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REDUCED-ORDER ENERGY MODELING IN RETRO-COMMISSIONING: A CASE STUDY OF AN ACADEMIC BUILDING

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ABSTRACT

This case study investigates the potential energy savings in retro-commissioning an existing building on the University of Virginia's campus using a reduced-order energy model. The retro-commissioning is focused on HVAC operation, including ventilation reduction and air terminal unit operation. The potential energy savings from the retro-commissioning's recommended measures are evaluated in a building reduced-order energy model. Prior to the evaluation, the energy model is iteratively calibrated using the building utilities data based on ASHRAE Guideline 14 to ensure accuracy. Based on the reduced-order energy model, the recommended measures result in more than 11% savings in energy cost annually.

INTRODUCTION

Rouss Hall, located on the campus of University of Virginia in Charlotesville, VA, originally opened in 1898. It went through major renovation along with the construction of the adjoining Robertson Hall in a project started in 2005. Rouss-Robertson Hall is an academic building and home for McIntire School of Commerce. It is 156,000 square feet of classrooms, computer labs, faculty offices and common spaces.

The design efforts of the Robertson Hall and major renovation of Rouss Hall started in early 2000s. The building is connected to campus chilled water and steam for cooling and heating. The main mechanical system is VAV with reheat. There are three manifolded air handling units (AHUs) with total designed supply airflow of 146,490 cfm serving most of the spaces. Classrooms are served by series fan powered terminal units (FATUs). There are fan coil units for certain electrical or IT rooms, and there are cabinet unit heaters (CUHs) serving vestibules at the entrances.

According to the basis of design documents, the mechanical ventilation system was designed based on ASHRAE 62 1989. That ASHRAE document requires 20 cfm of outside air per occupant in the building. Moreover, the number of occupants were assumed to be more than 2,300 people. With these assumptions, the mechanical design required the minimum outside air of 51,300 cfm for the building.

The newer versions of ASHRAE ventilation standard require much less outside air. For example, ASHRAE 62.1 2010 requires 5 cfm per person and 0.06 cfm per square foot for an office space. Moreover, based on the owner's information, the current building occupants are about 1400 people at peak, many less than the design assumption of 2300 people. In summary, the new less conservative ventilation requirements and less occupants were the main incentives to study a new minimum ventilation requirement for the building.

Lowering the system ventilation requires resetting minimum airflow setpoints of air terminals. Lowering the air terminal flow setpoints can lower the system ventilation. However, setting the setpoints too low can cause low system ventilation efficiency and high system ventilation rate (Cho et al. 2009). Resetting the minimum airflows from 30% to 20% in a typical DOE benchmarked energy model results in up to 30% annual energy savings (Zhang et al. 2014).

Based on the potential in the ventilation reduction and some operational improvements, this study recommends certain Energy Conservation Measures (ECMs). Next, these ECMs are evaluated in a simplified energy model, known as reduced-order energy model. Reduced-order energy models represent the general thermo-physical propoerties of a building with limited number of influential variables, including building geometry, mehanical systems, main space types, outside conditions, and thermal zones (Heidarinejad et al. 2017). The building exterior and the exterior zones are modeled in significant amount of details. In general, spaces are lumped in single zone if they are thermally similar. The schedules, temperature setpoints, and mechanical system are ususally modeled in details (Mancini et al. 2016).

The reliability of energy modeling for retro-commissioning is limited due to the many assumptions including occupancy (Li et al. 2015). To move toward accuracy, the energy model is calibrated with the actual utilities data. The calibration is met under criteria from ASHRAE Guideline 14 2002 Measurement of Energy and Demand Saving. The two criteria suggested by the guideline are Coefficient of variation of the root mean square error (CVRMSE) and Normalized mean bias error (NMBE). The energy simulation results shall meet CVRMSE and NMBE of less than 15% and 5%, respectively, in monthly calibration data. Various studies have tried to classify influential variables to reach the best calibration framework (Yang et al. 2015, Royapoor et al. 2015).

This study evaluates the potential for a dual minimum airflow setpoint for air terminals in an existing building. The dual minimum setpoint takes away the low system ventilation efficiency problem for low ventilation setpoints. Moreover, the evaluation is not based on a typical energy model. The novelty of this study is that it measures the dual minimum setpoints in a calibrated reduced-order energy model, along with some other ECMs.

The scope of this study is defined only around this building and it does not include any data or information about the campus or other buildings on campus.

APPROACH

At the existing conditions, the air terminal units have scheduled with two setpoints for the supply airflow, one maximum airflow for peak cooling condition, and one minimum airflow for peak heating condition or non-peak hours. To improve building performance, instead of one minimum airflow setpoint, two new setpoints can be set for the minimum airflows, serving two different conditions. As the building outside air is going to be reduced based on the new code, the minimum ventilation required for each space is going to be reduced, as well. The supply air flow from terminal units operating at non-peak conditions can be reduced to the minimum space ventilation, called minimum-minimum setpoint. At peak heating conditions, the terminal units need to supply and reheat more air to meet the space heating load, creating the unit minimum-maximum conditions.

There are some other factors that influence the building energy consumption that were looked in this study. The fans at series fan powered terminal units operate non-stop day and night. We evaluate the operation of these terminal units in separate ECMs and recommend new sequence of operation.

This study seeks other opportunities in the building operation for more energy savings, too. The operation of CUHs, and the sequence of operation in Reading Room and Pantry Room are discussed separately.

Based on the background presented in the introduction, this study has set the following objectives:

- Provide new outside air requirements for all the AHUs based on the space-by-space ventilation calculations.
- Provide space-by-space minimum-minimums, and minimum-maximum setpoints for air terminal units to maintain minimum required ventilation and heating airflows, respectively.
- Evaluate series fan powered terminal unit operation, and provide recommendations, and updated sequence of operation.
- Create reduced-order energy model based on the existing drawings.
- Calibrate the energy model with utilities data based on ASHRAE Guideline 14 2002 iteratively.
- Provide potential energy cost savings from the recommended measures using the energy model.

This study considers space-space ventilation requirement based on ASHRAE 62.1 2010, and finds the total system minimum outside air requirement. This calculation considers the number of occupants based on the furniture count in each space. The building exhaust rate is also considered. Knowing the space minimum ventilation requirement and minimum air terminal unit threshold for supply airflow, minimum-minimum setpoints are determined. New load calculation model is run in Trane Trace 700 for the heating condition. Based on the load calculation in the heating mode, new minimum-maximums are determined for air terminal units to meet the heating loads. The amount of savings from reduced outside air is estimated by the reduced-order energy model.

The fan powered boxes are looked at separately to find better sequence of operation. The operation in other rooms are seen separately for further savings opportunities.

The reduced-order energy model is created in Openstudio 2.3.0, running EnergyPlus 8.8.0 engine. OpenStudio gives flexibility in setting geometry and mechanical systems quickly using pre-built measures.

Assumptions

- The ASHRAE 62.1 version 2010 is the basis for the ventilation calculations in this study.
- The As-built drawings were used for the building geometry and furniture count.
- The furniture count is the basis for the zone population (P_z). The private offices are assumed to

have one occupant each, except dean's office on the top floor. The dean's office is assumed to have furniture count as the number of occupants.

- The total number of occupants (P_s), named system population in ASHRAE 62.1, is assumed to be 1400 people, given by the owner.
- In the load calculation, the winter heating design day is based on 99.6% coverage which is at 14.7 °F.
- The building operation in cooling mode, or terminal unit maximum flows are out of scope.
- The air terminal units are assumed to operate as low as 20% of the maximum flow in minimum-minimum setpoints, if other restrictions allow.

RESULTS

System Ventilation Calculation

S A complete space-by-space ventilation calculation is done. The summary of the calculations is shown in Table 2. There are 19 spaces on demand-control ventilation (DCV) which 16 of them are served by FATUs. Those spaces are considered regular spaces in the system ventilation calculations; however, they are separately considered in the ATU and FATU schedules for more

Table 1 ASHRAE 62.1 Calculations Summary

Parameter	Definition	Value	Dim
Ps	System Population	1,400	
Σ Pz	Sum of Zones Population	1,835	
D	Occupant Diversity	76%	
Σ Rp . Pz	Sum of OA Required Based on People	12390	cfm
Σ Ra . Az	Sum of OA Required Based on Area	6,153	cfm
Vou	Uncorrected Outside Air Intake	15606	cfm
Vps	System Primary Airflow	146490	cfm
Xs	Uncorrected system OA fraction	0.11	
Zp	Critical room OA fraction	0.48	
Ev	System Ventilation Efficiency	0.63	
Vot	Required Outside Air Intake	24796	cfm
	System Exhaust Air by Exhaust Fans	24595	cfm
	Added 10% Pressurization to Exhaust Air	27055	cfm
	Proposed Minimum Outside Air	**27300**	**cfm**

outside air turndown. A new load calculation was run in Trane Trace to find heat loss at each zone based on 99.6% ambient temperature of 14.7°F. Furthermore, the new heat loss at each zone was used to find the required heating airflow. The existing design sensible and latent cooling loads are used as the primary cooling airflow is not going to change. The space cooling and heating setpoints are assumed to be 76°F and 70°F, respectively. The maximum supply air temperature in winter is assumed to be 90°F. The ASHRAE required outside air is calculated for each space based on the space population and the area. The space types are mainly assumed ASHRAE office or classroom. Computer labs, pantry, and mechanical or electrical rooms are among the other space types considered in the calculations. The zones are assumed to have zone ventilation efficiency of E_z=0.8, based on Table 6-2 in ASHRAE 62.1. To find the system required outside air, first an uncorrected outside air intake V_{ou} is calculated based on the zone area and population rates. The total of zone outside air over the system primary airflow equals system outside air fraction X_s. The zone with the highest outside air fraction, called critical room, along with X_s determine the system ventilation efficiency E_v. This efficiency is used to find the total required outside air intake V_{ot}. The building exhaust through exhaust fans in spaces such as restrooms and IT closets is considered. The required outside air intake and the building exhaust are close. We have assumed 10% of exhaust air for pressurization. The proposed final minimum outside air is 27300 cfm.

Air Terminal Unit Dual Minimum Setpoints

After finding the new minimum system ventilation, the study focuses on the terminal unit settings. One objective of the study is to set two minimum airflow setpoints for air terminal units. One setpoint represents the minimum ventilation requirement called minimum-minimum (min-min), and one setpoint represents the required airflow for heating conditions, named minimum-maximum (min-max). By operating at two minimum airflows, the building uses the best opportunities for savings at non-peak conditions.

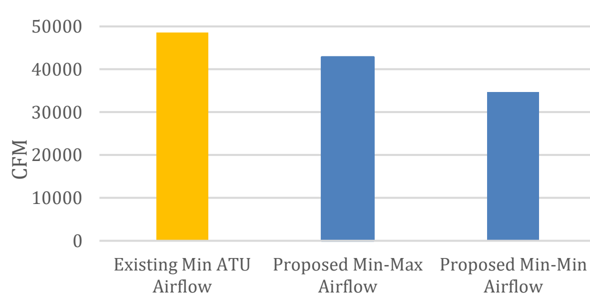


Figure 1 Sum of Air Terminal Units Minimum Airflows

The minimum-minimum and minimum-maximums are calculated in the space-by-space ventilation calculation. Based on these values, new air terminal schedules developed. The new air terminal schedules are in *Appendix 2*. The zone min-min and min-max might be different from the zone min-min and min-max. The reason is that multiple terminal units might serve a zone, or the terminal unit reach the unstable operation region under a limit if it heads operates at the zone's min-min. The minimum terminal unit airflow limit was also considered based on Titus Model ESV construction submittals. For the reheat coils, the amount of capacity used and the leaving air temperature from the coil are estimated. The chart below compares the proposed min-min and min-max setpoints with the existing minimum setpoint. The total min-min and min-max airflows are 30% and 12% lower than the existing total ATU minimum airflows, respectively.

Series Fan Powered Terminal Units Operation

The fan powered boxes are not included in the chart above. The existing fan powered units use a constant volume fan, recirculating the room air and mixing it with the primary air. The primary air supplied by the AHUs modulates between minimum and maximum setpoints. The unit operates with the minimum primary air either at the time of heating or the time no cooling is needed. On the call for outdoor air from CO_2 sensor, or cooling from thermostat, the primary air reaches the maximum setpoint. Based on the unit capabilities, this study suggests no change to the unit operation during occupied hours. However, there is the possibility to shut-off the fan powered units in the unoccupied mode. Accordingly, this study suggests a new sequence of operation for the units in the unoccupied mode.

The proposed sequence of operation for unoccupied mode requires new cooling and heating setpoints for zones served by fan powered units. The suggested cooling and heating setpoints are 60°F and 80°F, respectively. Basically, this sequence of operation recommends shutting off the unit and the primary air unless the room temperature goes beyond the unoccupied mode temperature setpoints. Moreover, the heating in unoccupied would be with no primary air. The cooling in unoccupied mode is like occupied mode with the only difference of higher temperature setpoint.

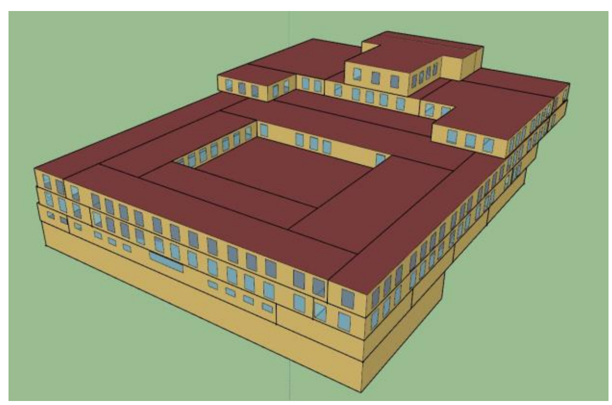
Minor Measures

In the retro-commissioning process, minor problems were found, including the CUH and air terminal units competing each other at vestibules. Moreover, there was potential in exhaust air turn down in the kitchen and the adjacent reading room, which was formerly a dining hall.

Reduced-order Energy Model Setup

The as-built drawings of the buildings were used to draw the geometry floor by floor in SketchUp with OpenStudio Plugin. The general layout of the building is considered. The resulted energy model resembles the exterior zones and surfaces as shown in *Figure 2*. The windows, including location and size are considered in details. This energy model combines similar spaces into single thermal zones, unless they are thermally different, as shown in *Figure 3*. For example, offices on one side of the building perimeter are combined. Shafts and elevators are ignored. Space types are reduced to main categories, including offices, classrooms, computer classrooms, corridors, pantry, mechanical room, electrical or IT room. The construction is assumed to be based on ASHRAE 90.1 2007. Some setpoints and schedules are estimated. The building maximum number of occupants is 1400 in the model. ASHRAE system 7 VAV with reheat is used as the mechanical system.

(a)

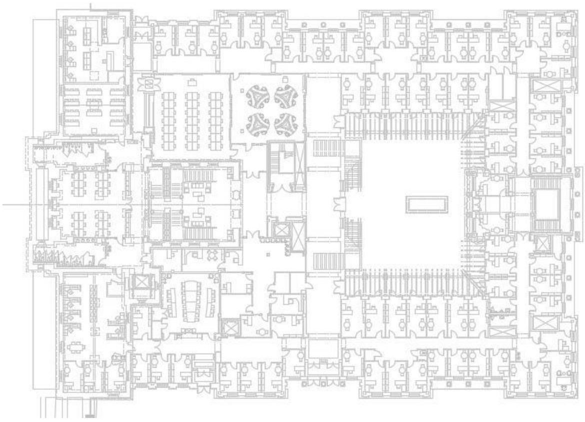


(b)

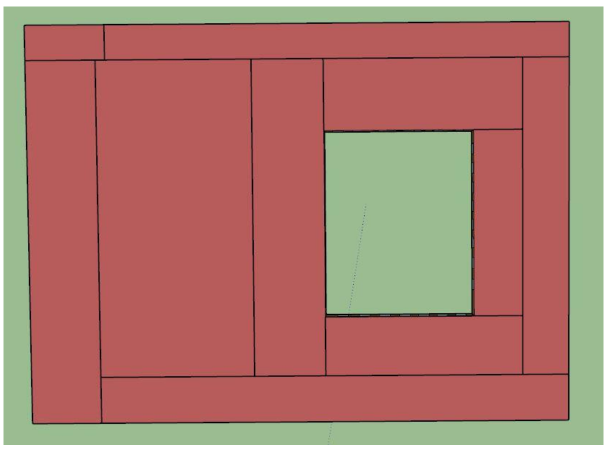
Figure 2 (a) Bird-eye view of Rouss-Robertson Hall (b) The Reduced-order energy model in Openstudio

Energy Model Calibration

The calibration in this study was based on the judgement and an iterative process to meet the ASHRAE Guideline 14 requirements. The parameters that were revised in the



(a)



(b)

Figure 3 (a) The as-built drawing of a floor (b) The energy model layout of the same floor

calibration were mainly the schedules. The winter and spring breaks have less equipment, lighting, and occupants load. Moreover, summer months require their own schedules because of the different academic semester. There were minor changes to the mechanical system, mainly the humidifier, to represent the design documents. The calibration criteria for electricty and campus chilled water based on the utilities data in 2017 are in Table 2. The steam is not investigated as there are concerns about the steam and heating system health. The discrepancy between the model and the metered data was a significant alarm for the hot water system.

Table 2 Calibration Criteria

Criteria	Chilled Water	Electricity	Limit
CVRMSE	11.0%	5.5%	< 15%
NMBE	3.7%	-3.5%	< 5%

Average utility rates for electricity, steam and chilled water are used as \$0.08/kWh, \$21.3/MMBtu, and \$16.1/MMBtu, respectively.

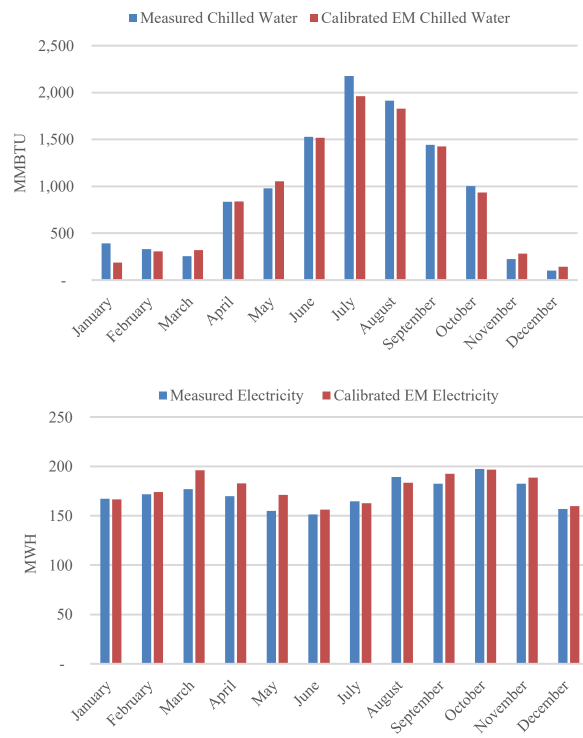


Figure 4 The electricity and chilled water measured vs. the calibrated energy model in 2017

Potential Energy Cost Savings

Based on the prior results, the following ECMs are listed:

1. System ventilation reduction
2. Air terminal unit dual minimum setpoint
3. Fan powered terminal unit unoccupied shut-off

The system ventilation reduction is simply set as hard sized minimum outdoor air requirement for the air system in OpenStudio. For the dual minimum setpoints, as the number of spaces is not the same between the design terminal units and the energy model, some simplification was required. This study has found the total fraction of minimum supply airflows to the maximum supply airflows before and after this ECM. The same fraction of minimum airflow is assigned to all terminal units in the energy model. For the fan powered units, they are scheduled to be off at nights. An electric load represents the constant-volume of the fan in the fan powered units during normal operation. The electric load is representing the fan is estimated based on the design documents and the area of the classrooms in the energy model.

The utility rates are based on the values given by campus. The total energy cost savings is equivalent to about 11% of annual building energy cost.

Table 3 Summary of ECMs

ECM #	Potential Annual Savings			
	Electric (kWh)	**Steam (MMBtu)**	**Chilled Water (MMBtu)**	**Monetary**
1	-	560	3213	$40,141
2	41282	209	299	$12,632
3	10976	129	72	$3,029
Sum	52258	898	3584	$55,793

CONCLUSION

This study has investigated the potential savings in retro-commissioning of an academic building with the focus on HVAC operation, including ventilation reduction and terminal unit operation. The case study includes a reduced-order energy model calibrated based on ASHRAE Guideline 14. The ventilation calculations based on ASHRAE 62.1 2010, setting dual minimum setpoints for the air terminal units and unocupied mode shut-off of fan powered boxes bring about 11% energy cost saving based on the calibrated energy model. In a nutshell, the reduced order energy model was well capable of estimating the recommended measures of retro-commissioning.

ACKNOWLEDGMENT

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