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An EnergyPlus / OpenStudio-based Fault Simulator for Buildings

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ABSTRACT

Building energy systems often consume in excess of 20% more electrical energy than was the design intent largely because of equipment performance degradation (e.g., filter or heat exchanger fouling), equipment failures, or detrimental interactions among subsystems such as cooling and then reheating of conditioned air. Identifying the root causes of efficiency losses is challenging because a gradual erosion of performance can be difficult to detect. Furthermore, diagnostic algorithm performance is limited by available fault ground truth data. An analytical framework and model-based simulation capability is desired to develop fault ground truth data that can be used to deploy robust diagnostics for building energy systems including building envelope, lighting, Heating, Ventilation and Air-conditioning (HVAC) equipment and systems, etc. Such fault simulators can also be used for fault impact analysis for risk management. An EnergyPlus/OpenStudio-based fault simulator is being developed for such purposes. EnergyPlus is a whole building simulation free program from DOE. This paper is focusing on the faults that are implemented using OpenStudio measures. These measures are created in OpenStudio Application or the Parametric Analysis Tool, which are written in Ruby scripts. These faults related measures act like add-on macro to make changes to the existing energy model to reflect faults. This fault simulator aims to simulate a variety of faults from building subcomponents and subsystems including building envelope insulation, occupancy schedule, air handler economizers, heating and cooling coils, fans, etc. The development of such a fault simulator using OpenStudio measures and testing results of fault impacts in terms of energy consumptions will be presented in this paper.

INTRODUCTION

Building heating, ventilation, and air-conditioning (HVAC) systems are very complex with many subsystems and equipment including cooling loops, heating loops, and auxiliary appliances (e.g., fans and pumps). It is not uncommon that HVAC systems and equipment fail to operate at the desired and normal conditions, leading to achieving up to 40% of the energy saving potentials (Narayanaswamy 2014). The failures, or faults, are categorized as either abrupt or degradation. (Haves, 1997). The typical abrupt faults are the sudden failure of equipment parts, like broken fans or stuck outside air dampers. The degradation faults usually go unnoticed like the fouled coils or the leaking valves that occur after some period of operation. The faults also cause the discomfort and poor indoor air quality for indoor environments (Mills 2010). Since the 1980s, fault detection and diagnosis (FDD) has received a lot of attentions and has been used to solve problems causing the abnormal energy consumption in buildings. For real HVAC systems, there are a number of FDD algorithms and tools available either by stand-alone software or embedded software (Hyvärinen and Kärki 1996). The International Energy Agency (IEA) Annex 25 investigated the building optimization and FDD (Hyvärinen and Kärki 1996), and they discussed the physical-model based FDD and data-driven based FDD (e.g., ARMAX model,).

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The IEA Annex 34 (Arthur and Jouko 2001) addressed the practical issues of HVAC FDD tools implementation in real buildings. But the model-based FDD methods are relying much on the accuracy of the reference models, which are sometimes not readily available. Yu and Paassen (2002) provided a general modeling method for model based FDD of building HVAC systems, which is composed of a hierarchical modeling procedure, parameterization and tunings. But this approach needs the integration of real data from building energy management system with the model. House and Vaezi-Nejad (2001) introduced a rule based FDD algorithm for air handling unit (AHUs) and validated its accuracy. For all these FDD algorithms, they need to be tested and validated using data that contains faults. Ideally, we would like to use the real operation data with known faults for this purpose. Functional tests in buildings could be performed to generate some faulty data. However, such a procedure is complicated, time consuming and sometimes cost prohibitive. An analytical framework and model-based fault simulation is well positioned for generating normal and faulty ground truth data to test different FDD algorithms. On the other hand, by studying the fault simulation, we can quantify fault impacts in terms of building energy consumption. This will enable facility managers to better understand the fault behaviors and the relationship between building energy consumption and faults.

Unfortunately, most of existing building simulation programs such as EnergyPlus (EnergyPlus 2015), TRNSYS (TRNSYS 2015), eQuest (eQuest 2015), etc. either have limited fault simulation capabilities or always assume normal status for HVAC systems and equipment. This paper presents a preliminary fault simulation using the OpenStudio platform. First, some background information about state-of-the-art fault simulation and OpenStudio will be introduced, and then fault modeling using OpenStudio Measures is illustrated using three typical faults (i.e., faulty outside air damper, faulty fan, and fouled heating coil). This will be followed by a case study of a fault impact analysis using a DOE medium office references building.

BACKGROUND

There are 417 building energy modeling and simulation programs listed on the DOE website (DOE 2015). However, most of them are not capable of fault simulation. Liu (1997) developed the AirModel, which is a building simulation tool for simple fault simulations of an airside system. But the AirModel cannot be used for HVAC waterside fault simulations. Liu et al. (2002) reviewed and assessed the AirModel for fault simulations of AHUs. They recommended EnergyPlus in lieu of AirModel for simulatiing faults. Nevertheless, EnergyPlus indeed has limited capabilities in fault simulation. Basarkar et al. (2011) identified and characterized 18 HVAC faults simulated in EnergyPlus with a goal to assess the fault impacts on building energy consumption and occupant comfort for retrofit analysis. It further demonstrated that EnergyPlus has a great potential for fault simulations. In the building community, researchers have been developing the dynamic faults models for building systems and equipment in Modelica (O'Neill and Chang 2011) as well.

OpenStudio provides a graphic interface of EnergyPlus for implementing the energy model changes and analyzing the energy influence thereafter. A measure in OpenStudio is a generic tool for model modification. A measure is a set of Ruby scripts (Ruby 2015) written by users for modifying specified parameters. It can be applied to individual models or generic models, which can greatly reduce the modeling time and efforts. The measures are usually used for energy efficiency and energy conservation purposes. Currently, there are a total of 185 measures for lighting, HVAC, reporting, etc. in NREL's Building Component Library (BCL) website (BCL 2015). For example, one of the measures is *Enable Economizer Control*. This measure can be used to control economizer (On/Off). Users can also develop their own measures for specific purposes. This feature makes the fault simulation possible through measures in OpenStudio that uses EnergyPlus as the simulation engine. Such fault simulation will only need a small portable interface written in Ruby scripts to be read into OpenStudio. Other fault simulation approaches include directly modifying the source code of OpenStudio/EnergyPlus, which is more time-consuming. Thus, OpenStudio measures provide much flexibility to manipulate the OpenStudio/EnergyPlus parameters and model variations. However, currently there are no fault-related measures in NREL's BCL (BCL 2015). One of the objectives for this pilot study is to create measures in OpenStudio for fault simulation in buildings. As long as the user can modify the parameters associated with building envelope, HVAC system, equipment, etc. into faulty states, a corresponding measure (if available) can be directly applied to simulate faults. For example, a fouled coil can be modeled by modifying the UA factor (defined as the product of overall heat transfer coefficient U (W/m^2-k [BTU/hr-sq.ft-F]) and the coil heat transfer surface area A (m^2 [ft^2]) using the measure described later in this paper.

METHODOLOGY

There are two ways to implement measures in OpenStudio. First, users can download the available measures from the BCL website and apply them to the baseline models directly, if these measures are the appropriate ones for the selected purpose. For example, the output reporting measures can be utilized to report available output variables from EnergyPlus in OpenStudio. Another way is to create the customized measure by following the instructions of the Measure Writing Guide (MWG 2015). The Measure Writing Guide is a good start for developing measures by object-oriented programming of Ruby to select or modify the appropriate EnergyPlus/OpenStudio objects of building envelope, HVAC system, equipment, operation schedules, etc. These measures can be translated, recognized, and implemented in OpenStudio. An important step is to explore the OpenStudio application and the user interface to mark down all the objects involved with the specific problem. Then following the Software Development Kit (SDK 2015) documentation, it is necessary to understand the inheritance diagram and member functions, where the user has to identify the appropriate models, functions, arguments, etc. After a customized measure is created, it is strongly recommended to debug the customized measure before any application.

In this paper, three faults measures are introduced. First, a general description of the fault itself and associated energy impacts is provided, followed by how the fault measure is created in OpenStudio. Then, functions related to the fault parameters that the user needs to modify or add directly are described. An inheritance diagram from the SDK documentation to assist the measure development is also provided.

1. Faulty outside air damper (stuck minimum damper position)

During normal operation of an air side economizer, the outside air fraction will vary based on the comparison of dry bulb air temperature (or enthalpy) between outside air and return air to achieve as much free heating or cooling as possible. During operation, the minimum damper position could become stuck at a higher percent open due to control loops or mechanical problems. The economizer would have no control of the normal minimum outside air fraction with such a fault. The outside air damper would vary between a higher minimum position and the maximum according to the control logic and operation. Bringing more outside air into the system when the system is required to be operated with a minimal outside airflow rate. This will lead to energy waste by heating the extra cold outside air in the winter and cooling the extra hot outside air in the summer.

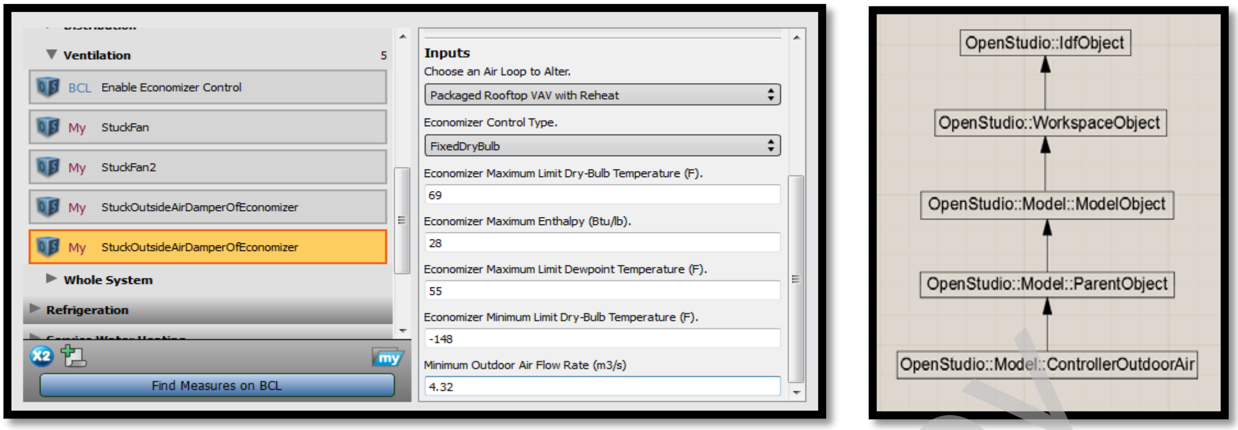
In OpenStudio/EnergyPlus, the amount of outside air is decided by the outside air controller. In this study, the minimal outside air flow rate is the product of the given minimum outside air flow rate and the minimum outside air schedule. (Note: There are other ways to define the minimal outside air flow rate in EnergyPlus.). The prerequisite is that the economizer be enabled (BCL 2015). In this fault measure, the minimal outside airflow rate can be modified by users. The measure also assigns a schedule for the minimal outside air flow rate. The minimum amount of outside air entering the HVAC systems is calculated by:

$$V_{air} = V_0 \times \mathrm{k} \qquad (1)$$

Where V_{air} is the actual (faulty) minimal outside airflow rate entering the system (m^3/s [CFM]), V_0 is the normal minimal outside air flow rate (m^3/s [CFM]), k is the schedule factor of the minimal outside airflow rate.

As an example presented in the study (see details in the next section), the minimal outside airflow rate is changed from 0.72 m^3/s (1,526 CFM) at the normal state to 4.32 m^3/s (9,154 CFM) for the faulty state. A snapshot of this measure's graphical user interface (GUI) in OpenStudio is shown in Figure 1(a). The inheritance diagram (SDK 2015) is a graph illustrating the complicated inheritance relationships among different objects of object-oriented programming in OpenStudio. This diagram helping helps developers to obtain proper functions for various measures development.

A snapshot for the inheritance diagram of faulty outside air damper measure is shown in Figure 1(b).



(a) Measure GUI Snapshot (b) Measure Inheritance Diagram Snapshot

Figure 1 Faulty Outside Air Damper Measure

2. Faulty supply fan with a stuck minimum speed

During normal operation, the variable air volume fan will vary the air flow rate according to the demand side airflow requirements. The airflow rate will vary from the minimum airflow rate to the maximum air flow rate. This faulty fan with a faulty minimum speed assumes the fan is out of control either due to a non-functional motor controller or damaged control communications. The fan will move more air than is required when stuck at a higher speed, or it will move less air when stuck at a lower speed. The fan power consumption and airflow rate are related as described in Equations (2)-(4) (EnergyPlus Engineering Reference 2015), where the fan performance curve equation (Equation (3)) is crucial.

$$f_f = m / m_{\max} \tag{2}$$

$$f_{pl} = c_1 + c_2 f_f + c_3 f_f^2 + c_4 f_f^3 + c_5 f_f^4 \tag{3}$$

$$Q_p = f_{pl} m_{\max} \delta P / (e_{tot}\, \rho_{air}) \quad or \quad Q_p = f_{pl} m_{\max} \delta P / (6350\, e_{tot}\, \rho_{air}) \quad (IP \quad unit) \tag{4}$$

Where m is the actual mass flow in kg/s (lb/min), $m_{\max}$ is the maximum flow or design flow in kg/s (lb/min), $c_1 \sim c_5$ are the 5 fan power coefficients, f_f is the flow fraction, δP is the design pressure rise in Pa (in. of water), e_{tot} is the fan total efficiency, ρ_{air} is the air density at the standard condition in kg/m^3 (lb/ft^3), f_{pl} is the part load factor, Q_p is the total fan power in W (hp).

When the system is required to be operated at the minimum airflow rate, a fan with a larger than the normal minimum speed will result in a higher flow fraction and a higher part load factor correspondingly. Therefore, this fault will increase the total power consumption whenever the system is operated compared to operating at the normal minimum airflow. When operating with an airflow rate between the faulty minimum airflow rate and the maximum airflow rate, there are no impacts on fan power consumption. An example of this measure is when the nominal fan minimum airflow rate is 0.0 m^3/s (0.0 CFM), we can change it to 4.0 m^3/s (8,476 CFM) to mimic a fan at a higher minimum speed.

3. Fouled heating coil

The fault simulation of a heating coil depends on the type of heating source, which could be gas, electricity, water, etc. In this paper, we present the principles of fouled heating coils for water and gas. During normal operation, the heating water coil works with a constant UA (the product of overall heat transfer coefficient and heat transfer surface area) value. After some degradations, the fouled heating coil will have a smaller UA value. This fault can be treated like introducing an extra thermal resistance to the heating coil. The equation to calculate UA value is given by:

$$UA = \frac{1}{R_x + \frac{1}{UA_0}} \tag{5}$$

Where UA is the actual reduced UA value of the fouled heating coil, R_x is the extra thermal resistance of the fouled heating coil due to the fouling, UA_0 is the nominal UA value for the unfouled or clean heating coil.

In OpenStudio/EnergyPlus, the fouled heating coil measure was implemented by giving the nominal UA value and the fouled factor. The equation is given as:

$$UA = UA_0 \times (1 - \mathrm{a}) \tag{6}$$

Where a is the UA downgrading coefficient with a range of [0, 1). This coefficient must be less than 1 because the UA value cannot be zero in reality.

The fault simulation for a gas-fired heating coil can be implemented by simply modifying the gas burner efficiency. During normal operation, the gas-fired heating coil works with a default gas burner efficiency (e.g., 0.8). In a fault situation, the gas burner efficiency will decrease, perhaps due to insufficient combustion. In this case study, the gas burner efficiency was changed to 0.4 for the faulty state directly using a developed measure.

CASE STUDY

In this section, an OpenStudio building model is used to simulate fault impacts from the three fault measures introduced in the previous sections. A general procedure for such a fault impact study such as this is summarized below:

- (Step I) Create the building and HVAC baseline model in OpenStudio. Run the simulation and obtain the building energy consumption for the baseline.
- (Step II) Identify the faults to be studied and obtain the model parameters to be modified, create or select the model measure for faults, and apply the measure to the model. Run the simulation and obtain the building energy consumption in faulty conditions.
- (Step III) Compare and analyze the building energy consumption for the two scenarios (normal vs. faulty).

The building model used in this case study is the DOE Medium office commercial reference building (DOE 2015). This office building has a total area of 53,628 ft^2 (4,982.2 m^2) with a total of 3 floors. The selected location is Chicago, Illinois. The reference building has no exterior shading or window shading. The HVAC system is the packaged DX rooftop unit (RTU) with a gas-fired heating coil. Each floor is served by one RTU. The air terminal units are VAV boxes with electric reheat coils. Since DOE reference building is not directly available in OpenStudio, we created an OpenStudio model using the EnergyPlus model as a starting point. The details of input parameters in OpenStudio are taken from the ASHRAE Standard 90.1-2004, Field et al. (2010) and Deru et al. (2010). The three fault simulations, namely, faulty outside air damper, faulty fan and fouled heating coil, are implemented in separate simulations through the three measures mentioned above in OpenStudio. The measures are applied to all three RTUs.

The annual building energy consumptions for electricity (MWH/MMBTU) and natural gas (GJ/MMBTU) for the normal case and three faulty cases are listed in Table 1 and Table 2 below. (MWH=10^3Kwh, MMBTU=10^6BTU, GJ=10^9J)

Table 1 Electricity Consumption

Electricity/MWH(MMBTU)	Normal	Faulty OA Damper	Faulty Fan	Fouled HC
Heating	163.74(558.70)	199.43(680.49)	163.78(558.85)	163.74(558.70)
Cooling	91.63(312.65)	100.13(341.66)	102.63(350.19)	91.63(312.65)
Fan	10.23(34.89)	12.68(43.26)	59.44(202.83)	10.23(34.89)
Total	571.48(1949.95)	618.12(2109.11)	631.74(2109.11)	571.48(1949.95)

Table 2 Natural Gas Consumption

Natural Gas/GJ(MMBTU)	Normal	Faulty_OA_Damper	Faulty_Fan	Fouled_HC
Heating	279.18(264.61)	1,132.35(1073.26)	209.04(198.13)	558.36(529.22)

Faulty Outside Air Damper. The comparisons of air temperatures of the first floor RTU related with the airside economizer for one typical summer day (July 21st) are presented in Figure 2 (Return Air Temperature, Outside (Intake) Air Temperature, Supply Air Temperature of RTU, Mixed Air Temperature). The blue line denotes the temperatures for the normal case and the black dash line denotes the temperatures for the case with a faulty economizer. We can see the mixed air temperatures are different between the normal and faulty cases, similar to the return air temperature. RTU supply air temperatures are also different between the normal cases and faulty cases. Such simulated faulty data can be used to test different FDD algorithms for economizer faults. The comparisons of energy consumption between the normal and faulty cases with a faulty outside air damper (stuck in minimum damper position) are shown in Figure 3.

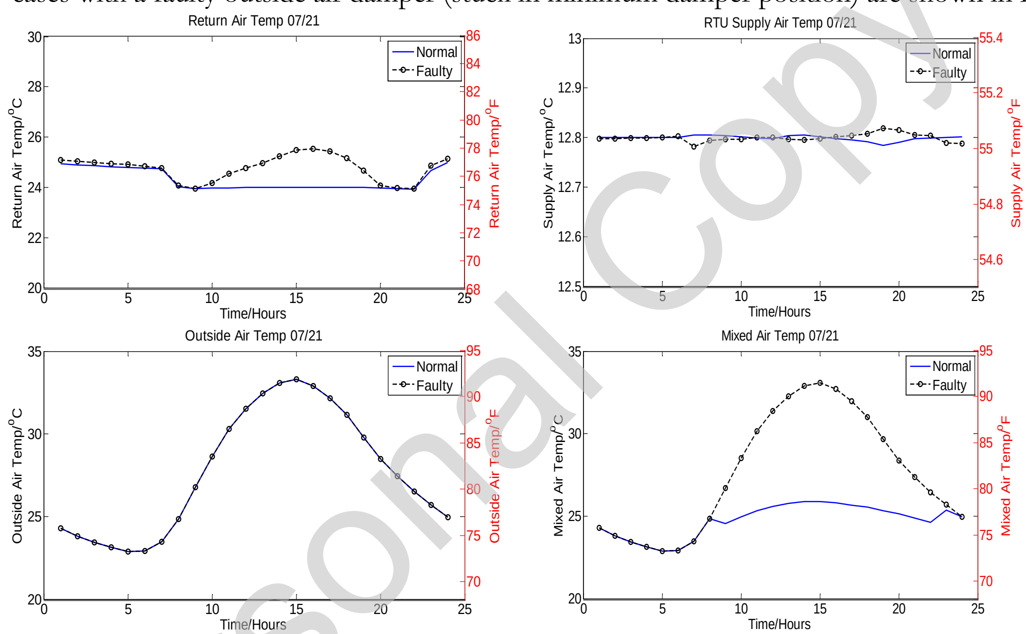
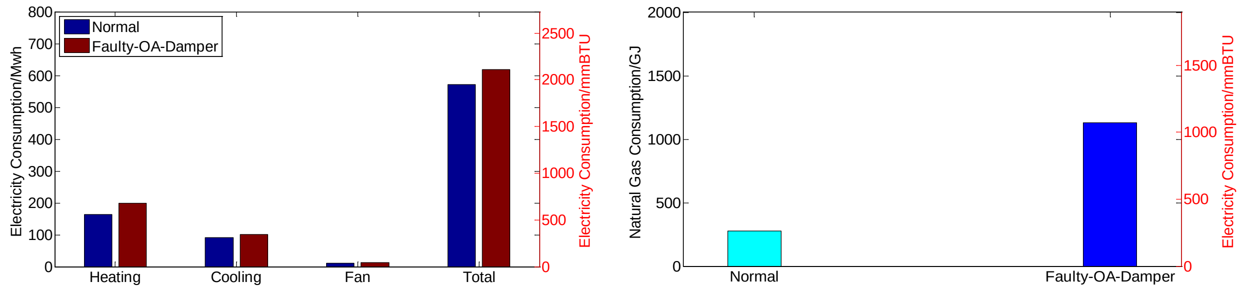


Figure 2 Air Temperature Comparisons for the Normal and Faulty Cases (Outside Air Damper)

The minimum outside air fraction stayed constant as 16.2% (calculated from the OpenStudio/EnergyPlus output variables) for fresh air ventilation demands in the normal case. In faulty states with a higher minimum airflow rate, the extra outside air caused a penalty for building energy consumption of electricity and gas. The VAV reheating coil energy demand increased by 21.8%, the RTU DX cooling coil energy demand increased by 9.3%, the fan energy demand increased by 24.0%, and the total electricity consumption increased by 8.2%. We can also see the energy penalty in natural gas consumption, where the gas consumption increased by 305.6%. This is consistent with our expectations for faulty outside air damper operation regarding electricity consumption and gas consumption.

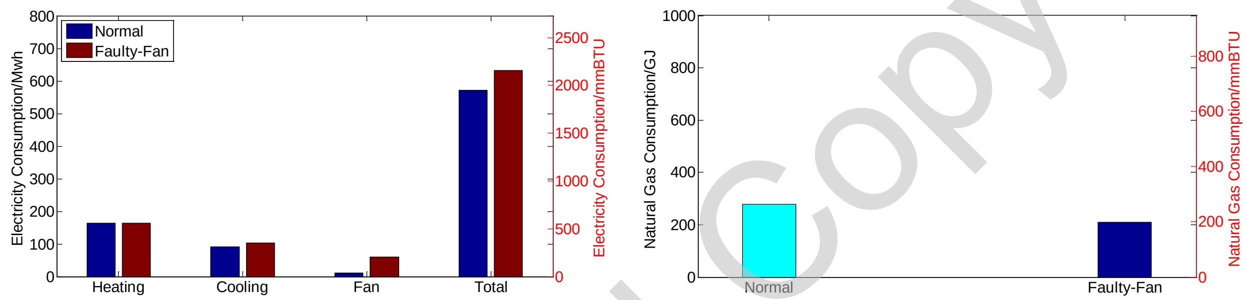
Faulty Supply Fan. The fan is a variable volume fan in the normal case. The faulty fan is operated at a speed between a higher minimum airflow rate and the given maximum airflow rate. The building energy consumption for both faulty and normal cases is plotted in Figure 4. In the cooling season, the electricity consumption for VAV reheating coil had almost no change, RTU DX cooling coil increased by 12%, the fan electricity consumption increased by 481.4%, and the total electricity consumption increased by 10.5%. The natural gas consumption decreased by 4.6%.

Fouled Heating Coil. The change in gas burner efficiency also had a big impact on the energy consumption in this case study, as shown in Figure 5. The electricity consumption from VAV reheating coils, RTU DX cooling coils and fans were the same for both cases. However the natural gas consumption in the faulty case increased by 200% in the heating season. This is due to the fact that natural gas consumption is proportional to the gas burner efficiency in the EnergyPlus modeling principle.



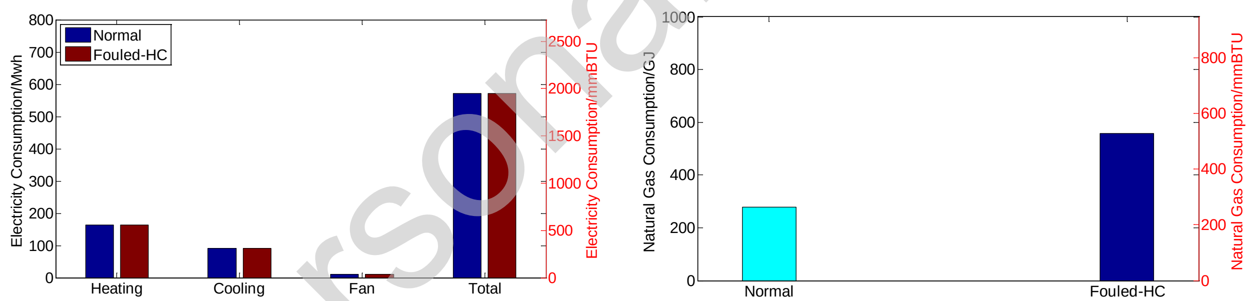
(a) Electricity Consumption (b) Natural Gas Consumption

Figure 3 Building Energy Consumption for a Faulty OA Damper



(a)Electricity Consumption (b) Natural Gas Consumption

Figure 4 Building Energy Consumption for Faulty Supply Fan



(a)Electricity Consumption (b) Natural Gas Consumption

Figure 5 Building Energy for a Fouled Heating Coil

These three faults all have considerable influence on the total building energy consumption. The case with a faulty outside air damper consumed more energy for both cooling and heating systems. The case with a faulty supply fan required more electricity consumption in the cooling season while less natural gas consumption in the heating season. The case with a fouled heating coil consumed more natural gas.

CONCLUSION

From this preliminary pilot study, we can see that the measures of OpenStudio provide an easy and scalable way to implement the faults of building envelope, HVAC systems, and equipment, etc. The data generated from this fault simulator and impacts of faulty HVAC systems and equipment on building energy consumption are consistent with what was expected. These results can be used as ground truth data for the development and validation of FDD algorithms for building applications. Thus, developing fault measures is a good approach to study the fault impacts in the simulation environment. The measures work like a portable interface to OpenStudio/EnergyPlus. However, there are some concerns in developing measures. These concerns include a required familiarity with Ruby language and capability of retrieving the appropriate member functions from OpenStudio for model change from SDK documentation. The OpenStudio program also has some limitations for fault simulation, such as limited HVAC systems available in current version (V1.7.0). Also, customized outputs other than EnergyPlus outputs are not available. An alternative powerful approach is to modify and recompile the source code of OpenStudio after adding more customized features. This alternative approach provides more freedom in developing customized HVAC systems and fault simulation measures, but is more time-consuming due to extensive code development for the energy modeler. Another good approach could be to develop generic measure GUIs for users to create customized measures by using a simple drag and drop method from the model objects instead of writing Ruby scripts.

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