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Modeling and Simulation of HVAC Faulty Operations and Performance Degradation due to Maintenance Issues

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ABSTRACT

Almost half of the total energy used in the U.S. buildings is consumed by heating, ventilation and air conditionings (HVAC) according to EIA statistics. Among various driving factors to energy performance of building, operations and maintenance play a significant role. Many researches have been done to look at design efficiencies and operational controls for improving energy performance of buildings, but very few study the impacts of HVAC systems maintenance. Different practices of HVAC system maintenance can result in substantial differences in building energy use. If a piece of HVAC equipment is not well maintained, its performance will degrade. If sensors used for control purpose are not calibrated, not only building energy usage could be dramatically increased, but also mechanical systems may not be able to satisfy indoor thermal comfort. Properly maintained HVAC systems can operate efficiently, improve occupant comfort, and prolong equipment service life.

In the paper, maintenance practices for HVAC systems are presented based on literature reviews and discussions with HVAC engineers, building operators, facility managers, and commissioning agents. We categorize the maintenance practices into three levels depending on the maintenance effort and coverage: 1) proactive, performance-monitored maintenance; 2) preventive, scheduled maintenance; and 3) reactive, unplanned or no maintenance. A sampled list of maintenance issues, including cooling tower fouling, boiler/chiller fouling, refrigerant over or under charge, temperature sensor offset, outdoor air damper leakage, outdoor air screen blockage, outdoor air damper stuck at fully open position, and dirty filters are investigated in this study using field survey data and detailed simulation models. The energy impacts of both individual maintenance issue and combined scenarios for an office building with central VAV systems and central plant were evaluated by EnergyPlus simulations using three approaches: 1) direct modeling with EnergyPlus, 2) using the energy management system feature of EnergyPlus, and 3) modifying EnergyPlus source code. The results demonstrated the importance of maintenance for HVAC systems on energy performance of buildings.
The research is intended to provide a guideline to help practitioners and building operators to gain the knowledge of maintaining HVAC systems in efficient operations, and prioritize HVAC maintenance work plan. The paper also discusses

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challenges of modeling building maintenance issues using energy simulation programs.

KEYWORDS
Building energy use, Building simulation, EnergyPlus, Fault modeling, HVAC maintenance

INTRODUCTION

Almost half of the total energy used in the U.S. buildings is consumed by heating, ventilation and air conditioning (HVAC) according to U.S. Energy Information Administration statistics. For too long, high efficiency design and optimum operational controls to improve energy performance of buildings have been the focus, and deficiencies in building operation and maintenance have been neglected. In fact, among various driving factors to energy performance of building, operation and maintenance play a decisive role. HVAC maintenance keeps plant and HVAC equipment in a healthy state in which HVAC system can function properly. This also includes troubleshooting of defective equipment to perform the intended function in a cost efficient manner, thus extending life serving time. Mill (2009) identified a wide diversity of system deficiencies and report frequency of system deficiencies for existing building and new constructions. The study also found that the most common problems were in air-handling and distribution systems for existing buildings.

Different practices of HVAC system maintenance can result in substantial differences in building energy use, maintenance costs, and equipment life. Based on discussions with HVAC engineers, building operators, facility managers, and commissioning agents, and literature review on maintenance standards (ASHRAE 2008, 2012; CIBSE 2008), maintenance practices for HVAC systems can be categorized into three levels depending on the maintenance effort and coverage:

1) proactive maintenance

The performance-monitored maintenance represents the good practice. The system operation problems can be identified and repaired before a failure occurs. It allows the maintenance manager has control over maintenance.

2) preventive, scheduled maintenance

This practice represents the average practice (business as usual). In this practice, maintenance is scheduled over time. For example, a filter in an air handler unit is replaced every 6 months. Preventive maintenance program may take too long to demonstrate results or fail to justify its cost.

3) reactive, unplanned maintenance

This maintenance repairs or replaces equipment only when it fails and investigates system performance issues based on occupants’ complaints. It is often practiced by facilities that are significantly understaffed and underfunded.

Table 1 summarizes the three practices of HVAC maintenance and their implications on equipment operating efficiency and energy use, equipment life, short term maintenance cost, and life cycle cost including maintenance cost, energy cost, and equipment replacement or repair cost. The good practice will lead to lowest life cycle cost, while the bad practice seems to save short term maintenance cost, it will result in the highest life cycle cost.

Table 1. *Three types of HVAC maintenance practices*

Maintenance Practice	Description	Equipment Efficiency	Operating Energy	Equipment Life	Short-Term Costs	Life Cycle Costs
Reactive (Bad)	Deferred or no maintenance, "run to fail".	Low	High	Short	Low	High
Preventive (Average)	Scheduled maintenance, periodic inspection, cleaning, and adjustment.	Medium	Medium	Medium	Medium	Medium
Predictive (Good)	Use periodic measurements to detect evidence that equipment is deteriorating and to avoid failing.	High	**Low**	Long	High	**Low**

Investigating the impacts of HVAC maintenance issues on building performance is a complicated research subject. The research requires not only on a good understanding of common practices on maintenance issues but also modeling techniques to simulate operation deficiencies. Most building energy simulation programs available today have limited capabilities of directly modeling HVAC operational faults or maintenance issues which occur in almost every building. Basarkar *et al.* (2012) implemented four types of equipment faults in a development version of EnergyPlus to simulate common faulty operation in building systems. The purpose of this study, reported here, is to continue previous research on fault modeling, develop modeling and simulation methods for maintenance issues and assess the impacts of common maintenance issues on building performance.

TECHNICAL APPROACH

EnergyPlus is used as the simulation tool in the study for modeling maintenance issues. EnergyPlus, developed by U.S. Department of Energy, is an open-source whole-building energy simulation program built upon sub-hourly zone heat balance and integrated solutions of building loads, HVAC systems, and central plant equipment. Three different approaches using EnergyPlus, in order of difficulty, are used to model HVAC maintenance issues:

1) Direct modeling with EnergyPlus (Direct Modeling)

Maintenance issues are directly modeled using existing inputs (either design input parameters or performance curves) in the current version of EnergyPlus. This modeling approach can be applied to such maintenance issues as supply air sensor offset, zone thermostat offset and outdoor air damper leakage. This approach is also applied to model simplified maintenance issues such as chiller or boiler fouling by introducing a degradation factor to the chiller or boiler efficiency inputs to the EnergyPlus models. The advantage of this approach is easy implementation.

2) Using the energy management system (EMS) in EnergyPlus

EMS is an advanced feature of EnergyPlus and designed for users to develop customized high-level, supervisory control routines to override specified aspects of EnergyPlus modeling in the EMS program. The EMS feature in EnergyPlus is flexible to allow users to simulate equipment operating with some maintenance issues by overwriting or adding algorithms in EnergyPlus within the specified aspects of current EMS capability. Use of EMS feature may require advanced knowledge of EnergyPlus and computer programming. EMS is used to model maintenance issues like dirty filters which increase pressure drop across the filter with operating hours.

3) Modifying EnergyPlus source code (Modified Code)

Modifying the existing EnergyPlus source code, the third modeling approach, is used when both direct modeling and EMS approaches cannot be applied to simulate any particular equipment or system deficiencies. This approach requires users to have a thorough understanding of the existing EnergyPlus source code and to write your own custom computer program based on existing code. Such HVAC maintenance issues as cooling coil fouling, outdoor air and return air temperature sensors offset adopt the third approach.

SAMPLED HVAC MAINTENANCE ISSUES

A list of common HVAC maintenance issues are reviewed and selected for the initial modeling and simulations. Based on literature reviews and our understanding of the physics and implications for each maintenance issues, we developed corresponding models and simulation approaches. Table 2 lists the issues with their potential impacts and modeling approach according to maintenance types, including sensor calibration, filter replacement, heat exchanger treatment, mechanical repair and refrigerant charge, are investigated using detailed simulation models.

Each maintenance issue list in Table 2 was modelled using EnergyPlus. A description of the implement model for selected maintenance issues is as follows.

<u>Temperature sensor offset</u>

Control sensors such as supply air temperature (SAT) sensors, zone thermostats, and outdoor air temperature (OAT) sensors may be out of calibration over a long term operation period. In this study, it is assumed that temperature sensors are offset by ±2˚C. For example, if a SAT sensor is offset by +2 ˚C and a designed supply air temperature to control is 13˚C, the actual supply air temperature due to sensor offset is 11 ˚C.

<u>Dirty filter</u>

In terms of filter replacement for reactive maintenance, it is assumed that filters in air handler units have not been replaced over a year. Therefore, pressure drop for air handler units has been increased and the maximum additional pressure drop is 500 Pa.

<u>Fouled cooling tower</u>

Cooling towers can become fouled due to unfavourable conditions. The study assumes certain fouling condition that overall heat transfer coefficient is reduced to 85% of design value.

Table 2. List of sampled HVAC maintenance issues

Maintenance Types	**Maintenance Issues**	**Impacts**	**Simulated Scenarios**	**Modeling Approach**
Sensor Calibration	Supply air temperature sensor (SAT) offset	controls, heating and cooling energy	temperature sensors are offset by ±2˚C	Direct modeling, adjust SAT setpoint
	Zone temperature sensor offset			Direct modeling , adjust thermostat settings
	Outdoor air temperature sensor offset			Modified Code, modify the economizer controls
Filter replacement	Dirty filter	pressure drop, fan energy, airflow	additional 500Pa of air pressure drop	EMS, adjust fan power for VAV systems
Heat exchanger cleaning/treatment	Fouled cooling tower	efficiency	overall heat transfer coefficient is reduced to 85% of design UA	Direct modeling, adjust cooling tower UA
	Chiller: fouled tubes	efficiency	chiller COP is reduced by 10%	Direct modeling, adjust chiller efficiency
	Boiler: hard water scale	efficiency	boiler efficiency is reduced by 10%	Direct modeling, adjust boiler efficiency
	Fouled heating /cooling coil	efficiency, comfort	overall heat transfer coefficient is reduced to 50% of design UAs	Modified Code, adjust coils UA
Mechanical repair	Outdoor air damper leakage	heating and cooling energy	30% OAD leakage	Direct modeling, adjust minimum OA flow
	Stuck outdoor air damper (OAD)	heating and cooling energy	OAD is stuck at fully open position	EMS, set constant OA flow
	Clogged OA screen	outdoor air flow is less than 100% during economizer mode thus increasing cooling energy	maximum percent of intake fresh air is reduced to 70%	Direct modeling, set maximum OA flow
Refrigerant charge	Chiller: over or under 10% refrigerant charge	efficiency	chiller COP is reduced by 10%	Direct modeling, adjust chiller efficiency

<u>Fouled Chiller/Boiler/Coils</u>

Fouling on heat transfer surfaces of boiler and chiller increases the thermal resistance and leads to reduced heat transfer. For the scenario of chiller/boiler fouling, both chiller COP and boiler efficiency are assumed to be reduced by 10%. For fouled cooling/heating coils, overall heat transfer coefficients are assumed to be reduced to 50% of design UAs.

Outdoor air damper (OAD) leakage

In the study, it is assumed that OAD leakage level is 30%. When the commanded outdoor air fraction is smaller than the leakage level, leaky damper cannot effectively control the air intake.

Stuck outdoor air damper (OAD)

Stuck OAD due to control and mechanical failure is another common fault in field. In this study, OAD is assumed to get stuck at fully open position. Cooling and heating energy penalties are introduced when outdoor air is not favourable for free cooling.

Clogged OA screen

Outdoor air intake screens may get clogged due to unfavourable locations or weather condition. The maximum percent of intake fresh air is assumed to reduce to 70%.

RESULTS AND DISCUSSIONS

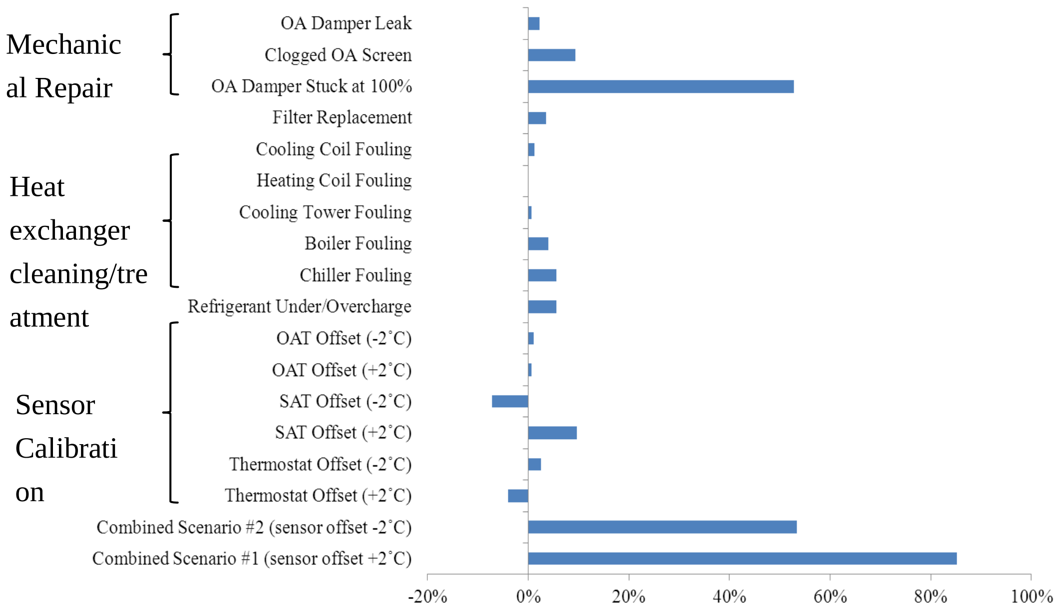

Figure 1. *The impacts of poor HVAC maintenance on HVAC source energy consumption for a large office building in Chicago, USA*

The energy penalty introduced by HVAC maintenance issues varies by a few factors including building and HVAC systems types, vintage (design efficiencies), and climates. In the study, the commercial building reference model (Anon.) for a large-size office building in compliance with ASHRAE Standard 90.1-2004 is used as a baseline representing good maintenance practice. The large-size office building consists of one basement level and 12 floors above ground served by 4 built-up VAV systems with 2 water-cooled chillers and one natural gas hot-water boiler.

The results, shown in Figure 1, demonstrated the energy penalty introduced by the reactive maintenance practice for the built-up VAV system located in Chicago. The percentages are derived by comparing the total source/primary energy use of HVAC systems for the reactive maintenance practice to those of the good practice (baseline reference model). The maintenance issues with significant energy impacts for Chicago are OA damper stuck at 100% position, blocked OA screen, supply air temperature offset, boiler/chiller fouling, and chiller refrigerant under/overcharge. Although there is no significant energy impact due to heating/cooling coil fouling, the numbers of unmet thermal comfort hours for both heating and cooling are significantly increased due to reduced system cooling and heating capacities. Two combined scenarios (#1 and #2) with different temperature sensor offsets were simulated in the study. The overall energy penalty by combining the sampled maintenance issues including sensor offset by +2 ˚C can reach 85% of overall HVAC energy consumption for Chicago climate.

Table 3. *The impacts of poor HVAC maintenance on HVAC end-use energy consumption for a large office building in Chicago, USA*

Maintenance Issues	Cooling/Chiller	Heating/Boiler	Fans	Pumps	Cooling Tower
OA Damper Leak	-0.04%	8.01%	0.00%	0.67%	0.06%
Clogged OA Screen	13.47%	0.00%	-0.01%	14.88%	16.27%
OA Damper Stuck at 100%	0.79%	183.93%	27.20%	11.37%	0.99%
Filter Replacement	0.57%	-1.24%	63.69%	0.82%	0.60%
Cooling Coil Fouling	1.52%	-0.01%	2.49%	4.14%	-0.12%
Heating Coil Fouling	0.00%	-0.62%	0.05%	2.48%	-0.03%
Cooling Tower Fouling	1.36%	-	-	0.00%	0.11%
Boiler Fouling	-	14.71%	-	-	-
Chiller Fouling	10.24%	-	-	1.00%	1.58%
Refrigerant Under/Overcharge	10.24%	-	-	1.00%	1.58%
OAT Offset (+2˚C)	0.57%	1.52%	0.00%	-0.14%	-0.59%
OAT Offset (-2˚C)	1.20%	-0.01%	2.87%	4.10%	-0.18%
SAT Offset (+2˚C)	6.87%	18.08%	-5.05%	12.14%	7.74%
SAT Offset (-2˚C)	-7.71%	-7.37%	13.06%	-14.75%	-8.74%
Thermostat Offset (+2˚C)	3.83%	-29.02%	21.57%	3.77%	5.00%
Thermostat Offset (-2˚C)	-3.05%	22.79%	-25.10%	-5.37%	-1.68%

Table 3 shows the impacts of maintenance issues on HVAC end-use energy consumption for chillers, boilers, fans, pumps and cooling towers. In the table, the value in each cell represents the percentage change of HVAC end-use energy consumption relative to that of the baseline model. If OA dampers in the built-up VAV system get stuck at 100%, heating and fan energy uses increase by 184% and 27%, respectively. As variable speed pumps are used in both chilled and hot water loops, pump energy uses have been increased for fouled cooling and heating coils. Cooling tower fouling causes a small increase in cooling energy use (no pump energy increase as the pump is constant speed in the condenser loop). Outdoor air temperature sensor offset interferes control thresholds for various operation modes of air-side economizers and therefore introduces extra energy use for heating and cooling. Supply air temperature sensor offset by +2˚C introduces about 7% cooling penalty, 18% heating penalty due to increased reheat, 5% less fan energy use due to the reduction of overall air flow rates, which SAT sensor offset by -2˚C reduces cooling and heating energy use by increasing the actual controlled supply air temperature.

CONCLUSION

This study applied three different approaches for modeling common HVAC maintenance issues. Sixteen scenarios on individual maintenance issues and 2 combined scenarios were simulated. The results demonstrated that the combined impacts of the selected maintenance issues on building energy use for a large office building in Chicago climate can reach up to 85% of overall HVAC source energy use due to reactive maintenance practice. Our on-going research focuses on identifying a broader list of HVAC maintenance issues for commercial buildings in various climates, and developing modeling approaches. The research findings can be used to provide a guideline to help practitioners and building operators to gain the knowledge of maintaining HVAC systems in efficient operations, and prioritize HVAC maintenance work plan.

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