall ratio, different window construction, such as low-e coating, or faced a different orientation the amount of solar gains would change, as would their effects to the office space.

When examining the shading position (open or closed) that the predictive system recommends, it is possible to find conditions that the reactive system does not account for. In particular, the predictive system will trigger before a reactive system would be able to, in order to delay overheating conditions and limit the dwell of overheating. During the night the system is able to consider the temperature decrease and can exploit it to precool the structure. The extended windows is able determine if the precooling is an advantageous technique considering any potential increase in the energy required to condition the space when the building begins to be heated for occupied periods.

4. CONCLUSION

This work confirms the initial conclusion that MPC is a possible solution for advanced control in buildings. Initial research shows that this simplified approach would be able to reduce the amount of energy used by an office. Much of this work shows effectiveness in principle, but elements are not optimally conditioned in many ways. In particular, the current methodology does not take into account occupant comfort within the zone or the potential interaction of the occupants with the shades based on their preferences. Further the ability for these systems to be incorporated into real world settings along with the feasibility of this work needs to be investigated.

Acknowledgments

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