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Journal

Building Simulation 2011, Sydney, Australia

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Basarkar, Mangesh

Publication Date

2011-11-01

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Modeling and simulation of HVAC Results in EnergyPlus

Mangesh Basarkar, Xiufeng Pang, Liping Wang,
Philip Haves, Tianzhen Hong Division

November 2011

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MODELING AND SIMULATION OF HVAC FAULTS IN ENERGYPLUS

Mangesh Basarkar, Xiufeng Pang, Liping Wang, Philip Haves, Tianzhen Hong
Lawrence Berkeley National Laboratory, Berkeley, CA, USA

ABSTRACT

One of the big challenges in comparing measured and simulated energy performance of buildings is that most energy models do not capture the significant impact of installation, operational and degradation HVAC system faults on actual energy performance in buildings. EnergyPlus, a comprehensive whole building performance simulation tool, also has limited capability of modeling HVAC faults. The research described in this paper identifies, characterizes and prioritizes common faults of HVAC equipment and control systems, some of which are incorporated in EnergyPlus. This research primarily supports the objective of assessing the effect of HVAC faults on whole building performance – energy consumption, and occupant comfort – for use in retrofit decision analyses for existing buildings.

INTRODUCTION

With the growing focus on reducing energy use of existing buildings, the use of energy simulation tools for retrofit analysis and in support of retro-commissioning activities has become increasingly important. However, all current simulation tools suffer from assumptions that control strategies work as designed, and HVAC equipment performs as rated. Several studies have shown that this is not the case**.** When studying the discrepancy between measured and simulated building energy performance, Norford *et al.* (1994), noted that an excess energy use within the building of up to 12% could be attributed to HVAC equipment not operating as specified, building conduction heat losses in excess of design stage predictions and minimum outdoor air intake differing from design values. Lee *et al.* (2009) documented the energy penalty associated with various air-side system faults. Their findings suggested that a single VAV box damper being stuck open on every floor could cause excess cooling energy use of 36%. As part of their fault detection and diagnosis studies, several authors have highlighted energy wastage caused by HVAC faults in buildings. Katipamula and Brambley (2005) found that poorly maintained, degraded and improperly controlled equipment wastes an estimated 15% to 30% of energy in commercial buildings. As all these studies have demonstrated, buildings are almost never operated as designed and equipment invariably fails or has faulty operation over the period of occupancy. As characterized by Haves (1997), these faults can either be abrupt, like a temperature sensor that suddenly fails, or they can develop over time, like a temperature or humidity sensor drifting over time, also called degradation faults. Fouling of heat exchange devices is another example of degradation faults. Wang *et al.*, (2009) also used the terminology hard and soft faults when referring to abrupt and degradation faults respectively. However, here we use the terminology, and deal only with, abrupt and degradation faults.

Given that industry readily acknowledges buildings are not operated or controlled ideally, it is to be expected that there would be wide differences between measured and predicted energy performance of buildings. Tools should provide the ability to model faults that may be expected to develop over a certain period of time, or faults that have been identified through retro-commissioning studies, which are typically conducted before any major retrofit targeted at energy savings is undertaken.

IDENTIFICATION OF COMMON HVAC FAULTS

Several sources of information regarding commonly occurring HVAC faults were identified. The most useful source found was a report produced by IEA Annex 25 (IEA 1996), a collection of reports on fault detection and diagnosis from researchers in a number of different countries. In addition to the IEA Annex documents, useful information was also found in the doctoral theses of Shun (2009) and Siegel (2002), as well as an ASHRAE Research Project, ASHRAE 1043-RP, conducted by Comstock and Brown (1999). These three studies covered common faults in secondary HVAC systems, fouling in heat exchangers and faults related to chillers respectively. Comstock and Brown (1999) also presented results on the frequency of occurrence and cost of repair of chiller faults in addition to identifying the most commonly found ones. While it is not possible to implement models of all the faults identified in this project in a whole building simulation program, a number of them were selected for EnergyPlus implementation based on their energy or comfort impact and their relative frequency of occurrence. In the interest of time, prioritization weightings was also assigned to the ease of implementation of the faults in EnergyPlus. Faults that require more detailed and complex models will be implemented in the next phase of this project.

Table 1 presents the faults that are documented as part of this study. Very little in terms of research has been conducted in the area of modeling strategies for common HVAC faults. Haves (1997) described two primary

methods for developing quantitative models of faulty HVAC component behaviour. One is the 'first principles model' i.e. a model based on a scientific analysis of the process, and the second is an 'empirical or black box model' that can be described by a neural network. As was further discussed by Haves (1997), faults may either be described by their effect on the performance of the component, or by their physical nature. It should noted that the development of fault models is hampered by the scarcity of measured data on the effects of individual faults on performance of HVAC equipment.

Table 1 lists some of the commonly occurring faults identified through the literature survey. The symptoms described are a combination of the qualitative effects of faults on performance. Of the faults presented in Table 1, four faults were chosen based on the selection criteria mentioned earlier for detailed modelling and implementation. Modeling strategies for each of these four faults are discussed in the next section. These modeling strategies are based on simplifying assumptions due to the lack of quantitative data in this area. Some faults require the addition of model parameters to specify fault severity while a few are simulated by modifying the parameters of the correct operation model. The faults that have been implemented in EnergyPlus are clogging of pipes in the plant loop, fouling of water heating coils, leaking outside air economizer dampers and zone temperature sensor offset. The next phase of the project will consist of modelling and implementation of some more faults from Table 1.

Table 1
List of common HVAC faults identified for implementation in EnergyPlus

Components	Faults	Symptoms
Boiler	Fouled water tube	Decreased boiler efficiency due to the increased thermal resistance of water tubes
Boiler	Steam pressure sensor out of calibration	Higher than expected flue gas temperatures result in reduced boiler efficiency if the sensor has negative offset. Lower than desired steam pressure if the sensor has positive offset.
Chiller	Fouled condenser	Decreased chiller efficiency and increased condenser outlet temperature
Chiller	Refrigerant leak	Reduced condenser pressure and compressor capacity, lead to inefficient cooling
Heating/Cooling coil	Valve or actuator stuck open or close	Unneeded simultaneous heating or cooling can occur if valve stuck open. If stuck closed, comfort penalty due to no heating or cooling when required
Heating/Cooling coil	Fouled coil	Reduced UA reduces coil capacity. Increases pump power (compensated for by reduced load)
Fan	Stuck at full/intermediate speed, fails to respond to control signal	Higher energy consumption if fan is stuck at speed higher than required. Reduced indoor air quality when it is stuck at lower speed
Mixing box	Stuck outdoor air damper	Outdoor air damper cannot modulate, resulting in energy penalty when outdoor air conditions are favourable for free cooling or minimum outdoor air is demanded for mechanical heating/cooling modes
Mixing box	Leaking outdoor air damper	Result in energy penalty when leakage rate is higher than the demanded outdoor air-flow rate. The energy impact may or may not be significant depending on system type, economizer type and building location.
Temperature sensor	Temperature sensor offset (SAT, RAT, OAT)	Outdoor air damper, return air damper and heating/cooling valve improperly controlled, resulting in energy penalty and thermal comfort issues.
Water distribution system	Clogging inside the pipe	Increase in the loop pressure drop causes higher energy consumption. Possible comfort issues due to insufficient water flow rate in the plant loop.
Pump	Stuck at full/intermediate speed, fails to respond to control signal	Higher energy consumption if pump is stuck at speed higher than required. Reduced indoor air quality when it is stuck at lower speed

Water distribution system	Poor pipe insulation/condensation on pipe	Depending on the location of the piping, can cause higher energy consumption due to thermal losses. Possible maintenance issue due to condensation on the chilled water pipe surface
VAV Box	VAV damper stuck	Can cause significant simultaneous heating and cooling and comfort issues depending on which position the damper is stuck at
VAV Box	Fouled reheat coil (water side)	Reduced heat transfer coefficient reduces coil capacity. Increased pump power (compensated for by reduced load)
VAV Box	Clogged/dirty reheat coil (air side)	Reduced heat transfer coefficient as well as increased pressure drop across coil
VAV Box	Reheat coil valve stuck	Unintended heating depending on which position the valve is stuck. Can cause comfort issues
Zone	Room air temperature sensor offset	Energy penalty and comfort issues depending on direction of offset

MODELING STRATEGIES FOR SELECT HVAC FAULTS

As noted in the previous section, four faults from Table 1 were selected for development of modelling strategies and EnergyPlus implementation. The following is a description of the implemented models:

1. Fault: Clogging in the plant piping loop.

   Symptom: Increased pump head, resulting in increased pump energy use.

   Model inputs: pump name, change in total loop pressure drop at design conditions due to clogging.

   Approach: EnergyPlus models a system curve for the entire plant loop.

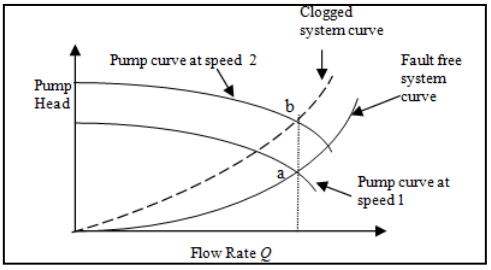


Figure 1 Effect on clogging on loop system curve

As shown in Figure 1, the presence of obstructions in the plant loop will change the system curve. To maintain the flow rate, the pump motor will switch to a higher speed as illustrated by the performance point moving from 'a' to 'b' in Figure 1. The resistances in the plant loop are illustrated in Figure 2.

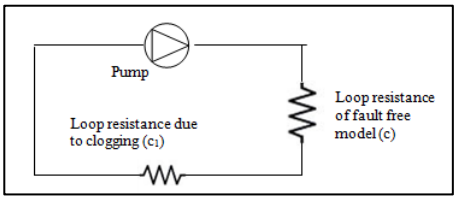


Figure 2 Plant loop resistances

For the clog-free pipe, the design pressure drop is given by:

$$\Delta P_{d,ff} = c * Q_d^2 \qquad (1)$$

where

c = resistence characteristic of clog-free portion of pipe

Q_d = water flow rate at design conditions

The measured design pressure drop across the clogged portion of the pipe (input provided by user) is given by:

$$\Delta P_{d,f} = c_1 Q_d^2 \qquad (2)$$

where

c_1 = resistence characteristic of clogged portion of pipe

The value of c_1 is calculated from Equation 2. The pressure drop across the clog is given by:

$$\Delta P_{p,f} = c_1 * Q_p^2 \qquad (3)$$

where

Q_p = water flow rate at part load conditions

The total pressure drop around the clogged circuit is:

$$\Delta P_f = (c + c_1) * Q_p^2 \qquad (4)$$

The pump power is:

$$Power = \Delta P_f * Q / \eta \qquad (5)$$

where,

Q = volumetric flow rate

η = fan efficiency, assumed constant

This model is only applicable for the case of a variable speed pump used in the plant loop. It also assumes that the pump can run at the higher speed required to offset the effect of the clogging.

2. Fault: Leaking economizer outdoor air damper.

   Symptoms: The actual mixed air temperature differs from the expected mixed air temperature when the damper is nominally closed. The economizer will lose the ability to control outdoor air fraction when the demanded outdoor air flow fraction is less than the leaking outdoor air flow fraction. This will lead to an energy penalty due to heating or cooling of excess outdoor air.

   Model inputs: outdoor air controller name, outdoor air leaking flow fraction.

   Approach: EnergyPlus does not currently model dampers and it assumes ideal control of dampers operating within the air loop. The leakage flow fraction is used to overwrite the calculated fault-free flow fraction when the leakage flow fraction is higher than the fault-free calculated flow fraction:

$$Q_{OA} = max(Q_{OA,f}, Q_{OA,ff}) \qquad (6)$$

   where

   $Q_{OA,f}$ = flow rate calculated from user specified leakage flow fraction

   $Q_{OA,ff}$ = flow rate calculated for fault-free model

   Figure 3 depicts the faulty versus fault-free operation of a leaking outside air damper.

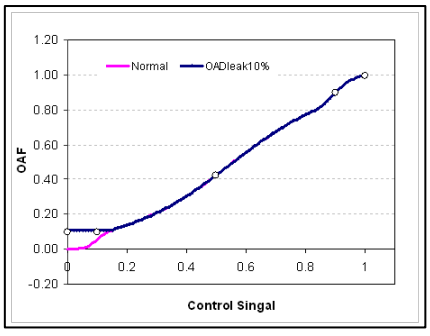


Figure 3 Effect of outside air damper leakage

3. Fault: Fouled water heating coil.

   Symptom: Reduced overall heat transfer coefficient (UA) causes reduced coil capacity and decreased temperature rise.

   Model inputs: heating coil name, inlet and outlet air and water temperatures

Approach: The fault model currently applies only to the simple Coil:Heating:Water coil model in EnergyPlus. The inlet and outlet temperatures entered by the user are used to calculate a new log mean temperature difference (LMTD) value for the fouled water coil:

$$LMTD = (\Delta T_A - \Delta T_B) / \ln(\Delta T_A/\Delta T_B) \quad (7)$$

where,

ΔT_A = temperature difference between the water inlet and the air outlet
ΔT_B = temperature difference between the air inlet and the water outlet

Using the new LMTD, a modified UA value for faulty operation is obtained from:

$$UA = Q / LMTD \quad (8)$$

where

UA = Product of thermal conductance and heat transfer area

Q = Heat transfer rate

The Coil:Heating:Water coil model in EnergyPlus assumes cross-flow geometry with both fluids unmixed. Equation 8 is not exact for this configuration but is a reasonable approximation for conventional heating coils, where the temperature differences between the fluids, ΔT_A , ΔT_B , are relatively large compared to the temperature change for each fluid. UA for the fault-free coil model is then overwritten by the new UA.

4. Fault: Room air temperature sensor offset.

   Symptom: The room air temperature sensor measurement deviates from the true value. The bias is constant.

   Model inputs: zone name, sensor offset

   Approach: The value of the offset is used to modify the schedule that determines the zone temperature set-points. The set-point is not overwritten for a sizing run. Equation 9 below defines the relationship used for modeling this fault.

$$T_{zsp,f} = T_{zsp,ff} - \Delta T \quad (9)$$

   where

   $T_{zsp,f}$ = effective zone set-point temperature for the faulty sensor case

   $T_{zsp,ff}$ = effective zone set-point temperature for the fault-free case

   ΔT= difference between the zone temperature reading and the actual zone temperature

When creating the modeling strategy for each fault, one of point of consideration was to select the fault modeling parameter that might be the easiest for a typical user to obtain. For example, when trying to model the clogging of a pipe, the parameter for fault severity selected is the change in the total pressure drop at design conditions.

ENERGYPLUS IMPLEMENTATION

EnergyPlus (2011) is the US Department of Energy's whole building energy simulation program. EnergyPlus in its current form can be used to model faulty component systems and sub-systems directly as done in the study by Lee *et. al* (2009).. However, direct modeling of faulty HVAC components can be a laborious and inflexible process. It limits users to modifying existing model input variables and requires the user to be extremely well versed with component models within the program. This limitation places an unnecessary burden on the user and can be a barrier to the simulation of faulty operations.

EnergyPlus also offers the use of a scripting language called the Energy Management System (EMS). EMS is primarily intended to be used for implementing control strategies within buildings. Some of the faults discussed above can be modeled using the EMS runtime language scripting facility. However, EMS scripting is meant for advanced users of EnergyPlus. EMS requires users to write their own control logic and, in most cases, has the limitation of only overwrite schedules during run time. Not all fault modeling strategies require only runtime modification of schedules.

Reusable fault models objects on the other hand do not require knowledge of internal component model implementation in EnergyPlus. They relieve the user of the burden of identifying modeling strategies for the faults to be simulated.

A new group of fault modeling objects has been created. Adding new simulation objects to EnergyPlus is a two step process. In the first step, an input data structure for each new model is defined. These data structures are added to the Input Data Dictionary (IDD) file of EnergyPlus. The IDD structure contains the complete definition

of all inputs associated with a particular object. Once the IDD structure is in place, the second step is to write code that reads input in the format specified above from an EnergyPlus Input Data File (IDF), the run time building data definition. Code also needs to be written and integrated within EnergyPlus to make the necessary modifications to inputs and outputs based on the fault model being simulated.

Another important aspect of the reusable fault model objects is the ability to distinguish between abrupt and degradation faults. Fault type is an input parameter that is part of the IDD structure for each fault model. The treatment of each fault model varies depending on its type. When a fault is described to be abrupt in nature, the applicability schedule is applied as an on-off schedule. The fault will be simulated starting from the time the schedule has a value of 1 and the building will be simulated to operate normally for a value of 0. In case of a degradation type of fault, the schedule can take a fractional value and will allow the user to model an HVAC fault getting progressively worse over time.

Implementation was carried out for each of the four fault models described in the previous section in a development version of EnergyPlus. Once these models and implementation strategies have been vetted and approved by the full EnergyPlus development team, they will be part of future official EnergyPlus release versions.

ASSESSMENT OF FAULT IMPACTS

A preliminary assessment of the energy impacts of the faults described above was carried out using the large office building model that is part of the DOE Commercial Reference Building Models (DOE, 2011). These standard reference models are created to represent 'typical' buildings found across the building stock in the US covered by the Commercial Buildings End-Use Consumption Survey administered by the Energy Information Agency (EIA, 2003). The reference models are intended to represent roughly 70% of the commercial building stock in the US. The assessment was carried out for two representative climates: Atlanta and Chicago. The large office building model is a twelve storey 498,588 square foot building that is constructed with one core and four perimeter zones on each floor. It has a standard overhead VAV system for each floor with one boiler and two chillers in the plant loop. The building envelope prescriptive minimums and HVAC system efficiencies are set as per ASHRAE 90.1 2004 requirements.

The results from simulations conducted for the climate of Chicago and Atlanta are shown in Figures 4 and 5 presented at the end of the paper. The results show the percentage change in HVAC cooling, heating, pump energy and the total HVAC energy use as compared to the baseline. A positive number represents an energy penalty.

A baseline or reference simulation run was carried out. Each fault model was added to this baseline and simulated individually. Finally, all fault models were added to the large office building and the combined model was simulated. For the sensor offset fault, both positive and negative offsets for the zone sensors were simulated as separate cases.

As regards the severity of the faults simulated, pipe clogging was simulated to cause a 20% increase in the chilled water loop total pressure drop at design conditions and a leakage flow fraction of 20% was specified for the leaking damper fault. A degradation of 20% in the UA was specified for the fouled heating coil and offsets of 0.5 K and -0.5 K were specified for positive and negative sensor offset fault model.

The results agree qualitatively with the expected behaviour of each fault model. Cooling energy increased very little in Chicago for any of the fault models. As expected, we only see increase in cooling energy use for a positive sensor offset and the case of all faults combined case with positive sensor offset. In terms of heating, the effect is more pronounced with Chicago being a heating dominated climate. The increase in heating energy use as compared to the reference ranges from a minimum of 2.5% for the leaking damper case to a maximum of 12.2% for the combined fault effects with the negative sensor offset. Pump power increase also ranges from 0.2% to 2.8% based on the fault simulated.

We see a decrease of energy use for heating when cooling increases or vice versa in certain cases. This is particularly true in case of the fouled water heating coil. The reduced UA reduces the heating capacity of the coil. Therefore, the zone heating set point cannot be maintained, particularly on some colder days. It is observed that there is a 20% comfort penalty calculated based on the time the zone set point was not met during occupied hours for heating. The heating energy use is reduced and there is a small increase in pump power as the hot water pump runs faster to compensate for the reduced heating capacity.

Figure 5 shows the results from a similar simulation exercise carried out for Atlanta. Like the Chicago results, the figure compares energy use for cooling, heating and pump operation for the implemented faults with respect to a fault free baseline. In Atlanta, the impact on cooling energy use is of higher magnitude. Cooling energy increase ranges from 1.3% for the all faults with positive sensor offset case to almost 13% for the damper leak

case. The heating also shows generally higher numbers ranging from 2% to 21% for the cases of negative sensor offset and when the negative offset is combined with the other fault models. Pump energy shows relatively similar behaviour as in Chicago with a range from 0.04% to 3.6% increases for certain faults. Similar to Chicago, the heating coil fouling also results in a modest increase in the number of heating unmet hours.

The results also give us a general idea of the magnitude of the energy performance penalty imposed due to each type of fault. Sensor offsets have the greatest energy impact followed by damper leakage, pipe clogging and heating coil fouling in that order. However, the energy penalty depends on the severity of each fault.

CONCLUSION

A number of common HVAC equipment faults were identified and detailed fault models were generated for four of them. These fault models have been added to a developmental version of EnergyPlus. The four fault models were tested for accuracy of implementation. The results indicate that the presence of HVAC faults can influence total HVAC energy use by as much as 22%, depending on the type of faulty behaviour and the severity of the faults under consideration.

Results from simulations carried out using fault models can also be used to help identify faulty behaviour from a set of measured data, as well as for developing automated fault detection and diagnosis algorithms.

ACKNOWLEDGEMENT

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State and Community Programs of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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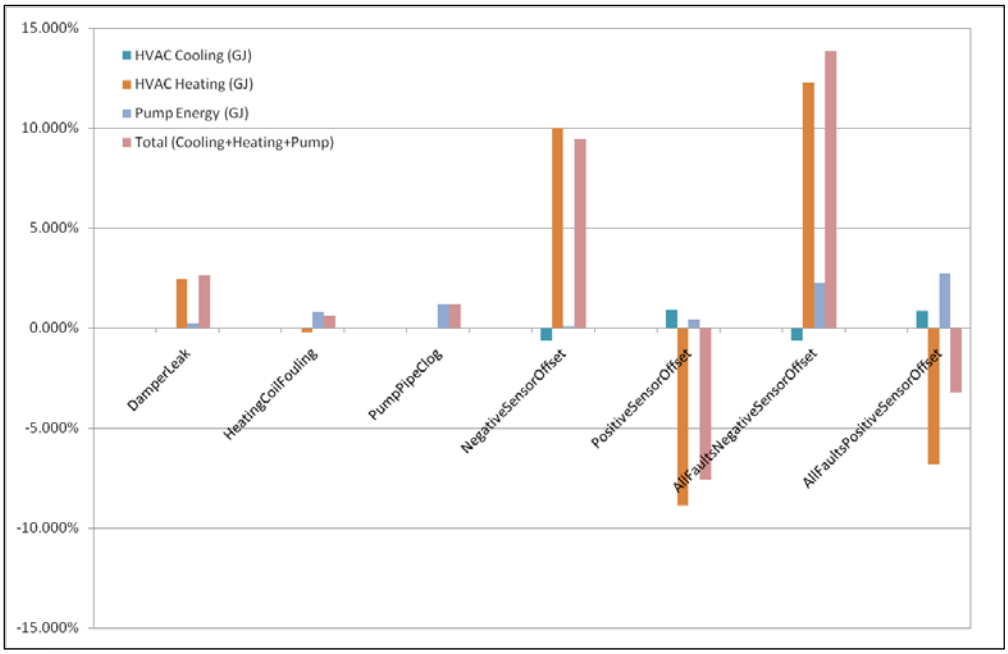


Figure 4 Large Office Simulation Results, Chicago

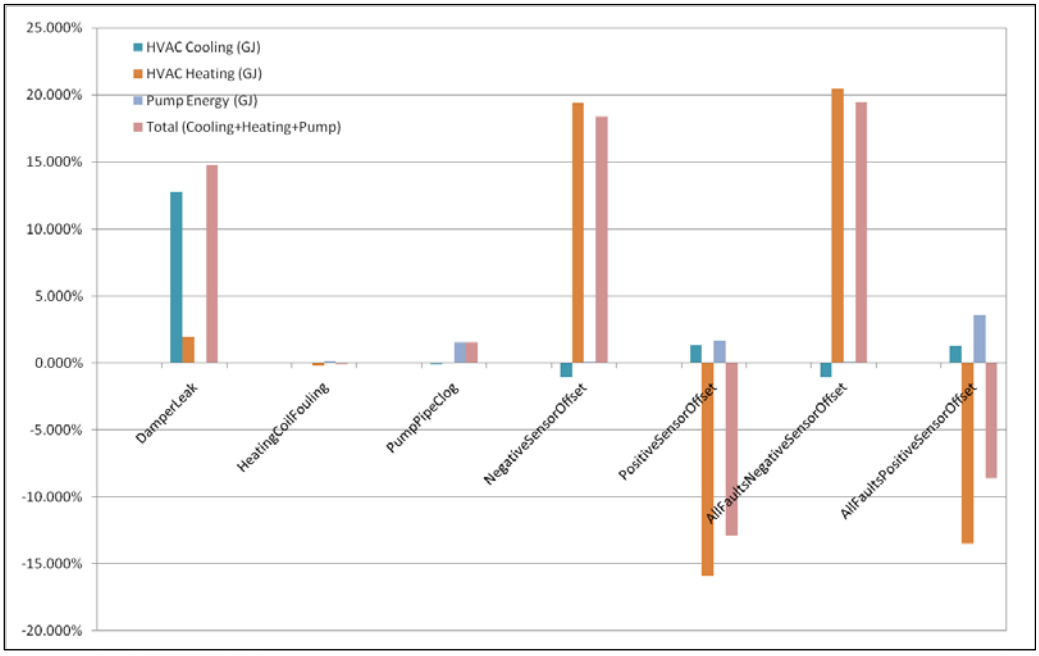


Figure 5 Large Office Simulation Results, Atlanta