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HVAC DEGRADATION AND ASSET MANAGEMENT– A NOVEL APPLICATION OF WHOLE BUILDING SIMULATION

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ABSTRACT

Heating, ventilation, and air-conditioning (HVAC) systems are crucial to maintaining habitable indoor environments. Enormous efforts have been spent in improving HVAC energy efficiency and indoor thermal comfort. Many simulation tools are available in this domain. However, most studies do not include system reliability and performance degradation, and few tools are dedicated to the performance assessment of HVAC systems for prolonged period. This study explores the possibility of using simulation techniques to estimate asset degradation. Asset loads are obtained from whole building energy simulation (EnergyPlus); and the degradation process is modeled as a combined consequence of operation and aging. Building models and degradation models are linked through EnergyPlus "External Interface". In addition, the effect of potential maintenance actions can be evaluated with such a setup. The technology demonstrated here is the foundation of the Building Energy Asset Management (BEAM) application, which provides predictive and evidence-based optimal solutions to HVAC maintenance.

INTRODUCTION

Buildings, both residential and commercial, account for over 40% of US annual energy consumption, 75% of electricity, in particular (EIA, 2012). HVAC systems are among the biggest energy consumers in buildings (USDOE, 2011). Numerous studies have proved that a considerable amount of energy can be saved by optimal operation and controls (Doukas et al., 2007; Fong et al., 2006; Huh & Brandemuehl, 2008; Mathews & Botha, 2003; Miyajima et al., 2007; Zhu et al., 2012). However, little - if any - attention has been drawn to performance decline and energy waste due to the lack of good state of repair and maintenance practices. It is widely known that energy transfer or conversion efficiency of HVAC system decays over time for a number of reasons. For example, fouling in cooling coils will raise chilled water pump load. Coolant leakage can reduce chiller's coefficient of performance (COP). Lack of lubricant increases friction of motors, so excess energy gets consumed by fans and pumps. In addition, equipment degradation can also lead to the failure of environment controls, which can be very costly.

In practice, routine inspections and scheduled or reactive maintenances are often performed to monitor, and - to some extent - mitigate the equipment degradation. However, these actions are usually expensive. Most of time, their cost-benefit relation may not be straight-forward. For this reason, property operators are seeking approaches that can justify their maintenance plans, with budget limits included in consideration. In order to find out what the optimal maintenance strategy for a system is, it is necessary to understand the degradation processes of mechanical systems. Studies reveal that degradation processes are rarely static. Instead, deterioration rate is closely related to (1) type of equipment, (2) environment condition, (3) load history, and (4) maintenance actions (Misra, 2008). Previous studies on equipment maintenance generally assume an average work environment and constant load. The strategies developed based on such assumptions are weakly founded - because variations in building configuration and operation can be significant. This study will develop a simulation platform that is able to capture environment conditions in a specific building configuration, while linking high frequency dynamics of building thermal behavior with relatively slow degradation of individual assets.

Many software packages are available for building energy simulation (USDOE, 2013). In this study, EnergyPlus developed by the United State Department of Energy (Crawley et al., 2001) is selected to build the simulation platform. It is originally used for design verification, code compliance and retrofitting plan validation, with emphasis on building energy consumptions. This whole building simulation platform is becoming popular in HVAC control optimization studies, in recent years. EnergyPlus simulation requires information about building architecture, system layout, equipment specification, control logics and operation schedules. Weather data is a separate input into the simulation. Within each simulation time-step, the software solves partial derivative equation (PDE) systems regarding mass/heat transfer in all zones, equipment and circulation loops. All processes are modeled deterministically, rather than stochastically (LBNL, 2013b).

EnergyPlus has an "External Interface" module that can exchange data with other programs via socket (LBNL, 2013a). In each simulation step, this module receives data from socket and maps it to three types of EnergyPlus variables, namely, "ExternalInterface: Schedule", "ExternalInterface:Actuator" and "ExternalInterface:Variable". Once that is complete, the simulated system status can be passed to the socket. This function extends EnergyPlus functionality for users by linking it with customized modules. An example of this application is given by Building Control Virtual Test Bed (BCVTB) - developed by the Lawrence Berkeley National Laboratory (LBNL) (Wetter & Haves, 2008). BCVTB serves as a server application that bridges two clients, one of which is the EnergyPlus simulation. The other client can be other simulation software (e.g., MATLAB and Dymola), physical hardware (e.g., control panel), or BACnet stack. Similar to BCVTB, MLE+ is a package of MATLAB scripts that turns MATLAB into server and exchanges data with EnergyPlus (Nghiem). Such coupled simulations, or co-simulation scenarios have been studied (Djunaedy et al., 2005; Elliott, 2000; Murakami et al., 2001; Pang et al., 2012; Sagerschnig et al., 2011; Trčka & Hensen, 2007; Trčka et al., 2009, 2010; Wetter, 2010; Wetter & Haves, 2008). The degradation simulation presented in this article adopts the MLE+ co-simulation platform and adds degradation models to EnergyPlus.

The rest of this article is organized as follows: Section 2 describes the design of the co-simulation platform, Section 3 details the degradation models of several HVAC components and modeling of maintenance actions, Section 4 presents a simple case study, and Section 5 discusses the application of this techqniue.

CO-SIMULATION PLATFORM

The co-simulation platform requires at least four pieces of information: (1) MATLAB program, (2) EnergyPlus model, (3) external interface configuration, and (4) weather input. The weather input requirement is not different to the one for ordinary EnergyPlus simulation. Special modifications are needed for the other three inputs.

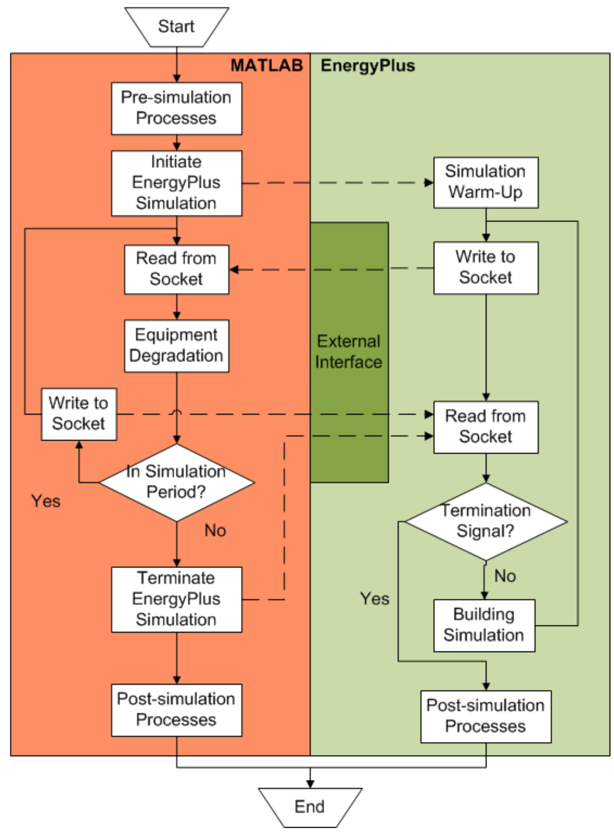

Figure 1 Co-simulation work flow

MATLAB program

As depicted in Figure 1, the work flow of co-simulation starts with the construction of EnergyPlus simulation process (*mlepProcess*) object in MATLAB. Object features, likes model file name, weather input file name, simulation time step, and maximum number of steps are configured at this time. Then the *start* method is called, which executes the simulation program, establishes the socket, and puts MATLAB program into “listening”. Data exchange starts when MATLAB program reads the output of EnergyPlus (*read* method), followed by passing the data stream to EnergyPlus (*write* method). Proper encoding and decoding are necessary to ensure that the protocol is followed by both sides of the communication. The data exchange stops when the total number of cycles is reached. Then, a signal is sent to terminate the EnergyPlus simulation (*stop* method).

EnergyPlus model

Original EnergyPlus model needs to be modified to activate its "External Interface". This can be done by, first, creating an "ExternalInterface" object. The following line will be added to the model.

```
ExternalInterface,
        PtolemyServer;
```

Three types of EnergyPlus variables can receive values from "External Interface". They can be defined as demonstrated in the follows.

```
ExternalInterface:Schedule,
        Supply Fan AvailSchd,
        On/Off,
        1;
ExternalInterface:Actuator,
        SF_TotalEff,
        Supply Fan,
        Fan,
        Fan Total Efficiency,
        0.7;
ExternalInterface:Variable,
        ExampleVar,
        1;
```

In the model snippets above, the first segment defines an "ExternalInterface:Schedule" object named "Supply Fan AvailSchd" that is of "On/Off" schedule type with initial value "1" ("On"). The second segment defines an "ExternalInterface:Actuator" object named "SF_TotalEff". It is the "Fan Total Efficiency" feature of the object named "Supply Fan", which belongs to "Fan" class. This feature has initial value set at "0.7". And the third segment defines an "ExternalInterface:Variable" object named "ExampleVar" with initial value "1".

The output variables, whose values will be passed from EnergyPlus to MATLAB in each data exchange cycle, should also be defined in the EnergyPlus model. The following lines define that the "Chiller Part Load Ratio" feature of "Chiller 1" object and "System Node Volume Flow Rate Current Density" feature of "Supply Fan Outlet 1" object will be output every "timestep".

```
Output:Variable,
        Chiller 1,
        Chiller Part Load Ratio,
        timestep;
Output:Variable,
        Supply Fan Outlet 1,
        System Node Volume Flow Rate Current
        Density,
        timestep;
```

External interface configuration

"External Interface" requires its configuration saved, with xml style annotation, to a separate file named "variables.cfg". The following shows the file that configures the data exchange of the above inputs and outputs. More details about EnergyPlus-MATLAB co-simulation can be found in (LBNL, 2013a) and (Nghiem).

```
<?xml version="1.0" encoding="ISO-8859-1"?>
<!DOCTYPE BCVTB-variables SYSTEM
"variables.dtd">
<BCVTB-variables>
  <variable source="EnergyPlus">
    <EnergyPlus name="Chiller 1"
      type="Chiller Part Load Ratio"/>
  </variable>
  <variable source="EnergyPlus">
    <EnergyPlus name="Supply Fan Outlet 1"
      type="System Node Volume Flow Rate
         Current Density"/>
  </variable>
  <variable source="Ptolemy">
    <EnergyPlus schedule="Supply Fan
      AvailSchd"/>
  </variable>
  <variable source="Ptolemy">
    <EnergyPlus actuator="SF_TotalEff"/>
  </variable>
  <variable source="Ptolemy">
    <EnergyPlus variable="ExampleVar"/>
  </variable>
</BCVTB-variables>
```

DEGRADATION MODELS

This article focuses on the impact of asset degradation on energy consumption; "degradation" is defined as the efficiency decrease of energy conversion and energy transfer processes. More specifically, a *condition index* (or *CI*) is used as a common metric that measures the energy efficiency of different assets. As shown in Equation (1), *CI* is defined as the ratio of nominal (expected) power usage (P_t^n) to the actual one (P_t), at time *t*.

$$CI_t = \frac{P_t^n}{P_t} \times 100 \qquad (1)$$

CI has range of 0~100. Normally, *CI* between 88 and 100 represents "excellent" conditions, and 0~10 represents "failed" conditions. According to an empirical model that assumes exponential efficiency decay on mechanical systems, an asset's energy performance correlates with its *effective age* ($A_{eff,t}$), using *CI*, as shown in Equation (2) (Hendron, 2006).

$$A_{eff,t} = \alpha \log(CI_t) + \beta \qquad (2)$$

where, α and β are component specific constants.

The effective age has unit of time, such as hours or days. It increases when the asset is in use and resets when a maintenance or repair action is conducted. In contrast, the *actual age* increases according to the clock, and has nothing to do with the condition of the asset. The increase of effective age can be quantified by Equation (3) (Kahle, 2007; Kijima et al., 1988; Misra, 2008).

$$A_{eff,t+\Delta t} = \left(A_{eff,t} + \eta L \Delta t\right) \times (1 - r) \tag{3}$$

where, L is the part load ratio (or PLR), which is defined as the ratio of load to capacity. And r is the *restoration factor* of a maintenance action. The restoration factor is an empirical measure of maintenance efficacy. It has a range of 0~1, and is specific to both asset type and action type. If no maintenance action is taken during the period $[t, t + \Delta t]$, the restoration factor is 0, and the load related increment of the effective age is proportional to PLR, with coefficient η.

If constants α, β and η can be obtained from literature, r can be obtained from expert opinion, maintenance log or metering data, and initial effective age, $A_{eff,0}$, can be assessed from metering data, it is possible to calculate *CI* based on the simulated load at any time. *CI* will be then converted to the energy efficiency measure for each different asset. Simulation of *CI* degradation is programmed in MATLAB.

Electrical chiller

The "Chiller:Electric:EIR" object in EnergyPlus models electrical centrifugal chiller performance based on user provided performance information at reference conditions and three performance curves. The performance curves calculate the chiller's cooling capacity and efficiency under off-reference conditions (LBNL, 2013b).

The three performance curves are (1) cooling capacity as function of temperature curve, or *CapFTemp*, (2) energy input to cooling output ratio (EIR) as function of temperature curve, or *EIRFTemp*, and (3) EIR as function of PLR curve, or *EIRFPLR*.

CapFTemp curve is a biquadratic function of the leaving chilled water temperature and entering condenser fluid temperature. It adjusts chiller cooling capacity when the fluid temperature is different to the reference value.

EIRFTemp curve is also biquadratic function of the same temperature variables as in *CapFTemp*. And *EIRFPLR* curve is a quadratic function of chiller's PLR. These two curves adjust the chiller's EIR (which equals to the reciprocal of chiller's COP) with respect to the fluid temperature and chiller load. When the chiller is fully ON, its power is calculated by Equation (4).

$$P = \frac{Q_{ref}\,PLR}{COP_{ref}} CapFTemp \bullet EIRFTemp \bullet EIRFPLR \tag{4}$$

In this study, *CapFTemp* and *EIRFTemp* curves are assumed to be static (i.e., the curve coefficients do not change), while *EIRFPLR* curve object is replaced by an "ExternalInterface:Actuator" object, whose value is calculated by the chiller degradation model from the MATLAB, using Equation (5).

$$EIRFPLR = \frac{100}{CI} \tag{5}$$

Meanwhile, the chiller PLR will be provided to MATLAB by the simulation. Such objects are defined as follows.

```
ExternalInterface:Actuator,
        Chiller_EIR_fPLR,
        EIRFPLR,
        Curve,
        Curve Result,
        1;
Output:Variable,
        Chiller 1,
        Chiller Part Load Ratio,
        timestep;
```

The corresponding lines in the configuration file are shown below.

```
<variable source="Ptolemy">
     <EnergyPlus actuator=
         "Chiller_EIR_fPLR"/>
</variable>
<variable source="EnergyPlus">
     <EnergyPlus name="Chiller 1"
         type="Chiller Part Load Ratio"/>
</variable>
```

Fan

The electric power of fans depends on the power of air movement (i.e., the output power), the mechanical efficiency (from motor to air), and the electrical efficiency (from drive to motor). The latter two efficiencies are often combined as one "total efficiency" term (Equation (6)).

$$P_{ref} = \frac{Q_{air,ref}}{e_{mech} e_{elec}} = \frac{Q_{air,ref}}{e_{tot}} \tag{6}$$

where, P_{ref} is fan power at reference condition, $Q_{air,ref}$ is fan reference output power, e_{mech}, e_{elc} and e_{tot} are fan mechanical, electrical, and total efficiencies, respectively, at reference condition(LBNL, 2013b).

In EnergyPlus, the fan objects of "Fan:ConstantVolume" or "Fan:OnOFF" type are modeled based on Equation (6). The fan total efficiency of such objects can be overridden by the "Fan Total

Efficiency" actuator, whose value is obtained by Equation (7).

$$e_{tot} = e_{mech} e_{elec} \frac{CI}{100} \quad (7)$$

The object definition is shown as follows.

```
ExternalInterface:Actuator,
     SF_TotalEff,
     Supply Fan,
     Fan,
     Fan Total Efficiency,
     0.7;
```

Fan objects in the "Fan:VariableVolume" category are able to work at off-reference conditions, where the air volume flow rate is a fraction of its maximum value. Two performance curves are required to adjust the fan power based on reference power calculation. They are *PowerRatioCurve* and *EfficiencyRatioCurve*. *PowerRatioCurve* is a quartic function that adjusts air movement power based on PLR (calculated by actual volume flow rate divided by its maximum value). And *EfficiencyRatioCurve* is a cubic function that adjusts fan total efficiency based on PLR. Both curves output modification factors at each timestep. The overall mathematical representation of off-reference fan power is given by Equation (8) (LBNL, 2013b).

$$P = P_{ref} \frac{Power\ Ratio\ Curve}{Efficiency\ \ Ratio\ Curve} \quad (8)$$

Therefore, in addition to providing dynamic total efficiency by the "Fan Total Efficiency" actuator, an alternative method of modeling the degradation of fans of "Fan:VariableVolume" type could be by manipulating the *EfficiencyRatioCurve* output via "External Interface", as shown below and Equation (9).

```
ExternalInterface:Actuator,
       SF_TotalEff,
       Supply Fan EfficiencyRatioCurve,
       Curve,
       Curve Result,
       1;
```

$$Efficiency\ \ Ratio\ Curve = \frac{CI}{100} \quad (9)$$

EnergyPlus provides another method of modeling fan power based on detailed physics, which is referred to as "Fan:ComponentModel". This fan model type considers drive efficiency, motor efficiency and belt efficiency as separate dynamic parameters (LBNL, 2013b). Each parameter is governed by one or more performance curves, which can be overrided from "External Interface". The coding in the EnergyPlus model and the configuration file is similar.

EnergyPlus does not output fan PLR, however, this value can be easily derived from system air volume flow rate at supply fan outlet node.

```
Output:Variable,
       Supply Fan Outlet,
       System Node Volume Flow Rate Current
             Density,
       timestep;
```

And the corresponding lines in the configuration file are shown below.

```
<variable source="Ptolemy">
    <EnergyPlus actuator=
        "SF_TotalEff"/>
</variable>
<variable source="EnergyPlus">
    <EnergyPlus name="Supply Fan Outlet"
        type="System Node Volume Flow Rate
         Current Density"/>
</variable>
```

Boiler

In EnergyPlus, the boiler performance is calculated using nominal thermal efficiency, and adjusted by normalized boiler efficiency curve output, as described in Equation (10).

$$FuelUse = \frac{Boiler\ \ Load}{Thermal\ Eff \bullet Normalized\ EffCurve} \quad (10)$$

The normalized efficiency curve represents the boiler efficiency change at different load levels and/or operating conditions. The value of this curve can either be calculated by EnergyPlus curve object, or come from the "ExternalInterface:Actuator" object, as shown in follows, together with the definition of output object for boiler PLR.

```
ExternalInterface:Actuator,
       Boiler_Eff,
       Boiler Efficiency Curve,
       Curve,
       Curve Result,
       1;
Output:Variable,
       Boiler 1,
       Boiler Part-Load Ratio,
       timestep;
```

The degradation model gives the curve output by Equation (11):

$$Normalized\ EffCurve = \frac{CI}{100} \quad (11)$$

And the corresponding lines in the configuration file are shown below.

```
<variable source="Ptolemy">
    <EnergyPlus actuator=
        " Boiler_Eff "/>
</variable>
<variable source="EnergyPlus">
    <EnergyPlus name="Boiler 1"
           type=" Boiler Part-Load Ratio "/>
</variable>
```

Maintenance strategies

A maintenance strategy can be characterized by the following three parameters: (1) scheduled or reactive,

(2) frequency and (3) action class. A reactive strategy is defineed as a maintenance action that is conducted only under certain conditions (e.g., observed *CI* lower than certain customizable threshold), while a scheduled maintenance strategy specifies the action frequency without considering the actual condition of the asset. Typical action frequency is once every 3 months (seasonal), 6 months (semi-annual) or 12 months (annual). As discussed above, the impacts of maintenance actions are characterized by the restoration factor, *r*, which is associated with the asset type and the action class. Action classes 1, 2, and 3 mean an increasing amount of effort spent, and reasonably, different restoration factors will be expected. In this study, they are assumed to be 0.1, 0.2, and 0.3, respectively.

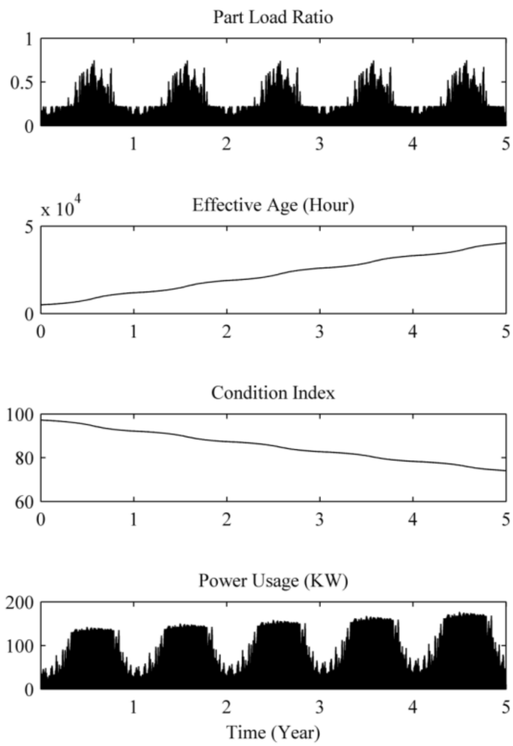

Figure 2 Chiller baseline performances (baseline)

CASE STUDY

In the case study, an EnergyPlus model was developed for a small one-story office/workshop facility, located in Mid-Atlantic region of North America. The building has 66,000 square feet conditioned area. The HVAC system includes one electrical centrifugal chiller, one gas fueled hot water boiler, and two air handling units (AHUs). As the purpose of this article is to demonstrate the possibility and the workflow of HVAC degradation simulation, the model calibration and validation are beyond the scope. For demonstration purposes, the chiller is the only asset subject to degradation and maintenance. Assumed values are used for the parameters of the chiller degradation model (Table 1).

A simulation for a period of five years is conducted, using the typical meteorological year (TMY3, (*National Solar Radiation Data Base*)) of the local weather as the weather input. Figure 2 depicts the simulated chiller performances in the baseline scenario, where there are no maintenance actions. The effective age monotonically increases, and the slope correlates with PLR. *CI* declines, accordingly, implying decreasing chiller efficiency. It also results in a higher demand. Observations on other assets, like boiler and fans, are similar, though results are not presented here.

Table 1 Degradation model parameters

ASSET	$A_{eff,0}$ (HOUR)	α	β	η
Chiller	5000	-130000	60000	3

We now consider potential maintenance strategies. Four scenarios are considered: no maintenance (Baseline), Class 2 action reactive to *CI* observation below 85 (Class 2 | *CI*<85), semi-annual Class 2 action, and annual Class 3 maintenance. (Figure 3)

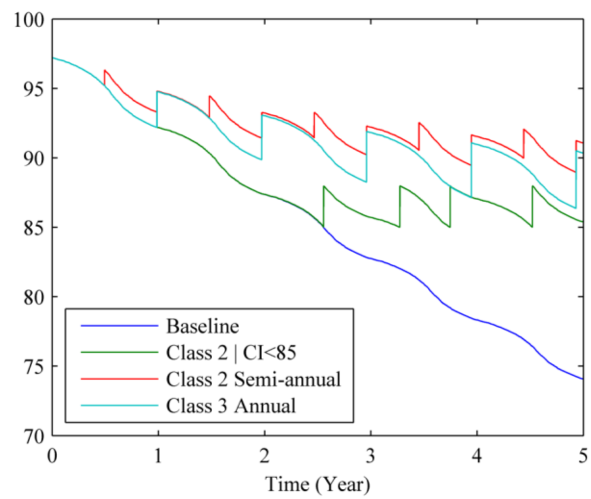

Figure 3 Chiller CI under different strategies

It appears that under "Class 2 | *CI*<85" strategy, no maintenance will be necessary until the summer of Year 3. And four maintenance actions will be needed in the last three years. In terms of energy saving (Figure 4) and asset condition, "Class 2 Semi-annual" strategy performs slightly better than "Class 3 Annual", however, both are significantly better than "Class 2 | *CI*<85". Finally, maintenance remarkably reduces energy consumption as the asset age increases.

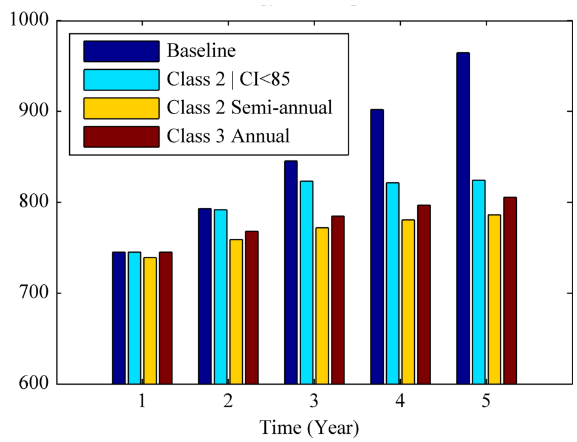

Figure 4 Chiller energy (MWH) under different strategies

DISCUSSION

In this study, the authors define *CI* for each energy consuming HVAC asset as the ratio between nominal energy usage and actual usage. Declining *CI* is related to the asset's effective age, and then to load history. The impact of maintenance actions is estimated by the restoration factor that quantifies the effective age change. Linking such degradation and maintenance models with whole building energy simulation enables quantitative and proactive evaluation over maintenance strategies. A simple case study is presented, and, although, the model parameters are not based on real data, performance engineering studies in other domains have demonstrated that they can be derived from literature, maintenance logs, and expert opinion (Kahle, 2007; Kijima et al., 1988; Misra, 2008).

The co-simulation technique demonstrated in this article provides a framework that links energy simulation with degradation simulation. This framework is also capable of simulating more types of degradation, not just degradation related to energy efficiency. For example, certain degradation processes decrease the asset capacity and result in thermal comfort violation or environment control failure (e.g. fouling). Previous studies have shown that it is possible to link the asset failure probability to its effective age (Mahani et al., 2014). Thus, it is appropriate to simulate such degradation and failures with the proposed framework.

A comprehensive software platform named Building Energy Asset Management (BEAM) is currently under development. BEAM integrates the co-simulation technique and the degradation/maintenance model demonstrated in this article, together with asset reliability model and building value model (Salahi et al., 2014). It minimizes energy cost, asset failure cost and maintenance cost by solving a multi-objective optimization problem. BEAM also has the capability of real-time condition monitoring and model retuning with trending data.

Several challenges exist with the proposed framework. Energy impact of certain degradation processes is not directly measurable. For example, the degradation on the building envelope will accelerate heat dissipation, but it is not easy to measure the energy waste from this process. Future research on measuring and modeling these degradation processes should be considered. The asset degradation model and building simulation model both require a large amount of data for model calibration. But data collection and model calibration are beyond the scope of this article.

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